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An Analysis of On-Farm Costs of Timing N Applications to Reduce N Losses

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Timing nitrogen applications to the biological needs of a crop is an effective way to reduce nitrogen losses to the environment. However, this strategy may carry a production risk and conflict with farmers' economic objectives. A field-level production decision model was used to estimate on-farm costs associated with timing nitrogen applications for crop needs in Indiana. For a risk-neutral farmer, the estimated cost is less than $1 per acre with a reduction of 11 pounds of residual nitrogen. For a risk-averse farmer, the estimated cost is up to $37 per acre with a reduction of 96 pounds of residual nitrogen.

Key words: application timing, compliance costs, environmental impacts, nitrogen

Introduction

The availability of nitrogen for plant uptake is one of the most important factors for a successful crop yield. As a result, farmers annually apply approximately 9.3 million metric tons of nitrogen fertilizer to crops (National Research Council 1993). However, nitrogen fertilizer also has contributed to contamination of surface- and groundwater through leaching and runoff (Nielsen and Lee; Phipps and Crosson). Nitrogen leaching can contaminate groundwater and threaten the safety of rural drinking water. Based on results of a 1990 national well survey administered by the U.S. Environmental Protection Agency (EPA), multiple drinking water wells in several states were found to have nitrate levels above recommended safety levels. Similarly, nitrogen runoff can cause the eutrophication of streams, rivers, and lakes which may damage ecosystems and biodiversity (National Research Council 1989). Farmers have several options for reducing the amount of residual nitrogen (nitrogen applied but not absorbed by the crop) in their production systems, including more accurately accounting for nitrogen inputs, using soil testing, determining realistic yield goals, and coordinating nitrogen applications with crop needs.

When applications are timed to coordinate with the biological needs of a crop, excessive application of nitrogen can be avoided so that less residual nitrogen is available

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for leaching, runoff, denitrification, and other losses. Because a single or split application during the growing season can match nitrogen supply to the crop's need without a reduction in yield, this practice often appears to be the least-cost method for applying nitrogen fertilizer. However, such a strategy may conflict with a producer's economic objectives when other cost factors are considered. For example, uncertain weather conditions may shorten the application window for growing-season fertilizer applications, increasing the risk of yield loss from inadequate nitrogen availability. Farmers' opportunity costs of labor also may be significantly higher during the growing season and late spring than during the late fall. Finally, fertilizer pricing patterns tend to encourage fall applications rather than spring or growing-season applications. Such economic considerations have led many farmers to apply nitrogen during the fall and early spring rather than during the growing season.

Several researchers have examined the impact of timing on yield (Polito and Voss; Stark and Tindall) and investigated farmers' decisions regarding timing of nitrogen applications (Feinerman, Choi, and Johnson; Huang, Uri, and Hansen). Following the analytical framework of Feinerman, Choi, and Johnson, and of Huang, Uri, and Hansen, we develop a field model to estimate the compliance cost of a timing restriction on nitrogen fertilizer applications at a particular field, considering the cost associated with the risk of failure to apply nitrogen. The model is used to analyze on-farm costs and the reduction in nitrogen fertilizer for corn farmers in the White River Basin of Indiana under an assumed timing restriction that would require farmers to apply nitrogen fertilizer only during the growing season. The environmental effect of the timing restriction in the Basin, measured by the reduction of residual nitrogen available for loss to the environment, also is examined.

A Field-Level Timing Decision Model

In this section, a field-level production decision model is presented for risk-neutral and risk-averse farmers to analyze how they make fertilizer timing decisions for a particular field. The field level is used for this analysis because the field is the target of most government cost-sharing programs for water quality improvement.

Consider the following production function:

$$Y(N_a \mid \mathbf{V}), \tag{1}$$

where yield (Y) is a function of the fertilizer-supplied nitrogen available for plant uptake during the growing season (N_a), and a vector of the site-specific variables such as the slope of the cropland, soil permeability, soil organic matter, and weather conditions ($\mathbf{V}$). It is assumed that $\partial Y/\partial N_a \geq 0$, and $\partial^2 Y/\partial N_a^2 \leq 0$, indicating diminishing marginal returns with each additional unit of nitrogen (a concave function). N_a is a decision variable, while $\mathbf{V}$ represents the characteristics of cropland over which a farm has very little control. The variable N_a is defined as:

$$N_a = N_f d_f + N_s d_s + N_g, \tag{2}$$

where N_f and N_s are the respective amounts of nitrogen fertilizer applied in the fall and spring before and at planting, and N_g is the amount of nitrogen fertilizer applied during the growing season. The parameters d_f and d_s represent the corresponding percentages of nitrogen applied in the fall and in the spring that is available for plant uptake during the growing season. In other words, these two parameters measure the relative effectiveness of the fall and spring applied fertilizer as opposed to the growing-season applied nitrogen fertilizer. The remaining portions of the fall and spring applied nitrogen fertilizers [$(1 - d_f)$ and $(1 - d_s)$] are not available to the plant, and may be lost to the environment before the growing-season application due to factors such as volatilization, denitrification, soil erosion, leaching, soluble nitrogen runoff, and nitrogen transformation in the soil. The amount of fall applied nitrogen fertilizer lost to the environment generally will be larger than that of spring applied nitrogen due to the highly unstable and movable nature of nitrogen fertilizer. When faced with an expected crop price of P_c; expected fall, spring, and growing-season nitrogen fertilizer prices of F_f, F_s, and F_g; and field operation costs of $C(N_f)$, $C(N_s)$, and $C(N_g)$ for fall, spring, and growing-season applications of nitrogen fertilizer, a farm will maximize expected utility of net farm income, $U(\pi)$:

$$\text{(3)} \qquad \text{Max } Z(N_a) = \text{Max } E[U(\pi)] =$$
$$\text{Max } E[U(P_c Y(N_a \mid \mathbf{V}) - F_f N_f - F_s N_s - F_g N_g - C(N_f) - C(N_s) - C(N_g))],$$

where E is the expectation operator, and π is net farm revenue. $U(\pi)$ is a monotonically increasing and concave von Neumann-Morgenstern utility function, where $\partial U(\pi)/\partial\pi \geq 0$, and $\partial^2 U(\pi)/\partial\pi^2 \leq 0$ (Anderson, Dillon, and Hardaker). Net revenue is defined here as total revenue less all nitrogen application costs. This is a useful simplification of the model since the focus of the study is on the compliance cost associated with a timing restriction. It is assumed that fertilizer prices, field operation costs, and the crop price are known.

Next, assume that farmers can always apply nitrogen fertilizer in fall and in spring before planting, and that they perceive a probability (P) of being unable to apply fertilizer during the growing season. This perception is a function of factors such as farmers' labor, capital, and budget constraints, as well as unknown weather conditions that can influence when and how fertilizer can be applied. Given the uncertainty of a growing season application, a risk-neutral farmer maximizes his or her expected utility of net farm income by maximizing expected profit (Arrow; Borch). The expected utility of a risk-neutral farmer becomes:

$$\text{(4)} \qquad Z(N_a \mid P) = E[U(\pi)] = (1 - P)U(\pi_1) + (P)U(\pi_2),$$

where

$$\pi_1 = [P_c Y(N_a \mid \mathbf{V}) - F_f N_f - F_s N_s - F_g N_g - C(N_f) - C(N_s) - C(N_g)];$$

$$\pi_2 = [P_c Y(N_a \mid \mathbf{V}, N_g = 0) - F_f N_f - F_s N_s - C(N_s) - C(N_s)].$$

Here, $Y(N_a \mid \mathbf{V}, N_g = 0)$ is the yield function when N_a includes no growing season nitrogen application. The objective function of a risk-neutral farmer becomes:

$$Z(N_a \mid P) = E[\pi] = (1 - P)\pi_1 + (P)\pi_2. \tag{5}$$

In contrast, a risk-averse farmer maximizes his or her expected utility of net farm income by maximizing the certainty equivalent, which is expected net income less the risk premium (Anderson, Dillon, and Hardaker; Newbery and Stiglitz). Generally, a large number of agricultural producers are risk averse (Wilson and Eidman; Tauer). Since the function for a risk-averse farmer in the Basin is not available, an approximate function is needed. For purposes of this study, the maximization of the expected utility function is formulated as the maximization of expected value-variance (EV) of net farm income. The objective function of a risk-averse farmer is approximated by equation (6) (Pratt; Robison and Barry):[1]

$$Z(N_a \mid P) = E[\pi] - \lambda \frac{\mathrm{Var}[\pi]}{2}, \tag{6}$$

where $E[\pi]$ is as defined in (5), λ is an assumed absolute risk-aversion coefficient, the term $\lambda * \mathrm{Var}[\pi]/2$ is the risk premium (Newbery and Stigliz), and the variance is defined as $\mathrm{Var}[\pi] = P(1 - P)(\pi_1 - \pi_2)^2$ (Huang, Uri, and Hansen).[2] The risk-aversion coefficient (λ) is zero for risk-neutral farmers and greater than zero for risk-averse farmers. As λ increases, the more risk averse a farmer becomes.

Maximization of the objective function [equation (6)] is used to determine the optimal application timings and application rates of nitrogen for risk-averse farmers. Equation (6) shows that risk-averse farmers maximize the certainty equivalent (CE) net revenue, which is expected net revenue less the risk premium. Consequently, the CE net revenue for a risk-averse farmer is expected to be less than the expected net revenue of a risk-neutral farmer except when P is equal to zero or one, where the variance collapses to zero, and the expected net return for a risk-neutral farmer is the same as the CE net revenue of a risk-averse farmer. Because specific information about the risk preference of a farmer in Indiana's White River Basin is not available, the absolute risk-averse coefficient used in this study is obtained from other studies. The absolute risk-averse

[1] The validity of using the maximization of an EV model as the approximation of the maximization of expected utility to analyze the effects of risk on the farmer's behavior requires assumptions about the utility function and absolute risk coefficient used in the EV model (Newbery and Stiglitz; Robison and Barry; Anderson, Dillon, and Hardaker). The key assumptions can be identified by examining the relationships between the utility of certain income (EV) and expected utility (EU). The Taylor's expansion of the farmer's utility of certain income, $U(E[\pi] - \omega)$, about the mean is: $EV = U(E[\pi]) - \omega U'(\pi) + \phi(v)$, where π is net income, ω is a risk premium, and $\phi(v)$ denotes other terms of the expansion. Also, the Taylor's expansion of the farmer's expected utility, $E[U(\pi)]$, about the mean is: $EU = U(E[\pi]) + (U''[\pi]/2)v + O$, where v is the variance, and O denotes the other terms of the expansion. Assuming both $\phi(v)$ and O are very small relative to other terms in the expansions, the equality condition ($EV = EU$) for these two Taylor's expansions is: $\omega = -U''(\pi)/U'(\pi)(v/2)$. The EV model then can be expressed as: $U(E[\pi]) - R(\pi)v/2$, where $R(\pi) = U''(\pi)/U'(\pi)$. If the change in net income is relatively small with respect to the farmer's overall wealth, $R(\pi)$ can be a constant (λ), and the model becomes: $EV = E[\pi] - \lambda(v/2)$.

[2] Two conditions are required for determination of the variance: (*a*) π_1 and π_2 are independent, and (*b*) both are constants corresponding to the farmer's perceived probability, P, of being unable to apply nitrogen during the growing season. The first condition is met because of the way the objective function (5) is formulated, i.e., a farmer either is able or not able to apply nitrogen during the growing season. The second condition also is met for the following reason: Before the planting, the farmer can determine the optimal nitrogen application rates for the fall and spring seasons, and the optimal application rate for the growing-season application, by maximizing the objective function (5) for a give value of P. Corresponding to the optimal application rates, the optimal values for π_1 and π_2 can be determined. With known π_1 and π_2, the farmer can compute the expected net income and the corresponding variance of net income.

coefficient (λ) is assumed to equal 0.02, which is the upper bound for a relatively high level of risk aversion for the situation when the utility function is unknown (Boggess and Ritchie).[3]

The optimal fertilizer timing obtained from the models must be validated because of the discontinuity effect of the fixed field operation costs. For example, consider a solution generated by the model suggesting that the local optimal application strategy is to make a split-season application, applying 190 pounds of nitrogen in the spring and 20 pounds of nitrogen in the growing season. This split-season application requires two field operations and may not be the global optimum. A possibility exists that the marginal net revenue of the additional yield attributed to the 20 pounds of nitrogen applied in the growing season may be less than the cost of an additional fixed-field operation required for the growing-season application, and that a single fertilizer application in the spring is the global optimum. To ensure this split-season application is indeed the global optimum, the net revenue of this split-season application must be greater than that of a spring-only application. If not, a spring-only application is the global optimum. This procedure is used later to determine the optimal application timing in case studies.[4]

Estimating the Compliance Costs

The compliance costs farmers face with a nitrogen timing restriction are estimated as the difference in expected net farm income (risk-neutral farmers) or the difference in the CE net revenue (risk-averse farmers) calculated with and without the timing restriction. To estimate this cost, first consider the options of an unrestricted farmer and then compare the net revenue generated by the optimal decision with the net revenue generated under the timing restriction.

The following analysis focuses on the effects of a restriction of spring application on a farmer's income under both risk-neutral and risk-averse management scenarios when the farmer can apply nitrogen fertilizer in the spring before planting and during the growing season.[5] An unrestricted risk-neutral or risk-averse farmer has three available

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[3] Boggess and Ritchie computed the scaled values of the absolute risk-averse coefficient for varying degrees of risk aversion. Their estimate of the absolute risk-averse coefficient for a high risk-averse farmer is 0.02. The coefficient unit is the rate of change in utility per dollar of net return per acre (Raskin and Cochrane). Comparing this value with the coefficients used by Boggess and Ritchie, the value is comparable to the coefficient used by Kramer and Pope. However, it is less than that used by Danok, McCarl, and White, but much larger than the coefficients used in other studies (McCarl and Bessler). Furthermore, for the P value between 0.05 and 0.10 (the likely range for the Basin), it is comparable to the upper bounds based on Chebyshev's inequality, but about 10 times larger than the upper bounds based on the statistical inference rule of normality distribution, and about 10 times less than the upper bounds based on the nonnegative certainty equivalent rule (McCarl and Bessler).

[4] A detailed discussion on the conditions under which a growing-season application only, a split-season application, a spring-season application only, or a fall-season application only is optimal is presented in Huang, Uri, and Hansen. To avoid the problem of discontinuity of the fixed-field operation cost (the fertilizer application costs excluding the nitrogen fertilizer cost), the optimization models probably can be reformulated and solved as a mixed-integer optimization problem. The fixed-field operation cost will become a variable cost to a farmer when considering an additional application of nitrogen fertilizer. However, the mixed-integer formulation is not used because the General Algebraic Modeling System (GAMS) (Brooke, Kendrick, and Meeraus), which was used for this study, is not designed to solve such problems.

[5] The analysis can be easily extended to include the fall application of nitrogen fertilizer. The fall nitrogen application is not the focus of this study because most nitrogen fertilizer applied in the fall generally will be lost to the environment before the growing season (Mesinger). In the White River Basin, over 50% of the fall application can be lost by leaching (Aldrich). Most farmers can reduce nitrogen fertilizer use by switching from the fall application to the spring application without reduction in net farm income unless the price of nitrogen fertilizer is much lower in the fall than in the spring. The fall nitrogen application has been restricted in central Nebraska where a high level of nitrate is found in the groundwater (Central Platte Natural Resource District).

application options: (*a*) apply all nitrogen during the growing season (growing-only), (*b*) apply nitrogen during both the growing season and the spring (split-season application), or (*c*) apply all nitrogen during the spring (spring-only). As previously discussed, we assume the growing-only and split-season application options have an associated probability of failing to apply nitrogen during the growing season (P). In contrast, the spring-only option is assumed to be a certain event. As a result, the expected net revenue generated by a spring-only application acts as a minimum level of profit a farmer can expect to receive in a given period.

For a risk-neutral farmer, the expected net revenue of a spring-only application ($N_s > 0$, and $N_g = 0$) for a given P can be derived from equation (5), and is expressed by equation (7):

$$Z(N_a \mid P, N_s > 0,\ N_g = 0) = E[\pi] = \pi_2. \tag{7}$$

Also from equation (5), the expected net revenue of a split-season application is shown by equation (8):

$$Z(N_a \mid P, N_s > 0,\ N_g > 0) = E[\pi] = (1 - P)(\pi_1) + P(\pi_2), \tag{8}$$

and the expected net revenue of a growing-only application is shown by equation (9):

$$Z(N_a \mid P, N_s = 0,\ N_g > 0) = E[\pi] = (1 - P)(\pi_1). \tag{9}$$

Notice that $E[\pi]$ is independent of P in equation (7), but not in equations (8) and (9). An unrestricted risk-neutral farmer weighs the net revenue generated in equations (7), (8), and (9) to make the optimal timing decision. An unrestricted risk-averse farmer would do the same using the certainty equivalent derived from equation (6).

For a risk-averse farmer, the CE net revenue for a spring-only application is the same as in equation (7); the CE net revenue for a split-season application can be obtained by equation (8), and for a growing-only application is shown by equation (10):

$$Z(N_a \mid P, N_s = 0,\ N_g > 0) = (1 - P)\pi_1 - (\lambda/2)P(1 - P)(\pi_1)^2. \tag{10}$$

Under a growing-only timing restriction, farmers must apply all nitrogen during the growing season. Consequently, the expected net revenue of risk-neutral farmers is expressed by equation (9), and the CE net revenue of risk-averse farmers is expressed by equation (10).

The compliance cost, $D(P)$, for both risk-neutral and risk-averse farmers is the difference between the expected maximum net revenue achieved without a timing restriction and the expected net revenue achieved with a timing restriction for a given level of P. This is shown in equation (11):

$$\begin{aligned} D(P) = \operatorname{Max}[&Z^*(N_a \mid P, N_s > 0,\ N_g = 0),\ Z^*(N_a \mid P, N_s > 0,\ N_g > 0), \\ &Z^*(N_a \mid P, N_s = 0,\ N_g > 0)] - Z^*(N_a \mid P, N_s = 0,\ N_g > 0), \end{aligned} \tag{11}$$

where Z^* is the optimal expected net revenue (or CE net revenue) corresponding to three different application timings. The first term on the right-hand side of equation (11) gives the maximum expected net revenue (or CE net revenue) without a timing restriction, while the second term on the right-hand side of the equation gives the maximum expected net revenue (or CE net revenue) with a growing-only timing restriction.

Note that the field-level model used here is likely to overestimate a farmer's compliance costs because the model does not consider alternative farming practices the farmer may use to minimize compliance costs (portfolio effects). For example, a risk-averse farmer can reduce compliance costs by growing corn after soybeans. Soybeans can provide a substantial amount of nitrogen in soil for subsequent corn production even though the farmer has failed to apply nitrogen during the growing season. The risk-averse farmer can harvest corn after soybeans to reduce compliance costs. Overestimation of compliance costs can be large, particularly for a risk-averse farmer. A farm-level model would have to be used to capture the portfolio effects.

Data and Assumptions

A production function was estimated using data from *The 1991 Area Studies Survey* for the White River Basin in Indiana [U.S. Department of Agriculture (USDA) 1991]. The data were collected as part of the President's Water Quality Initiative and were designed to link agricultural production activities to environmental characteristics for selected watersheds in the U.S. Each observation coincides with a sample point from the National Resources Inventory (NRI) survey which is conducted every five years. The White River Basin covers approximately 11,350 square miles, draining parts of central and southern Indiana. Agriculture is the primary land use in the region, accounting for 55% of the area. Of the agricultural land, 42% was planted to corn in 1991 (USDA 1993).

The data were restricted to isolate the impacts of nitrogen fertilizer. Therefore, the sample used for this study included only fields that grew full-season corn without manure or cover crops, planted corn the previous year, and applied nitrogen within a reasonable range of crop needs.[6] Under these restrictions, the survey yielded 96 usable observations. Fifty percent of these farms applied nitrogen fertilizer during the spring only (at or before planting). Another 40% split their nitrogen applications between the spring and growing season. Finally, a small group of farmers (10%) applied nitrogen only during the growing season. The average rate for spring-only applications was 170 pounds of nitrogen per acre, for growing-only applications the average rate was 142 pounds, and for split applications the average amount applied was 170 pounds per acre per year.

The perceived probability of farmers being unable to apply nitrogen fertilizer during the growing season (P) was estimated with a combination of expert opinion and published weather data. The weather data were collected for the White River Basin from 1961–90, and include cumulative rainfall during the growing season (National Climate

[6]The reasonable range was determined using the biological relationship between corn and nitrogen. The sample used must meet the condition that the minimum nitrogen application is set at 0.9 pounds of nitrogen per bushel of corn. This assumption was felt to be reasonable because one bushel of corn contains approximately one pound of nitrogen (Martin, Leonard, and Stamp).

Data Center). Experts determined that rainfall in excess of seven inches during June or during July would prohibit a growing-season application (Hawkins). According to time-series weather data, the probability of more than seven inches of rainfall during June or July is between 5% and 10%, with the probability varying by county (Hawkins). It is expected that the actual P for a given farm would be greater than the proxy because other factors such as soil type, machinery, and labor availability impact the feasibility of a successful fertilizer application. However, these other factors are farm specific, making it difficult to generalize across farms.

Finally, the price of corn was assumed to be $2.45 per bushel (USDA 1992); a spring broadcasting cost of urea fertilizer was $3.62 per acre, and $0.23 per pound of nitrogen applied; and a side-dress application of anhydrous ammonia was $6.65 per acre, and $0.13 per pound of anhydrous ammonia nitrogen. Broadcasting urea in spring and side-dressing anhydrous ammonia in the growing season are two common practices in Indiana (Doster 1990, 1993).

The Production Function

A quadratic production function was developed to estimate the relationship between corn yield and the timing of nitrogen fertilizer applications. This specification exhibits both increasing and decreasing marginal returns and can be used to estimate nitrogen losses associated with the timing of nitrogen fertilizer applied in corn production. Consider the following function:

$$
\begin{aligned}
(12) \qquad Y = {} & \alpha + a_1[N_s(d1) + N_g] + a_2[N_s(d1) + N_g]^2 \\
& + a_3KF + a_4RF + a_5SP + a_6Percent + a_7OM \\
& + a_8PH + a_9Rain + a_{10}PP + a_{11}K + a_{12}WC \\
& + a_{13}Date + a_{14}Temp + \epsilon,
\end{aligned}
$$

where N_s and N_g are as previously defined. The coefficient $d1$ is used to estimate the efficiency of nitrogen applied during the spring and is statistically derived. It represents the percentage of fertilizer applied in the spring that is available for plant uptake during the growing season. All other variables are related to weather, planting date, or soil characteristics, and are defined in table 1.

Results of White and Glejser tests (Maddala) indicate no evidence of heteroskedasticity. The matrix of correlation coefficients shows some correlations among the explanatory variables, but no significant evidence that the presence of correlation has had an effect on the estimation (Belsley, Kuh, and Welsch). The estimated coefficients on both the linear term and the quadratic term have the expected signs—positive and negative, respectively—and are statistically significant at the 5% level (see table 2). The positive sign on the first term of the quadratic function indicates that yield increases with each additional unit of nitrogen, and the negative sign on the second quadratic term suggests the presence of decreasing marginal returns with each additional unit of nitrogen applied. The coefficient $d1$ was statistically estimated; it indicates that 58% of the nitrogen applied during spring is available to the plant during the growing

Table 1. Definitions of Variables Used in Quadratic Corn Yield Production Function

Variable	Definition	Mean	Std. Dev.
Y	Yield (bu./acre)	106	53
N_s	Nitrogen applied in spring (lbs./acre)	98	159
N_g	Nitrogen applied in growing season (lbs./acre)	69	145
KF	Erodibility factor	0.35	0.12
RF	R-factor	185	44
SP	Soil permeability	1.32	0.53
Percent	% slope	2.61	6.64
OM	Organic matter (%)	2.44	2.17
PH	Soil pH	6.35	0.73
WC	Water-holding capacity	0.22	0.03
Temp	Sum of average monthly temperature (°F) deviations from the state's average in the growing season (June–August)[a]	8.15	3.83
PP	Phosphorus applied (lbs./acre)	67	80
K	Potassium applied (lbs./acre)	76	120
Date	Deviation from planting date[b]	2,260	4,285
Rain	Sum of rainfall deviation from the state's average in the growing season (inches)[c]	1.86	1.22

[a] The state's average temperature during the growing season is 72°F.
[b] Deviation from planting date is the difference between the planting date and the Basin's average planting date. For example, if the planting date of the sample is 5/20/91, and the Basin's average planting date is 5/02/91, the difference (52,091 - 50,291) is 1,800.
[c] The state's average rainfall is 16.2 inches.

season, and implies that 42% of the nitrogen is available for leaching and other losses.[7] As expected, both climate variables are significant at the 5% level. None of the site-specific variables were significant, suggesting that there may not be enough variability between observations in the survey.

The Baseline Scenario with No Timing Restriction

To calculate the compliance costs of a timing restriction on both risk-neutral and risk-averse farmers, it is necessary to determine how farmers in the White River Basin of Indiana would behave in the absence of a timing restriction. Maximizing the objective function [equation (5) for a risk-neutral farmer, and equation (6) for a risk-averse farmer] determines the optimal timing and application rate of nitrogen for corn farmers in the Basin.

[7] The estimated $d1$ from the quadratic function is comparable to the estimate from the linear plateau (LP) function (Frank, Beattie, and Embleton). The estimated $d1$ for the LP function is 0.62, while the estimate for the quadratic function is 0.58. Both estimates are statistically significant.

Table 2. Estimates for the Quadratic Corn Production Function

Parameters	Estimates	Std. Error	Approx. t-Ratio	Approx. Prob. > $\lvert t \rvert$
α (intercept)	33.745	95.335	0.35	0.7249
α_1 (linear term)	1.233	0.473	2.61	0.0108
α_2 (quadratic term)	-0.00373	0.001657	-2.25	0.0269
α_3 (*KF*)	-17.135	79.772	-0.21	0.8305
α_4 (*RF*)	-0.020	0.1983	0.10	0.9187
α_5 (*SP*)	-6.528	10.685	-0.61	0.5430
α_6 (*Percent*)	-0.484	0.987	-0.49	0.6252
α_7 (*OM*)	0.207	4.161	0.05	0.9605
α_8 (*PH*)	3.861	9.739	0.40	0.6928
α_9 (*Rain*)	11.861	3.451	3.44	0.0009
α_{10} (*PP*)	-0.0747	0.0724	-1.03	0.3057
α_{11} (*K*)	-0.0352	0.0464	-0.76	0.4501
α_{12} (*WC*)	-121.129	165.147	-0.73	0.4654
α_{13} (*Date*)	0.00062	0.00067	0.93	0.3563
α_{14} (*Temp*)	2.539	1.157	2.19	0.0311
$d1$	0.5840	0.1281	4.56	0.0001
$R^2 = .33$				

The optimal nitrogen application rates, optimal timings, and expected net revenue of the baseline scenario for risk-neutral and risk-averse farmers are presented in tables 3 and 4, respectively.[8] As expected, the optimal timing of nitrogen fertilizer application changes when a farmer's perceived probability (P) of failing to apply nitrogen fertilizer changes. For the risk-neutral farmer, when P is between 0.0 and 0.08, the optimal timing is the growing-only application; when P is between 0.08 and 0.13, the optimal timing is the split-season application; and when P is greater than 0.13, the spring-only application is optimal.

Figure 1 expands on the information presented in table 3 by showing the optimal timing of nitrogen applications and the total amount of nitrogen applied for all values of P between 0.0 and 0.25. Note, in figure 1, that there are two points, $P = 0.08$ and $P = 0.13$, where there is more than one optimal solution. At $P = 0.08$, either a growing-only or a split-season application is optimal. This occurs because the marginal net revenue of applying additional nitrogen fertilizer in the spring for a split application is approximately equal to the additional field operation cost for that spring application. At $P = 0.13$, either a split-season application or a spring-only application is optimal. This occurs because the marginal net revenue of applying additional nitrogen fertilizer in the

[8] The optimal nitrogen fertilizer application rates for a growing-only and for split-season applications are respectively close to the survey average application rates. However, the optimal nitrogen application rate for spring-only (246 pounds/acre) is far larger than the survey average application rate (170 pounds/acre). The larger application rate is influenced by the estimate that 42% (1 - $d1$) of nitrogen applied in the spring is lost before the growing season. We also used a second model with the linear plateau function to estimate the optimal nitrogen fertilizer application rates. For spring-only and for growing-only, the application rates are 152 pounds/acre and 242 pounds/acre, respectively. These two estimates are very close to those shown in tables 3 and 4.

Table 3. N Application Rates, Expected Net Revenue, and Optimal Application Timing for Baseline Scenario with No Timing Restriction: Risk-Neutral Farmer

P	Timing	Application Rate (lbs./acre)	Optimal Timing	Expected Net Rev. ($/acre)
0.0	Spring	0.00	Growing-only	305.84
	Growing	158.48		
	Total	158.48		
0.08	Spring	0.00	Growing-only	281.38
	Growing	158.38	(Split-season)[a]	
	Total	158.38		
0.10	Spring	24.51	Split-season	280.09
	Growing	144.16		
	Total	168.67		
0.13	Spring	81.48	Split-season	275.91
	Growing	110.89	(Spring-only)[b]	
	Total	192.37		
0.15	Spring	246.68	Spring-only	275.61
	Growing	0.00		
	Total	246.68		

Note: *P* denotes probability of failing to apply nitrogen fertilizer during growing season.
[a] Either a growing-only or a split-season application is optimal (see figure 1).
[b] Either a split-season or a spring-only application is optimal (see figure 1).

Table 4. N Application Rates, CE Net Revenue, and Optimal Application Timing for Baseline Scenario with No Timing Restriction: Risk-Averse Farmer

P	Timing	Application Rate (lbs./acre)	Optimal Timing	CE Net Rev. ($/acre)
0.0	Spring	0.00	Growing-only	305.84
	Growing	158.48		
	Total	158.48		
0.03	Spring	52.77	Split-season	283.91
	Growing	127.66	(Growing-only)[a]	
	Total	180.43		
0.05	Spring	92.79	Split-season	279.19
	Growing	104.29		
	Total	197.08		
0.08	Spring	125.00	Split-season	275.48
	Growing	85.48	(Spring-only)[b]	
	Total	210.48		
0.10	Spring	246.68	Spring-only	275.61
	Growing	0.00		
	Total	246.68		

Note: *P* denotes probability of failing to apply nitrogen fertilizer during growing season.
[a] Either a split-season or a growing-only application is optimal (see figure 2).
[b] Either a split-season or a spring-only application is optimal (see figure 2).

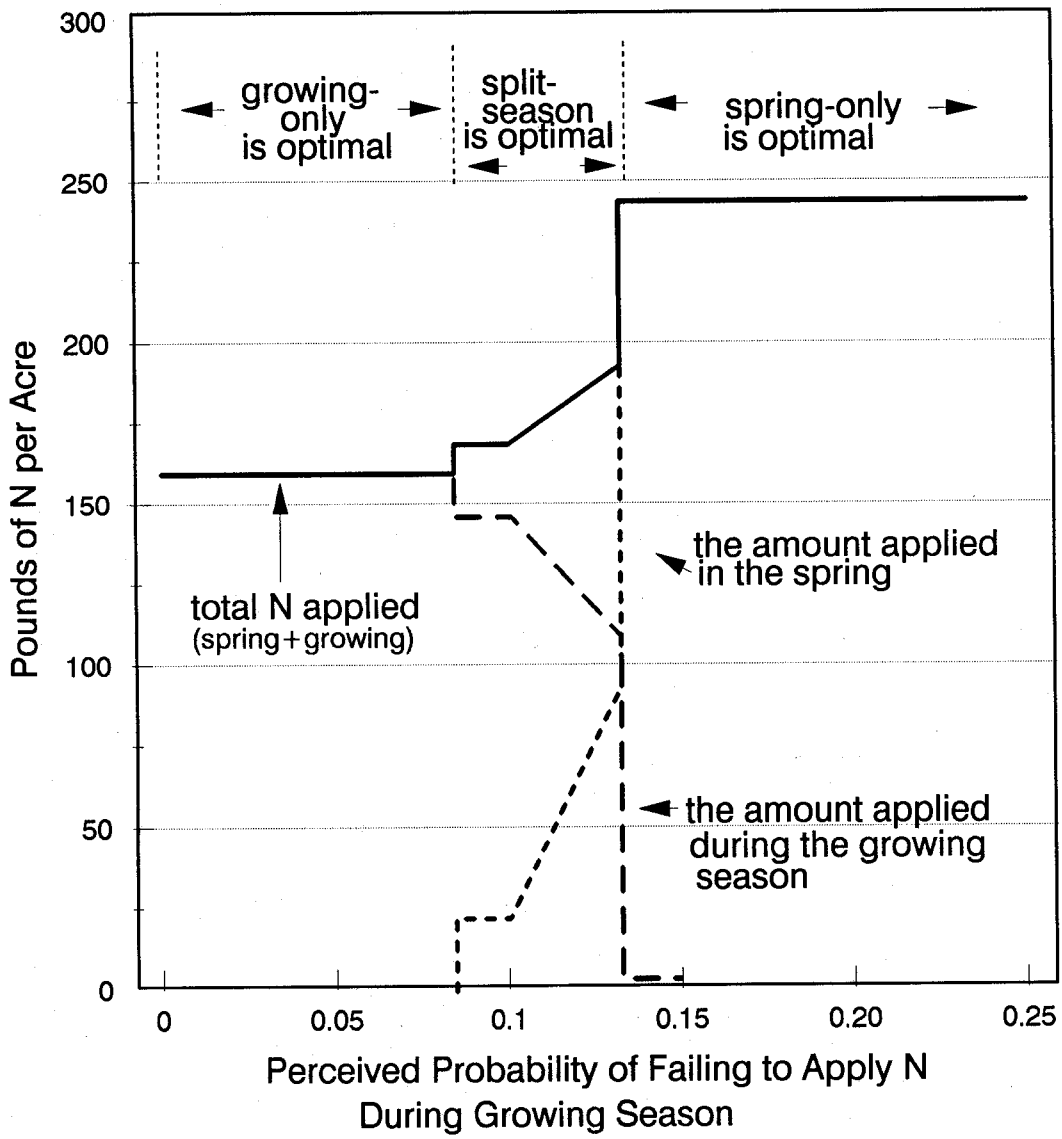

Figure 1. Optimal nitrogen application rates of risk-neutral farmers

growing season for a split application is approximately equal to the additional field operation cost for that growing-season application.

For a risk-averse farmer (table 4), when P is less than 0.03, the optimal timing is a growing-only application; when P is between 0.03 and 0.08, the optimal timing is a split-season application; and when P is greater than 0.08, the spring-only application is optimal. Figure 2 shows the risk-averse baseline scenario—application timing and rates—for all values of P between 0.0 and 0.25.

A comparison of figures 1 and 2 shows that there are differences in how risk-neutral and risk-averse farmers apply nitrogen fertilizer as P increases. A risk-averse farmer switches from a growing-only application to a split-season application sooner than does a risk-neutral farmer as the value of P increases, but also switches from a split application to the spring-only application sooner. The total application rates for a split-season application are larger for a risk-averse farmer when P is greater than 0.03 and less than 0.13. As P increases beyond 0.03, the risk-averse farmer considers the spring application as the primary treatment. Consequently, more nitrogen is applied to compensate for the loss that will occur between the time of the application and the time of the crop's needs. The result is a higher level of nitrogen fertilizer application and a larger nitrogen loss in the risk-averse scenario.

Compliance Costs of the Timing Restriction

The cost for a risk-neutral farmer to comply with the application of nitrogen fertilizer only during the growing season is estimated using equation (11) for each given level of P. The results are presented in figure 3, where the horizontal axis represents the perceived probability of being unable to apply nitrogen fertilizer during the growing season, and the vertical axis represents the expected net return measured in dollars per acre per year. The compliance cost for each given level of P is the vertical distance between the solid and dashed lines. The solid line shows the expected maximum net revenue without the timing restriction. It also shows the optimal timings for applying nitrogen fertilizer as P changes. When P is equal to zero, the expected net revenue for an unrestricted farmer is $306 per acre. When P is greater than 0.13, the expected net revenue is $276 per acre per year, a constant. The dashed line represents the expected maximum net revenue for a farmer restricted to growing-only applications, assuming that farmers will harvest the crop even if they have failed to apply nitrogen fertilizer during the growing season, because the return ($83/acre) from the harvested crop is larger than the harvest costs ($35/acre), which include field operations and drying grains (Doster 1993). (The crop yield for estimating the return is the intercept, α, in table 2.)

As P increases, the expected net revenue declines. Expected net revenue is represented by a straight line intersecting the left vertical axis at $306 per acre when P is equal to zero, and intersecting the right vertical axis at $235 per acre when P is equal to 0.30. The dashed line and the solid line overlap when P is less than 0.13. The compliance cost, as shown in figure 3, is zero when P is less than 0.13. As P increases, an unrestricted farmer prefers to use a split-season application or a spring-only application, causing the compliance cost to increase. Recall that the probability of not getting in the field during the growing season in the White River Basin was exogenously

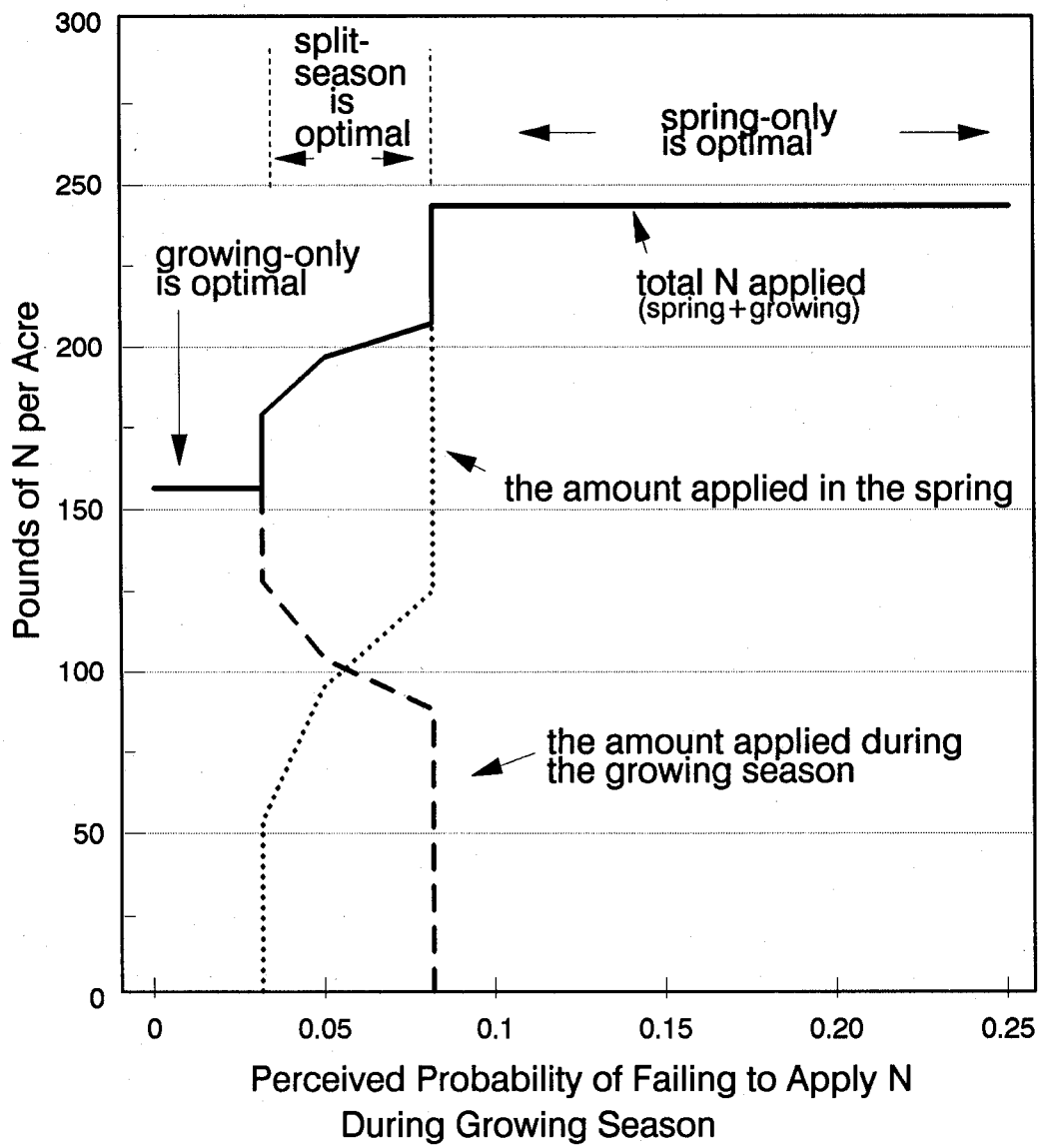

Figure 2. Optimal nitrogen application rates of risk-averse farmers

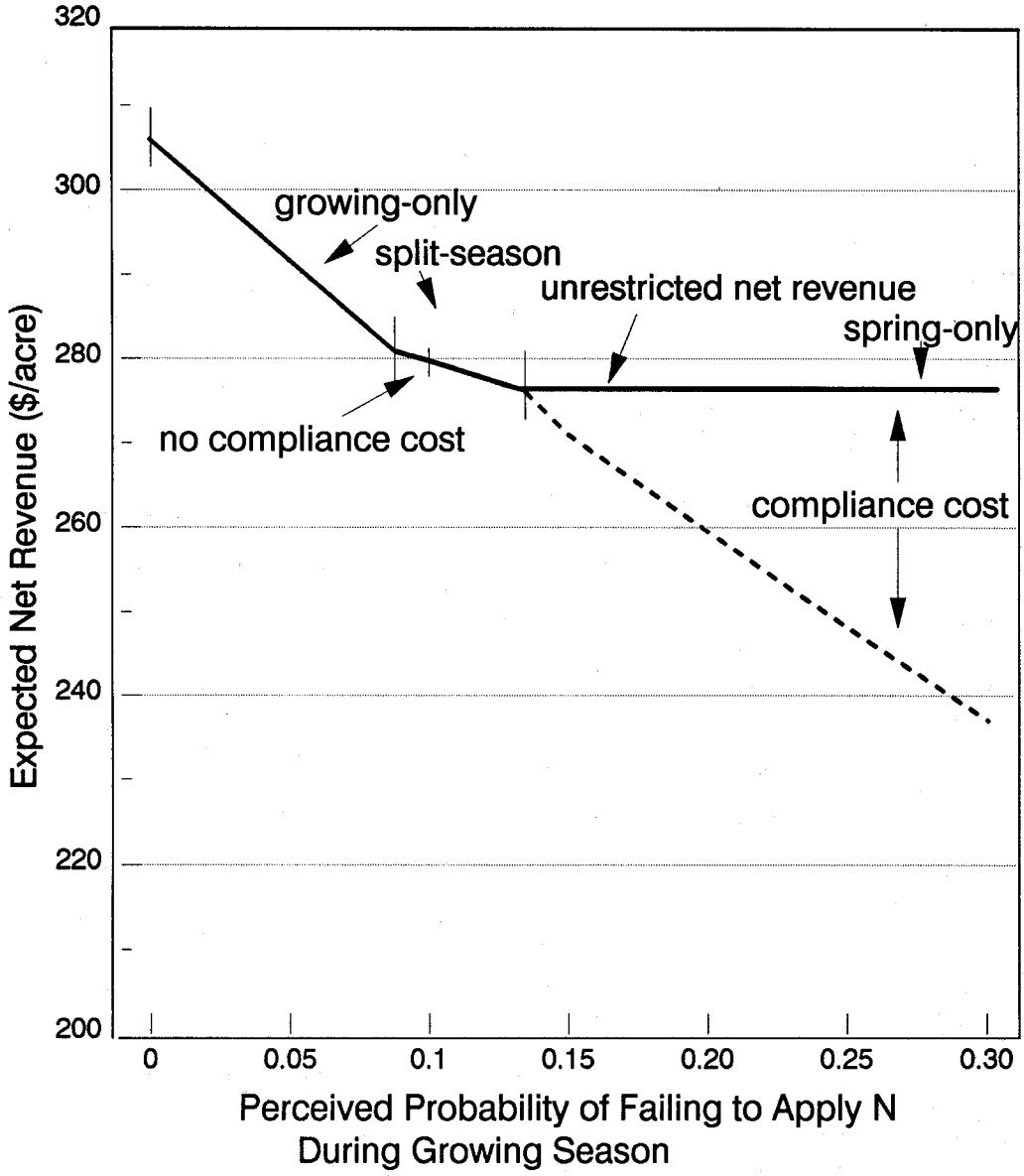

Figure 3. Compliance costs for risk-neutral farmers

determined and was estimated to be about 0.1. At this P level, a timing restriction of the growing-season only application would have no cost to the farmer because the difference in revenue between the optimal strategy for unrestricted farmers and the growing-only application is very small (less than $1/acre). However, at $P = 0.15$, it would cost a risk-neutral farmer $4 per acre per year to comply with the growing-only timing restriction in the White River Basin.

A similar discussion holds for farmers who are risk averse (figure 4). As in figure 3, the compliance cost in figure 4 is the vertical distance between the solid line and the dashed line. The solid line represents the CE net revenue for an unrestricted risk-averse farmer for each given value of P. It also shows the optimal timings of applying nitrogen fertilizer as P changes. The dashed line represents the CE net revenue for risk-averse farmers restricted to a growing-only fertilizer application, assuming farmers will harvest the crop even if they have failed to apply nitrogen fertilizer during the growing season. The compliance cost is $37 per acre for risk-averse farmers in the Basin where the probability of not getting in the field during the growing season is 0.1. As noted previously, the model used here may overstate the compliance costs of risk-averse farmers. Therefore, at $P = 0.1$, $37 is likely the upper bound. The farmer can reduce this compliance cost by increasing organic nitrogen in the soil through the application of manure or by using a crop rotation that includes a nitrogen-fixing crop. Organic nitrogen in the soil can reduce yield loss even if the farmer failed to apply nitrogen fertilizer in the growing season.

By comparing the compliance costs in figures 3 and 4, it is apparent that restricting farmers to growing-season applications only can cause a larger compliance cost to risk-averse farmers than to risk-neutral farmers. For risk-averse farmers, the compliance cost increases much faster as P increases. The sharp increase in the compliance cost of risk-averse farmers is due to the rapidly increasing risk premium as the level of P increases.

Reduction in Nitrogen Fertilizer Use

The growing-only timing restriction also is expected to change the quantity of nitrogen applied, which may have a significant impact on environmental damage from leaching and runoff. The expected reduction in nitrogen fertilizer use for risk-neutral and risk-averse farmers is shown in figure 5. The expected reduction is the difference in the expected nitrogen fertilizer application rate with and without the proposed timing restriction. For example, for a risk-neutral farmer, the expected nitrogen fertilizer application rate is 158 pounds per acre when P is equal to 0.08, and is 154.6 pounds per acre when P is equal to 0.1.[9] Under the restriction, at $P = 0.10$, the expected nitrogen fertilizer application rate is 142.2 pounds per acre [(1 - 0.1) × 158]. Thus, the timing restriction is expected to save 12.4 (154.6 - 142.2) pounds of nitrogen per acre (point C in figure 5). By repeating this procedure, the reduction of nitrogen fertilizer for each given value of P can be computed for a risk-neutral and a risk-averse farmer, as shown in figure 5.

[9] The expected nitrogen fertilizer application rates $E[N]$ per year per acre are computed using the following three formulas: (*a*) for a growing-only application, $E[N] = (1 - P)N_g$; (*b*) for a split-season application, $E[N] = N_s + (1 - P)N_g$; and (*c*) for a spring-only application, $E[N] = N_s$. For a split-season application, for example, at $P = 0.1$, the expected annual nitrogen fertilizer application rate is: 25 + (1 - 0.1) × 144 = 154.6 pounds/acre.

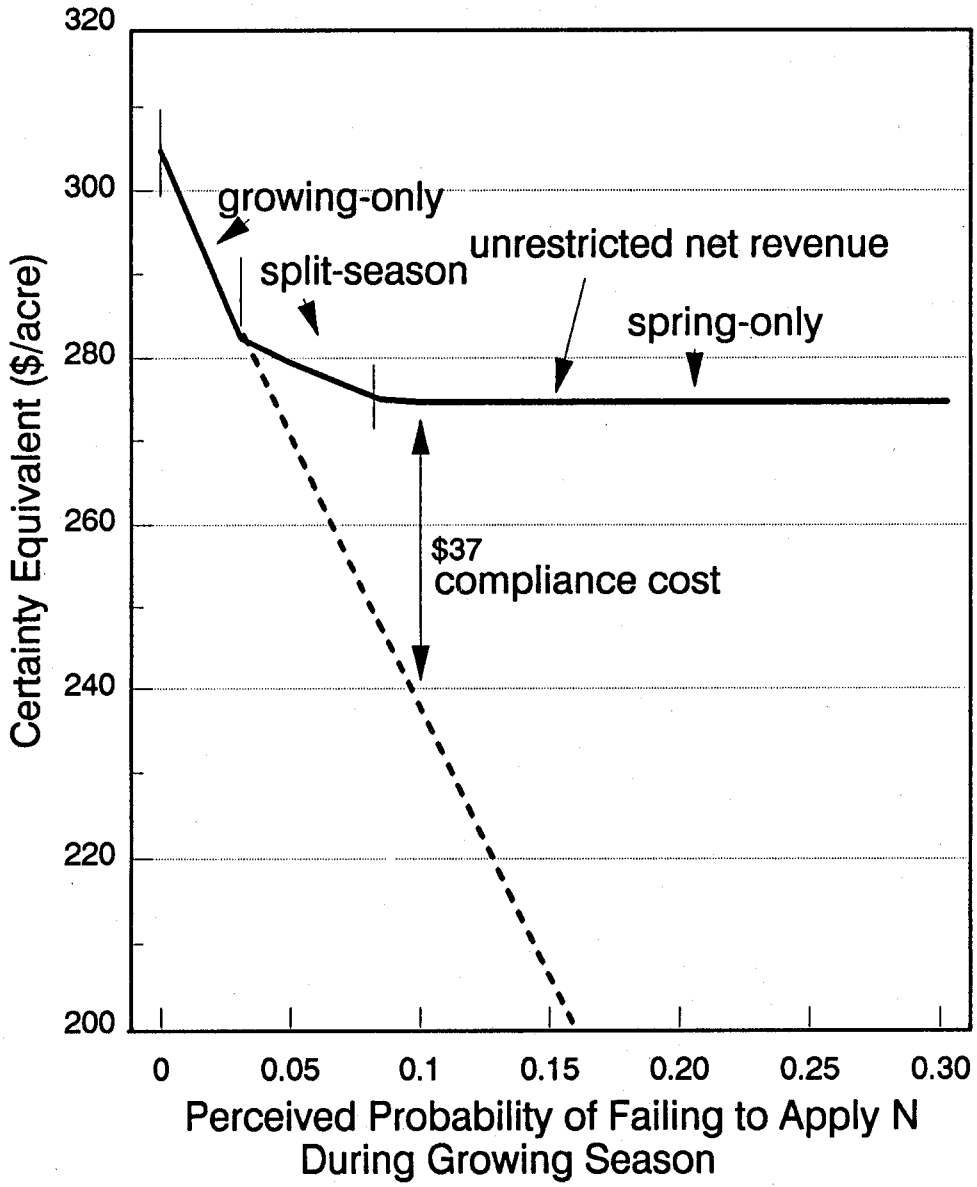

Figure 4. Compliance costs for risk-averse farmers

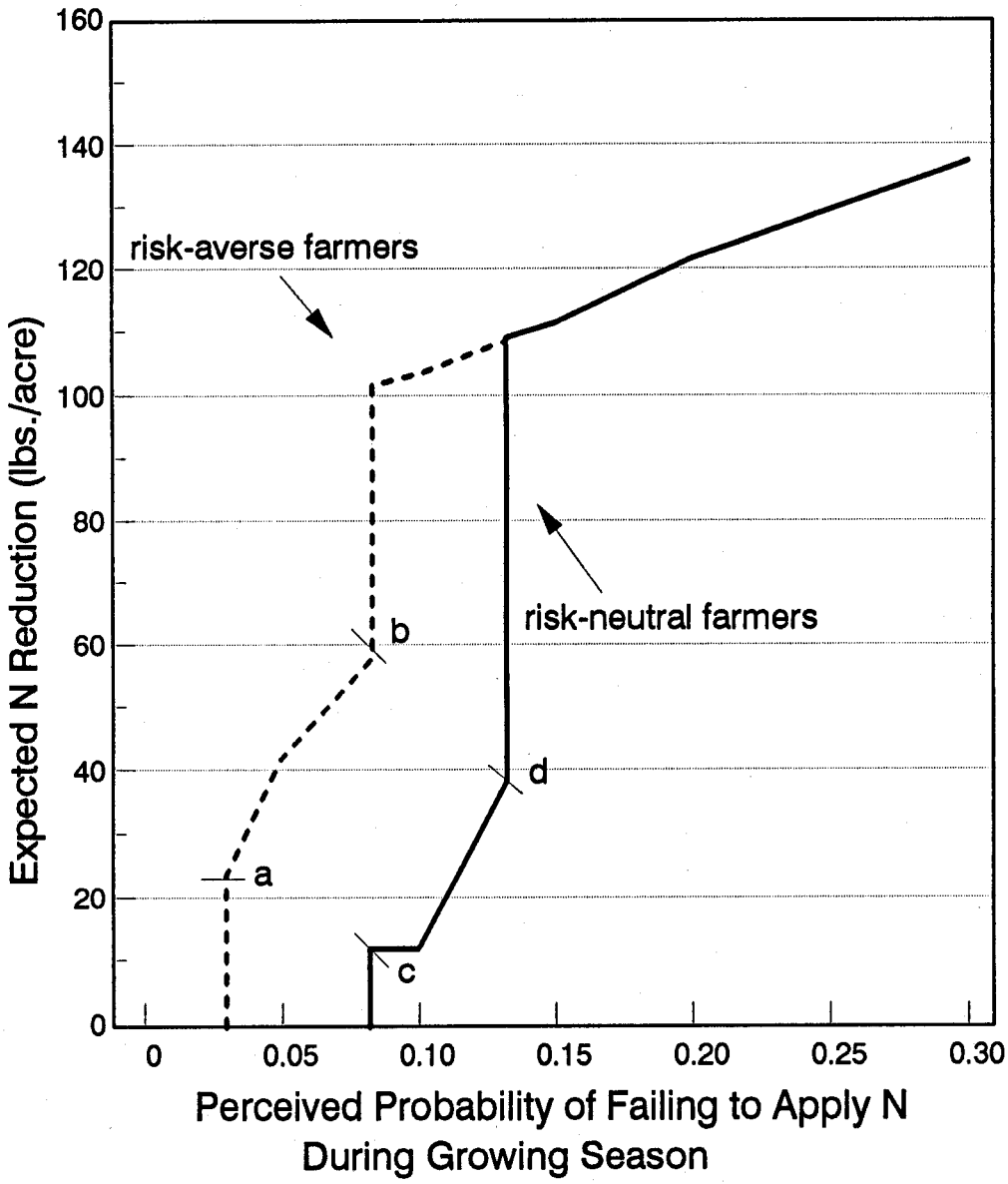

Figure 5. Expected reduction in nitrogen fertilizer use for risk-neutral and risk-averse farmers under a timing restriction

The growing-only timing restriction has a larger impact on the quantity of nitrogen applied by risk-averse farmers than on risk-neutral farmers. The relative change in nitrogen fertilizer use between these two types of farmers increases as the value of P increases from 0.0 to 0.08, and then decreases as P continues to increase. For example, when P is equal to 0.08, a risk-neutral farmer is expected to reduce nitrogen application by 12.4 pounds per acre, while a risk-averse farmer is expected to reduce nitrogen application by 60 pounds per acre. When P is greater than 0.13, both risk-neutral and risk-averse farmers are expected to reduce nitrogen application by the same amount because the spring-only application is optimal for both types of farmers when the application timing is not restricted.[10]

It is interesting to note that at some values of P, there is no need for the timing restriction to reduce application rates of nitrogen fertilizer. These P values are 0.08 and 0.13 for a risk-neutral farmer, and 0.03 and 0.08 for a risk-averse farmer. At these P values, farmers can switch from a split-season application to a growing-only application, or from a spring-only application to a split-season application, to reduce nitrogen application rates without a reduction of their net income. For example, for a risk-neutral farmer, when $P = 0.13$, both split-season and spring-only applications are optimal. A growing-season only restriction will result in a reduction of 39 pounds per acre of nitrogen fertilizer for the farmer who used the optimal split-season application before the restriction (figure 5). For the farmer who used the optimal spring application before the restriction, it will result in a reduction of 110 pounds per acre of nitrogen fertilizer. At this P value (0.13), a risk-neutral farmer can reduce the nitrogen application rate by 71 pounds per acre (110 - 39) without a reduction in net revenue simply by switching from the optimal spring-only application to the optimal split-season application. Similarly, a risk-averse farmer at $P = 0.08$ can reduce the nitrogen fertilizer rate by 42 pounds without a reduction in net revenue.[11]

Environmental Implications

The potential for environmental damage from nitrogen is measured by the amount of the expected residual nitrogen that may be lost to atmosphere, and to ground and surface water. Expected residual nitrogen is defined as the difference between the expected amount of nitrogen fertilizer applied on the field and the expected amount of nitrogen removed from the field through the crop harvested.[12] Nitrogen removed from the field is the product of bushels of corn harvested and pounds of nitrogen in one bushel of corn grain (0.9 pounds per bushel) (The Fertilizer Institute). Residual nitrogen

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[10] For example, at $P = 0.13$, the expected reduction in nitrogen fertilizer is the difference between the optimal amount of nitrogen fertilizer (247 pounds/acre) applied in the spring and the expected optimal amount of nitrogen fertilizer applied for the growing-season only [(1 - 0.13) × 158 = 137 pounds/acre]. The expected reduction for both types of farmers is: 247 - 137 = 110 pounds/acre.

[11] Recall that at $P = 0.08$, either a split-season or a spring-only application is optimal for a risk-averse farmer. The reduction will be 101 pounds/acre for the farmer who uses an optimal spring application before the restriction. And it will result in a reduction of 59 pounds/acre for the farmer who uses an optimal split-season application. The expected reduction is: 101 - 59 = 42 pounds/acre.

[12] The expected amount of residual nitrogen, $E[RN]$, is estimated by the following equations: (*a*) for a growing-only application, $E[RN] = (1 - P)N_g - 0.9[(1 - P)Y_1]$; (*b*) for a split-season application, $E[RN] = N_s + (1 - P)N_g - 0.9[(1 - P)Y_1 + P(Y_2)]$; and (*c*) for a spring-only application, $E[RN] = N_s - 0.9(Y_2)$. Here, Y_1 and Y_2 are, respectively, the optimal yields obtained in the model's solution for π_1 and π_2, which are defined in equation (4).

Table 5. Expected Reductions in Residual Nitrogen and Expected Compliance Costs for Risk-Neutral and Risk-Averse Farmers Under a Growing-Only Timing Restriction

Perceived Probability (P)	Reduction in Residual N (lbs./acre)	Compliance Cost ($/acre)	Optimal Timing w/No Timing Restriction
Risk-Neutral Farmer:			
0.0	0	0	Growing-only
0.08	0 (0)	0	Growing-only (Split-season)[a]
0.10	11	0	Split-season
0.13	23 (94)	0	Split-season (Spring-only)[a]
0.15	95	4	Spring-only
0.20	97	15	Spring-only
Risk-Averse Farmer:			
0.0	0	0	Growing-only
0.03	0 (21)	0	Growing-only (Split-season)[a]
0.05	36	8	Split-season
0.08	50 (92)	25	Split-season (Spring-only)[a]
0.10	96	37	Spring-only
0.15	100	69	Spring-only

[a] The timing application within parentheses also is optimal.

commonly is used as an environmental indicator because fertilizer nitrogen is highly unstable and mobile and can be easily lost to the environment. However, the links between residual nitrogen and nitrogen loss generally are uncertain. Nitrogen loss depends on site-specific physical characteristics, location, and random weather events. It is assumed, because the model used in this study is static, that residual nitrogen or mining of nitrogen will not affect the next year's crop yield.[13]

Table 5 shows the expected reduction in residual nitrogen and the corresponding expected compliance cost under a growing-only timing restriction for risk-neutral and risk-averse farmers. A risk-averse farmer is expected to reduce residual nitrogen by a larger amount but at a higher cost than a risk-neutral farmer. For example, at $P = 0.1$, a risk-neutral farmer is expected to reduce residual nitrogen by 11 pounds per acre with no compliance cost, while a risk-averse farmer is expected to reduce residual nitrogen by 96 pounds per acre with a compliance cost of $37 per acre. As seen in table 5, there are four points—$P = 0.03$ and 0.08 for risk-averse, and $P = 0.08$ and 0.13 for risk-neutral farmers—where there are two optimal solutions for each point. While these two optimal solutions will have the same compliance cost, they will differ in the reduction of residual nitrogen. For example, for a risk-averse farmer, at $P = 0.08$, both split-season and spring-only applications are optimal and both have the same compliance cost ($25) but differ in reduction of residual nitrogen (50 and 92 pounds per acre, respectively).

[13] Mining of nitrogen occurs if farmers harvest the crop even though they have failed to apply nitrogen fertilizer in the growing season when a growing-only timing restriction is imposed.

Conclusions

A restriction on nitrogen fertilizer application timing generally is considered to be an effective tool for reducing agricultural nonpoint sources of pollution because of low monitoring costs. A growing-season only timing restriction can match the biological needs of a crop to reduce excessive application of nitrogen, but can introduce a compliance cost. The growing-season only restriction analyzed here is likely to cause reductions in net revenue for both risk-neutral and risk-averse farmers in the White River Basin in Indiana. For risk-neutral farmers, their cost to comply with the restriction is less than $1 per acre, which is relatively small and well within the range of actual payments received ($10–$12 per acre) under the USDA's Water Quality Incentive Program (WQIP). The potential environmental benefit is a modest reduction in expected residual nitrogen (about 11 pounds per acre per year). For risk-averse farmers, a timing restriction would impose a larger compliance cost (as much as $37 per acre per year), but would garner a substantial reduction in residual nitrogen (96 pounds per acre per year).

The large compliance cost for a risk-averse farmer suggests that some risk-averse farmers in the White River Basin would resist a growing-season only timing restriction. Unfortunately, it is the risk-averse farmers who could make the most substantial contribution to improving environmental quality. Compensation for risk-averse farmers under the current voluntary incentive program [through the Environmental Quality Incentives Program (EQIP)] is unlikely to be adequate to offset the very high compliance costs.

For these farmers, less costly alternative approaches must be investigated. One possibility is to use crop insurance schemes to cover the net revenue loss from not being able to apply nitrogen fertilizer during the growing season. Another alternative approach is to use new production technologies to reduce negative environmental impacts of nitrogen while minimizing producer risk of lost profits. For example, farmers may be able to apply nitrogen fertilizer mixed with nitrogen inhibitors before planting and avoid the need for a growing-season application. Nitrogen inhibitors can stabilize nitrogen in the soil to more efficiently supply nitrogen to the crop when needed. Farmers also can spray nitrogen fertilizer with a delivery vehicle, such as an airplane, during the growing season when the weather conditions will not permit an on-field application. Both technologies require additional application costs and currently are regularly used by some farmers. Studies are needed to evaluate the economic and environmental implications of using these and other new technologies and to guide policy choices that could allow farmers to achieve environmental objectives at least cost with available technologies.

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