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Using Insurance to Enhance Nitrogen Fertilizer Application Timing to Reduce Nitrogen Losses

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ABSTRACT

Nitrogen applied before planting is more vulnerable to loss to the environment than nitrogen applied during the growing season, but the growing season application can increase the risk of lower yields caused by adverse weather that prohibits farmers to complete N application. An expected utility framework is used to illustrate the potential economic benefit of insurance for a farmer to reduce this risk cost. An expected-value variance analysis is used to illustrate the potential benefit of insurance to Iowa corn growers who apply N fertilizer only during the growing season.

Key Words: *insurance, nitrogen fertilizer, and application timings.*

Agricultural use of chemical and organic nitrogen (N) fertilizers is a major contributor of nonpoint source pollutants leading to a variety of water quality problems in the United States. These problems include groundwater contamination and eutrophication in streams, rivers, and lakes (Phipps and Crosson; Nielsen and Lee; U.S. Environmental Protection Agency; Hallberg; National Research Council). To mitigate these problems, the U.S. government made available to farmers a variety of voluntary cost-sharing programs in the 1996 Farm Bill to entice adoption of best nitrogen management practices. For example, under the Environmental Quality Incentives Programs, the

government can pay up to 75 percent of the cost of nitrogen management practices over a five-to-ten-year period (Federal Agriculture Improvement and Reform Act (FAIR)). Additionally, the government has recently proposed a variety of public policies to help farmers adopt nitrogen management practices to improve N use efficiency and reduce N losses to the environment (e.g., Clean Water Action Plan).

Timing application of N fertilizer to coincide with the nitrogen need of a crop can avoid excessive application of N and reduce the amount of residual nitrogen lost to the environment.¹ A split or a single application of N fertilizer during the growing season can match N supply to the crop's need without a reduction in yield and can be a least costly practice for N fertilizer application. Many farmers in

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¹ The amount of residual nitrogen is the amount of N applied to a field in excess of the amount of N in the harvested crop and crop residue removed from the field (Meisinger; Huang).

the United States already have adopted such a timing practice. However, many farmers still apply N fertilizer in the fall or early spring before planting (Taylor).

There are various reasons for farmers to apply N fertilizer before planting (Bundy; Hoefft). Some farmers prefer a fall application because they want to have their fieldwork done in the fall to avoid possible delays in planting in the spring. Some farmers with clay soils may prefer a fall application because they want to avoid the compaction of soil caused by the operation of the heavy fertilizer spreading equipment during the growing season. Some farmers practice fall application because they can minimize N loss in soils that have a low leaching potential by adding N inhibitors and by applying N before planting when the temperature is low.

Yield loss and income variation caused by weather conditions during the growing season are the main concerns that discourage most farmers from growing season application of N fertilizer application (Bundy; Hoefft). Unfavorable weather conditions during the growing season can stop the farmer from entering the field to apply N fertilizer, and lack of N can reduce crop yield and cause an income loss to the farmer. The cost of bearing this income risk may be so large (or at least be perceived to be so large) that the adoption of growing season N application may not help the farmer improve the certainty equivalent (CE) net income (the expected net income subtracted by the risk cost) (Huang, Hewitt, and Shank). Furthermore, even though the adoption may improve the CE net income, the possibility of income losses in some years may not be acceptable to a safety-first, risk-averse farmer who needs to maintain a certain level of annual net farm income. Research has found that farmers generally are risk averse (e.g., Wilson and Eidman; Tauer). To motivate risk-averse farmers to adopt better timing of N fertilizer application, risk-management tools such as insurance can be employed to help farmers reduce the real or perceived risk cost.

An adoption insurance program can reduce farmers' risk cost associated with the adoption of a specific practice. Such a program transfers

risk from one insurance participant (farmer) to other participants who are more able or willing to bear the risk cost and to an insurance company or the government for whom the bearing of risk is less costly. An insurance company through risk-pooling can offer insurance to a participating farmer at a cost that is less than his or her perceived risk costs (Newbery and Stiglitz). Such insurance may enable individual farmers to increase their CE net income by adopting a risky but environmentally friendly best-nutrient management practice, which they would not otherwise adopt. Participation in an adoption insurance program can be voluntary for the farmers who currently are adopting the practice or planning to adopt it.

An adoption insurance program also allows an insurance company to improve its net income by capturing the difference between the amount that the farmer is willing to pay for the risk reduction and the reduced risk cost that the insurance company is able to achieve by risk-pooling. Currently, some insurance companies are marketing an insurance policy tailored to the adoption of a split-N application before and after planting to reduce N use (Agricultural Conservation Innovation Center). When the insurance program benefits both the farmers and the insurance company, society as a whole benefits from the increased net farm income by the adoption—a Pareto optimal move to increase social benefit.

The objective of this study is to illustrate the potential economic and environmental benefits of using insurance to provide farmers incentive to adopt a growing-season-only (GS-only) application instead of a before-planting-only (BP-only) application of N fertilizer. The potential effect of insurance on the financial gain to farmers and the reduction of N fertilizer use to reduce residual N that may be lost to the environment will be demonstrated. Also, the adoption of a GS-only N fertilizer application for continuous corn production in Iowa is used to illustrate the potential benefit of adoption insurance. Under a GS-only insurance policy, if an insured farmer can't apply N fertilizer during the growing season and has a lower income than expected, he or she will be compensated for the loss of revenue

through the indemnity. The farmer's yield history is used to calculate indemnities and premiums. To qualify for an indemnity, the insured farmer must keep field records.

Why Adoption Insurance?

A simple static insurance model is employed to demonstrate how insurance can increase a risk-averse farmer's incentive to adopt a GS-only N fertilizer application. The model assumes that a farmer's decision to adopt a GS-only application is based on maximizing his or her expected utility of net returns. The assumed utility function exhibits positive but diminishing marginal utility. A farmer adopts a GS-only N fertilizer application if it results in a greater expected utility of net farm income (net return) than the expected utility of using other application alternatives. The advantage of insurance is illustrated by comparing the expected utility of models with and without insurance.

No-Insurance Case

Assume that there are two states of nature. In the bad state, a farmer perceives a probability (p) of not being able to apply N fertilizer during the growing season, thus suffering a yield loss and a reduced net income, Z_f . In the good state, he or she perceives probability $(1 - p)$ of being able to apply N fertilizer in the growing season, receiving a net income Z_g . Thus the farmer's expected net income before insurance is a random variable Z defined by (Huang, Hewitt, and Shank):²

- (1) $Z_s = p_c Y(N_i) - p_f N_b - p_f N_g - C(N_b) - C(N_g)$, with probability $(1 - p)$.
- (2) $Z_f = p_c Y(N_i | N_c = 0) - p_f N_b - C(N_b)$, with probability p .

² Both Z_g and Z_f are deterministic and determined primarily by their expected yield functions. These yield functions ideally should be estimated by using the time-series yield data from a specific site, which generally reflects the effect of the annual random variation of the weather condition (such as wet, normal, or dry) in the growing season on crop yield.

Where p_c and p_f are the prices of crop and N fertilizer, respectively; $Y(N_i)$ is the yield response to the total amount of N available, N_p , in the growing season; N_b is the amount of N applied before planting; and N_g is the amount of N applied during the growing season. N_i is the effective fertilizer, which is the sum of $d N_b$ plus N_g where d is the percent of N_b available during the growing season (Feinerman, Choi and Johnson).³ For an optimal N_p , the farmer will have to apply more N fertilizer in the spring before planting than after planting because $(1-d)$ of N applied before planting will not be available for crop growth in the growing season. $C(N_b)$ and $C(N_g)$ are field operation costs for applying N_b and N_g , respectively. These two costs are assumed to be constants.

A risk-averse farmer determines the optimal timing of N fertilizer application and its N application rates, N_b and N_g , by the maximization of the expected utility function (3)

$$(3) \quad U(Z) = (1 - p) U(Z_g) + p U(Z_f).$$

The optimal application timing can be an N application before planting, or a split-N (SN) application before planting and after planting, or a growing season application.

The model can be used to evaluate the advantage of switching to new application timing and the need for insurance if the farmer perceives a probability (p) of being unable to apply N fertilizer during the growing season (Huang, Hewitt and Shank). For example, if the farmer is currently practicing a BP-only application and if he or she wants to adopt a new practice, a GS-only application, he or she can use the model to determine $U(Z)_b$ (the utility of expected net income) of a BP-only application (by setting $N_g = 0$ and $p = 1$) and

³ To simplify the analysis, N applied is grouped into two timings: before planting and after planting (during the growing season). In this study, N applied before planting includes N applied in the fall, in the spring, and at the planting. N applied after planting includes a single application, and a multiple N applications at different stage of crop growth. Corn yield responds to these timings differently. To achieve the same yield level, farmers must apply more N to compensate for the N losses if the application timing is farther from the time of corn grain-bearing period.

$U(Z)_g$ (the utility of expected net income) of a GS-only practice (by setting $N_b = 0$ and $p = 0$), and then compare these two expected utilities to determine whether there is an advantage to adopting a GS-only N application over a BP-only application. The farmer will have an incentive to adopt a GS-only application when $U(Z)_g$ is larger than $U(Z)_b$; otherwise, the farmer may not have incentive to do so. When $U(Z)_g$ is less than $U(Z)_b$, however, insurance may be useful to help farmers increase their expected utility of the GS-only application to exceed the expected utility of the BP-only application. This is described next.

Complete Insurance Case

When the adoption insurance is available to the farmer, the net income with insurance is a random variable V given by

$$(4) \quad V_g = Z_g - \beta, \quad \text{with probability } (1 - p).$$

$$(5) \quad V_b = I + Z_b - \beta, \quad \text{with probability } p.$$

where V_g is the farmer's net income from a successful GS-only application and V_b is his or her net income from not being able to apply fertilizer during the growing season. β is the amount of insurance premium paid by the farmer for the indemnity coverage I and is specified as

$$(6) \quad \beta = p I + A.$$

Where $I = \theta [Z_g - Z_b]$, $\theta (0 < \theta \leq 1)$ is the coverage rate and $[Z_g - Z_b]$ is the loss of net income, when the farmer fails to apply N fertilizer during the growing season. If the farmer chooses a complete (full) coverage of loss, $\theta = 1$. $p I$ is an actuarially fair insurance premium. $A = \alpha p I$ ($0 < \alpha < 1$) is the administration cost to be charged by the insurance company for the service. If the farmer is offered an actuarially fair insurance premium, $\alpha = 0$. If the farmer pays an actuarially fair insurance premium, the farmer can maximize his or her expected utility by choosing a full coverage of losses (Nelson and Loehman; Ashan, Ali, and Kurian).

An insurance decision model determines the values of N_b and N_g that maximize expected utility of the net income given by

$$(7) \quad \text{Maximize } U(V) = (1 - p)U(V_g) + pU(V_b).$$

subject to a constraint (8) that the expected utility of net income V be greater than or equal to the expected utility of net income of a BP-only application.

$$(8) \quad U(V) \geq U(Z)_b.$$

The optimal solution of a GS-only application can be obtained by setting $N_b = 0$ in the model.

Impact on Net Income

An insurance program uses a mean-preserving risk-reducing method to help farmers reduce risk cost and thereby increase their expected utility of adopting a risky N application timing (Newbery and Stiglitz 1981). Insurance reduces the spread of distribution of net incomes between the good state and the bad state, while keeping the mean value unchanged. By doing so it reduces the farmer's income risk (risk-bearing cost). As shown in equations (4) and (5), insurance reduces the spread of net incomes between the good state and the bad state by subtracting an insurance premium β from the net income of the good state and by adding the payoff $(I - \beta)$ to the net income of the bad state. When the farmer pays an actuarially fair insurance premium, insurance does not change the mean value of net income $E[V]$ ($=E[Z]$), but it reduces variance $Var(V)$ to 0 for full coverage of the loss $(Z_g - Z_b)$.⁴ Because the farmer receives $E[Z]$ annually regardless of good or bad state, the utility corresponding to this annual net income is

⁴ Substituting $p(1 + \alpha)I$ for β , where $I = [Z_g - Z_b]$, in equations (4) and (5), it can be shown that $E[V] = (1 - p)[Z_g - p(1 + \alpha)(Z_g - Z_b)] + p[Z_b + (Z_g - Z_b)(1 - p(1 + \alpha))] = (1 - p)Z_g + pZ_b - p\alpha I = E[Z] - A$, and that $Var(V) = p(1 - p)[Z_g - p(1 + \alpha)(Z_g - Z_b) - Z_b - (Z_g - Z_b)(1 - p(1 + \alpha))]^2 = 0$. When the farmer pays an actuarially fair insurance premium ($\alpha = 0$), the expected net income is not changed $E[V] = E[Z]$.

$U(E[Z])$, which, according to Jensen's inequality, is always greater than $U(Z)$ when an insurance program is absent. Thus an insurance program provides farmers an opportunity to reduce their risk cost to maximize their expected utility of net income. By switching from a BP-only practice to a GS-only practice, the farmer increases his/her expected utility as much as the difference between $U(E[Z])_g$ and $U(Z)_b$ —the difference between the utility of expected net return of adopting a GS-only practice and the utility of the current BP-only practice. Assuming the application of the BP-only practice is always possible, the maximum income that the farmer gets, therefore, is the difference between $E[Z]_g$ and $E[Z]_b$; that is the difference between the expected net income of a GS-only application and the expected net income of the BP-only application.

When the insurance premium includes the cost of insurance service ($\alpha > 0$), the farmer's CE net return is reduced. An insurance program improves the farmer's CE net return only if the difference between the expected net return of a GS-only application and the cost of insurance service is greater than the expected net return of a BP-only application. That is, $(E[Z]_g - A)$ must be greater than $E[Z]_b$.

Impact on Fertilizer Use

Will insurance affect a risk-averse farmer's N fertilizer application rate? This can be determined by comparing the rule for determining N fertilizer application rate without and with insurance. In the no-insurance case, a risk-averse farmer determines optimal N fertilizer application rates N_b and N_g by the following first-order condition (9) and (10) obtained from the maximization of (3)

$$(9) \quad \partial U(Z)_g / \partial N_b (1 - p) [p_c d\partial Y(N_i) / \partial N_i - p_f] + \partial U(Z)_g / \partial N_b p [p_c d\partial Y(N_i | N_g = 0) / \partial N_i - p_f] = 0.$$

$$(10) \quad p_c \partial Y(N_i) / \partial N_i - p_f = 0.$$

With the presence of insurance, the risk-averse farmer determines the optimal amounts of N_b and N_g for full coverage by the first-

order conditions of the model (7) and (8). By the maximization of the Lagrangean of the model: $L = U[V] + \lambda(U[V] - U[Z]_b)$, where λ is the Lagrangean multiplier, the first-order conditions are:

$$(11) \quad \partial U(V) / \partial N_b + \lambda(\partial U(V) / \partial N_b) = 0.$$

$$(12) \quad \partial U(V) / \partial N_g + \lambda(\partial U(V) / \partial N_g) = 0.$$

$$(13) \quad \lambda(U(V) - U(Z)_b) = 0.$$

There are two scenarios for the condition (13): the constraint (8) is binding ($\lambda > 0$ and $U(V) - U(Z)_b = 0$) and constraint (8) is not binding ($\lambda = 0$ and $U(V) - U(Z)_b > 0$). The farmer has an incentive to adopt a GS-only application only if $U(V) - U(Z)_b > 0$. Thus only the second scenario that the constraint is not binding is assumed. The first-order conditions becomes (14) and (15) as demonstrated in the appendix:

$$(14) \quad [1 - (1 + \alpha)p] [p_c d\partial Y(N_i) / \partial N_i - p_f] + [(1 + \alpha)p] [p_c d\partial Y(N_i | N_g = 0) / \partial N_i - p_f] = 0.$$

$$(15) \quad p_c \partial Y(N_i) / \partial N_i - p_f = 0.$$

The influence of insurance on reduction of the N fertilizer application rate is investigated under three scenarios: (a) the farmer pays an actuarially fair insurance premium ($\alpha = 0$), (b) the farmer pays an insurance premium including an actuarially fair insurance premium and the cost for administering insurance ($\alpha > 0$), and (c) the farmer is subsidized for a portion of the insurance premium ($\alpha < 0$).

In the first scenario ($\alpha = 0$), the first-order conditions (14) and (15) become the first-order conditions for the risk-neutral farmer. By comparing the first-order conditions for the neutral farmer with the first-order conditions (9) and (10) for the risk-averse farmer, Huang, Uri and Hansen (1993) showed that for a given level of p , the risk-neutral farmer will apply an equal amount or less N fertilizer than a risk-averse farmer for the same yield level, assuming all other things are equal. An insurance program thus induces a risk-averse farmer to reduce the N fertilizer application rate.

In the second scenario ($\alpha > 0$), the risk-averse farmer also may reduce the N fertilizer application rate, but the reduction is smaller than under the first scenario. This is because the probability weight $[1 - (1 + \alpha)p]$ in equation (14) is less than the probability weight $(1 - p)$, and the probability weight $[(1 + \alpha)p]$ in equation (14) is larger than the probability weight p when $\alpha = 0$ in equation (14). The smaller probability weight for the successful application implies that the farmer will apply more N fertilizer. It should be noted that α can not be so large that the utility of expected net return, $E[Z]_e - p\alpha(Z_s - Z_f)$, becomes less than the utility of the BP-only practice, $U(Z)_b$. If this happens, the farmer will not have an incentive to adopt a GS-only N fertilizer application.

In the third scenario ($\alpha < 0$), the risk-averse farmer also reduces the N fertilizer application rate, the reduction is larger than under the first scenario. In this scenario the farmer's insurance premium is reduced (or subsidized). The probability weight $[(1 + \alpha)p]$ in equation (14) is smaller than the probability weight p in equation (14) when $\alpha = 0$. The smaller probability weight for the failing application implies that the farmer with insurance will apply less N fertilizer than the farmer in the first scenario. For example, if $\alpha = -1$ (insurance premium is fully subsidized), the rule (first-order conditions (14) and (15)) to determine N fertilizer application rate becomes $p_i \partial Y(N_i) / \partial N_i - p_i = 0$. For this rule the optimal timing of N application is always a GS-only application regardless of the value of p , implying that less N fertilizer will be applied.

The presence of insurance, therefore, may induce a risk-averse farmer to reduce N-fertilizer use by behaving like a risk-neutral farmer in making the fertilizer use decision. As the risk-averse farmer switches the application timing from a BP-only to a GS-only application, the reduction in N fertilizer use can be very substantial.

An Expected-Value Variance Formulation for an Empirical Analysis

An expected-value variance (EV) analysis is a practical and valid method for an empirical

study of insurance when the expected utility function of the farmer is unknown. Using the EV analytical framework, maximization of expected utility of net income ($EU(Z)$) is formulated as the maximization of expected-value variance of net income, which is CE net return (income). (For a discussion of validity of an EV formulation to approximate a utility function, see Anderson, Dillon, and Hardaker; Robison and Barry; Newbery and Stiglitz.) A risk-averse farmer will select a practice that maximizes CE net return with respect to N fertilizer applied. For the random variable Z denoting the net return from adopting an N fertilizer timing application (defined by (1) and (2)), the CE net return is defined as

$$(16) \quad CE(Z) = E[Z] - \gamma/2 \text{Var}(Z).$$

where $\text{Var}(Z)$ is the variance of net return which, in this study, is $p(1-p)(Z_s - Z_f)^2$; γ is an assumed absolute risk-aversion coefficient, which is assumed to be 0.02 for a strong risk-averse farmer (Boggess and Ritchie 1988).⁵ $\gamma/2 \text{Var}(Z)$ is the risk cost. Using this EV framework and assuming a large number of farmers who have identical and independent risk (Robison and Barry), the range for an insurance premium β^* for GS-only application is shown in (17):

$$(17) \quad p(Z_s - Z_f) \leq \beta^* \\ \leq p(Z_s - Z_f) + \gamma/2 \text{Var}(Z).$$

The lower bound in (17) is the minimum insurance premium—the actuarially fair insurance premium—which the insurance company must charge the farmer for a full coverage of income loss to maintain an actuarially sound insurance service. The upper bound is the

⁵ The absolute risk-averse coefficient is a key parameter for estimating the risk premium. It varies from 0 for a risk-neutral farmer to a positive value for a risk-averse farmer. As the value increases, the farmer becomes more risk-averse. Different levels of value have been suggested for a risk-averse farmer by researchers (Huang, Hewitt, and Shank). The value 0.02 used in this study for a high level of risk-aversion is comparable to value 0.01 for a moderate level of risk-aversion suggested by Babcock and Hennessy.

maximum insurance—the actuarially fair insurance plus the maximum risk cost to the farmer—which is the maximum insurance premium that the farmer is willing to pay for insurance. At this maximum insurance premium for GS-only application, the farmer who currently practices a GS-only application would be indifferent towards participating or not participating in an insurance program.

A sustainable insurance premium, β^{**} , for the adoption of a GS-only application must be both actuarially sound to an insurance company and also must provide a farmer who currently practices a BP-only application with an incentive to switch to a GS-only application. If the farmers select a full coverage, β^{**} must be greater than the actuarially fair insurance premium plus the cost of administering the insurance program (A). It also must ensure that the amount of the expected net income with insurance ($E[V]$) ($= Z_s - \beta$, which can be derived from (4) and (5)), is greater than the expected net income of the current BP-only ($E[Z]_b$). Using these two inequalities, a sustainable insurance premium for the adoption of a GS-only application must satisfy the following condition.

$$(18) \quad p(Z_s - Z_b) + A \leq \beta^{**} \leq Z_s - E[Z]_b$$

The potential benefit of an insurance program can be assessed by inequality (18). A risk-averse farmer can expect to improve CE net income if the insurance premium is less than the difference in net income between a successful GS-only application (Z_s) and the expected net income of the current BP-only application ($E[Z]_b$). If the farmer only pays the actuarially fair insurance premium, he/she can capture the potential maximum gain in CE net income, which is the difference in the expected net income between the GS-only application and the BP-only application.⁶

⁶ It is possible for β^{**} to be greater than β^* if the upper limit of the sustainable insurance premium in equation (18) (the gain from the adoption of the GS-only application) is greater than the upper limit of insurance premium in equation (17). In such situations, the farmer can use this increased income gain to pay for a portion of β^{**} .

An Iowa Case Study

An Iowa case study is used to illustrate the potential economic and environmental benefits of using an insurance program for the adoption of a GS-only N fertilizer application. Agricultural production in Iowa provides an excellent setting in which to study the adoption of better N fertilizer application timing to improve N use efficiency. Of major corn growing states, Iowa has the largest percentage of corn acres receiving N fertilizer in the fall and in the spring before planting. Results from the Agricultural Resource Management Study (ARMS) survey for 1996⁷ show that 20 percent of planted acres in Iowa received N fertilizer only in the fall and about 41 percent of planted acres received N fertilizer only in the spring, while only about 8 percent of planted acres received N fertilizer exclusively during the growing season. As noted previously, N fertilizer applied in the fall or the spring before planting is vulnerable to losses to the environment. Corn acres currently using a BP-only N fertilizer application will be targeted for the adoption of a GS-only N fertilizer application to improve N use efficiency. It is assumed that the farmer currently practices a BP-only N fertilizer application for corn, which is always possible to complete before planting, and that the farmer who adopts a GS-only N fertilizer application may not be able to enter the field to apply N fertilizer during the growing season in some years due to adverse weather.

Data and Assumptions

The model requires the estimation of the farmer's perceived probability (p) and the estimation of the production function (Y). A weather

⁷ In 1996, the U.S. Department of Agriculture conducted the Agricultural Resources Management Study (ARMS). Annual data were collected on fertilizer and pesticide use, tillage systems employed, cropping sequences, whether the cropland is designated as highly erodible, and information on the use of other inputs and production practices. The survey covered corn, cotton, soybeans, wheat (winter, spring and durum), and potatoes. Only selected states were surveyed, but about 80 percent of the total planted acreage for the respective crops were covered.

simulation model was used to determine the farmer's perceived probability that he or she may not be able to apply N fertilizer during the growing season and a regression analysis was used to estimate a production function of different N application timings. Historical weather conditions, machinery capacity, soil type, and labor availability during the growing season are key factors that determine the probability. In this study only the precipitation during the growing season was considered. The weather simulation model developed by the Agricultural Research Service (Hanson *et al.*) was used to estimate probabilities of daily precipitation. Iowa was divided into three weather zones: Western Iowa, represented by weather stations at Omaha and Sioux City; Central Iowa, represented by weather stations in Des Moines and Mason City; and Eastern Iowa, represented by weather stations in Dubuque, Waterloo, and Ottumwa. The simulation model estimated the probability of daily precipitation x in each of these three weather zones for June and July. The probability that a farmer will not be able to apply N fertilizer during these two months was $P(x > r)$, where r was the maximum daily precipitation that would make soil conditions such that it would be difficult or impossible for machinery to enter the field. The value of r was between 0.25 inches and 0.5 inches, depending on soil type (Cruse). The averages of the estimated probabilities for the three weather zones were used in this study. The averages were $p(x > 0.25 \text{ inches}) = 0.15$ and $p(x > 0.5 \text{ inches}) = 0.10$. These estimates are consistent with the estimates used by Feinerman, Choi, and Johnson.

Production functions were estimated by using cross-section data from the 1996 ARMS survey. The estimated production function can be interpreted as the yield function for the "average field" in Iowa.⁸ Sampling methods and data collection techniques used in the

1996 ARMS are given by Kott and Fetter. A total of 1009 cornfields were surveyed in Iowa. The data used for estimating the production function were restricted in this study so as to isolate the impact of N fertilizer applied on yield. The sample used in the estimation included only the fields where farmers grew full-season corn without applying manure and planted cover crops in winter and where they planted corn the last two years without the use of N inhibitors. Under these conditions the 1996 ARMS survey yielded 63 usable observations representing 962,000 acres. About 51 percent of these acres had N fertilizer applied during the spring only before planting and 9 percent had N fertilizer applied only in the fall.

The Production Functions

Three functional specifications were used to evaluate the consistency of the estimates of the relationship between corn yield and the timing of N fertilizer application. The specifications used included a quadratic (QD) function, the linear-plateau (LP) function, and the Mitscherlich-Baule (MB) function. The quadratic function exhibits diminishing marginal returns, the linear-plateau function places a plateau on the yield response to N, and the Mitscherlich-Baule function exhibits diminishing marginal returns with an asymptotic yield plateau in response to N fertilizer application (Frank, Beattie, and Embleton; Beattie and Taylor).

The standard least-square method in SAS (Statistical Analysis System) procedures was used for the estimation. The estimation results are shown in Table 1. Collinearity and heteroscedasticity testing reveals that estimation of each production function is acceptable. Two estimated coefficients, d and aI , are particularly important for this study. Coefficient d is used to estimate the efficiency of N fertilizer applied before planting. It represents the percentage of N fertilizer applied before planting that is available for plant uptake during the growing season. Coefficient aI , the intercept, is the expected corn yield if the farmer fails to apply all fertilizers. These two estimates, d

⁸ An ideal set of data for estimating a production function for a representative field would be from the time series data obtained over years from controlled experiments with varied timings of N fertilizer application and from various experiment sites with different site variables. Such data is currently not available for this study.

Table 1. Coefficient Estimates for Quadratic, Linear-Plateau, and Mitscherlich-Baule Production Functions (see note below)

	Quadratic Function	Linear Plateau	Mitsch-Baule
<i>a1</i>	82.23** ^a (14.48) ^b	84.80** (13.15)	75.31 ^d (na)
<i>a2</i> (Phosphate (<i>P</i>))	0.022 (0.089)	0.058 (0.085)	0.061 (0.09)
<i>a3</i> (Potash (<i>K</i>))	-0.019 (0.727)	-0.046 (0.071)	-0.004 (0.075)
<i>b1</i>	1.233** (0.406)	0.940** ^c (0.533)	0.037 (0.028)
<i>b2</i>	-0.006** (0.002)	na ^f	20.80 (29.88)
<i>d</i> (proportion of Nb available)	0.364** (0.114)	0.346** (0.147)	0.335* (0.20)
<i>T</i> (plateau)	na	141.25** (7.848)	139.10** (10.24)
<i>Adj. R-Squared</i> ^e	0.13	0.17	0.10

^a Statistically significant at the 0.05-level using t-test.

^b Standard error.

^c Statistically significant at the 0.10-level using t-test.

^d Computed value by assuming *Ng* and *Nb* to be zero in the estimated function.

^e Coefficient of determination.

^f Not available

Note: These three functions are specified as

(i) Quadratic Production Function

$$Y = a1 + a2 P + a3 K + b1 ((Nb) d + Ng) + b2 ((Nb) d + Ng)**2$$

(ii) Linear-Plateau Production Function

$$Y = a2 P + a3 K + \text{Min} [a1 + b1 ((Nb) d + Ng), T]$$

(iii) Mitscherlich-Baule Production Function

$$Y = a2 P + a3 K + T [1 - \exp(-b1(b2 + (Nb) d + Ng))]$$

where *Nb* and *Ng* are the amounts of N fertilizer, respectively, applied before planting in the fall, in the spring, and after planting in the growing season. *P* and *K* are the amounts, respectively, of phosphate and potash applied and *a1*, *d*, *a2*, *a3*, *b1*, *b2*, and *T* are coefficients to be estimated.

and *a1*, obtained from each of the three productions are comparable.

The estimated LP function was used for the illustration. It was selected for the illustration over the other two functions because it has the largest adjusted R-squared among three yield functions considered. The appropriateness of using the estimated LP function against the other two estimated functions was investigated using a non-nested J-test (Davidson and Mackinnon). Test results indicated the LP function is appropriate at the statistically significant level less than 0.01. The estimate of the intercept *a1* (84.80 bus./ac.) found to be relatively higher than the estimate (65 bus./ac.) which Voss and Shrader obtained in their study of long-term continuous corn yields without application of N fertilizer. This differ-

ence is expected because in this study some of N absorbed by the plant is from the carry-over N in the soil. Also, the estimate of the efficiency *d* (0.346) is relatively small compared to the estimate for N fertilizer applied in the spring (Feinerman, Choi, and Johnson). This may be attributed to the inclusion of the fall application data in the estimation of the production function. The estimates of plateau *T* (141.25) appear to be reasonable.

The estimated probabilities and the LP production function were used to construct an EV model to assess the potential economic benefit of adoption insurance to a risk-averse farmer. The potential economic benefit was assessed by comparing the farmer's CE net return from adopting a GS-only N application without insurance and the net return when insured. The

Table 2. Optimal Application Timing, N Fertilizer Application Rate, and Expected Net Revenue for Iowa Farmers Planting Continuous Corn, No Adoption Insurance

	Risk-Neutral Farmer	Risk-Averse Farmer
<i>Probability of not applying N fertilizer during growing season (p) = 0.10.</i>		
Application timing	Before and after planting	Before and after planting
Application Rate		
Before planting (lbs./ac)	0.00	173.56
After planting (lbs./ac)	60.05 ^a	0.00
Total (lbs./ac)	60.05	173.56
Expected Yield (bu/ac)	135.61	141.25
Expected Net Revenue (\$/ac) ^b	315.43	307.73
(Certainty Equivalent Net Return)		
<i>Probability of not applying N fertilizer during growing season (p) = 0.15.</i>		
Application timing	Before and after planting	Before and after planting
Application Rate		
Before planting (lbs./ac)	0.00	173.56
After planting (lbs./ac)	60.05	0.00
Total (lbs./ac)	60.05	173.56
Expected Yield (bu/ac)	132.78	141.25
Expected Net Revenue (\$/ac) ^b	309.49	307.73
(Certainty Equivalent Net Return)		

^a The relatively low N fertilizer application rate reflects a large amount of soil-N in Iowa soil. Even if the farmer in one year misses the N fertilizer application during the growing season, he or she still can expect to harvest 84.80 bushels of corn per acre. Continuously mining soil-N can deplete soil-N and may not be sustainable and an increase of the application rate may be needed to reduce the mining.

^b For a risk-neutral farmer, expected net revenue = gross revenue - N fertilizer cost - field operation cost. For a risk-averse farmer, certainty equivalent net return = expected net revenue - risk premium.

procedure to assess the benefit included three parts. The first part determined the optimal N application timing and the cost of adopting a GS-only practice without insurance (the baseline scenario). The second part determined the ranges of the sustainable insurance premium for the adoption of the GS-only application and the potential economic benefit of the adoption insurance to a risk-averse farmer. The third part compared the farmer's CE net return from adopting a GS-only application without insurance and net returns when insured. In this case study the administrative cost and the problems associated with adverse selection, moral hazard, and the correlation of events were not addressed because the requisite data was not available. The price of corn was assumed to be \$2.45 per bushel and the price of N fertilizer \$0.2 per pound (USDA). The broadcasting cost of N fertilizer including fixed and field operation costs for a BP-only application was assumed to be \$3.62 per acre, and a side-dressing application cost for a GS-

only application was assumed to be \$6.65 per acre (Doster).

Optimal Nitrogen Application Timing without Insurance

The N fertilizer application timing decision model was employed to determine the optimal N fertilizer application timing for Iowa farmers who continuously plant corn annually on the same field. The optimal N fertilizer application rate, optimal timing, and expected net revenue for a risk-neutral and a risk-averse farmer are presented in Table 2. When the perceived probability (*p*) of the farmer failing to apply N fertilizer during the growing season is 0.10, the optimal application timing for a risk-neutral farmer is a GS-only application, applying 60.05 pounds of N fertilizer before planting, yielding 135.61 bushel of corn. For the risk-averse farmer, the optimal application timing is a BP-only application for, applying 173.56 pounds of N fertilizer before planting.

Table 3. A Risk-Averse Farmer's CE Net Return for a BP (before planting)-Only N Fertilizer Application and for a GS (growing season)-Only Application in Planting Continuous Corn, No Adoption Insurance

	GS-only	BP-only	Difference
	\$ /acre		
<i>p</i> = 0.10			
Expected net income	315.43	307.73	7.70
Risk-premium	-12.88	0	-12.88
CE net return	302.55	307.73	-5.18
<i>p</i> = 0.15			
Expected net income	309.49	307.73	1.76
Risk-premium	-18.25	0	-18.25
CE net return	291.21	307.73	-16.52

Thus the risk-averse farmer applies 113.51 pounds N fertilizer more than the risk-neutral farmer for a gain of about 5.64 bushels of corn.

When the perceived probability of the farmer failing to apply N fertilizer during the growing season is 0.15 for the risk-neutral farmer, the optimal N fertilizer application timing is also a GS-only application, applying 60.05 pounds of N fertilizer after planting and yielding 132.78 bushels of corn. For the risk-averse farmer, the optimal N fertilizer application timing is an also a BP-only application, applying 173.56 pounds of N fertilizer before planting, yielding 141.25 bushels of corn per acre. This result indicates that the risk-averse farmer applies 113.51 pounds of N fertilizer more than the risk-neutral farmer for a gain of about 8.47 bushels of corn.

For the risk-averse farmer, the optimal application rates and yields of the BP-only application are comparable to the survey's average application rate and yield. The optimal application rates (173.56 pounds for $p = 0.1$ and for $p = 0.15$) are comparable to the survey's average application rate (154.00 pounds) of the BP-only application. The optimal yields (141.25 bushels for $p = 0.10$, and for $p = 0.15$) are also comparable to the survey's average yield (135.60 bushels). Because the adoption of the GS-only application can reduce N-fertilizer use substantially, developing an insurance program to provide a farmer in-

centive to adopt a GS-only application is the focus of next investigation.

Cost of Adopting a GS-only Application without Insurance

For a risk-averse farmer when $p = 0.10$, a switch of N fertilizer application timing from a BP-only application to a GS-only application can cost the farmer \$5.18 of CE net return (\$302.55-307.73) (Table 3). This result indicates that in the absence of insurance a risk-averse farmer will not adopt a GS-only N fertilizer application. The cost mainly comes from the risk-premium (\$12.88). An insurance program that reduces this cost potentially enhances the farmer's incentive to adopt a GS-only application. A program that reduces this risk-premium to zero would allow the farmer to have an increase in CE net return of \$7.70 per acre (the difference in expected net income between the GS-only and the BP-only practice) by switching from a BP-only application to a GS-only application.

When $p = 0.15$ (Table 3), a risk-averse farmer without insurance would have a larger reduction in CE net return, about \$16.52, by switching N fertilizer application timing from the BP-only to a GS-only application. An insurance program would help a farmer adopting a GS-only application increase CE net return by reducing risk cost (\$18.25) and thereby increasing CE net return (\$1.76). Since this gain

(\$1.73) is relatively small, the insurance may not provide the farmer adequate incentive to adopt the GS-only application. As p increases, the expected net income of the GS-only decreases and becomes smaller than the expected net income of the BP-only application. In such situations, insurance would not provide the farmer incentive to adopt the practice.

Sustainable Insurance Premiums and Benefits of Insurance

First, the maximum insurance premium of β^* that induces a risk-averse farmer currently using the GS-only application to be indifferent to either participating or not participating in a GS-only insurance program can be determined. Assume the farmer buys insurance for full coverage of yield loss in the case of failing to apply N during the growing season, and the cost of insurance service is zero ($\alpha = 0$). When $p = 0.10$, the indemnity I for full coverage is computed by $(Z_s - Z_f)$, which is \$119.64 (327.40–207.76).⁹ By using inequality (17), the maximum insurance premium β^* that the farmer would be willing to pay is $[0.10 \times (\$119.64)] + [0.01 \times (\$119.64)^2 \times 0.10 \times 0.90] = \24.85 , which yields \$302.55 of the CE net return (Table 3). With this maximum insurance premium of \$24.85, however, a farmer currently using the BP-only application may have no incentive to switch N fertilizer application timing from a BP-only to a GS-only application. This is because the CE net return (\$302.55) is less than the CE net return of \$307.73 for a BP-only N fertilizer application. A reduction in the insurance premium for full-yield coverage is needed to ensure that the farmer will have the requisite incentive to switch production practices.

Next, the sustainable insurance premiums for which a risk-averse farmer would be willing to switch from the BP-only to the GS-only application and pay for the coverage of full

yield loss can be determined by inequality (18). The maximum sustainable insurance premium (β^{**}) that the farmer would be indifferent to switching N fertilizer application from a BP-only to a GS-only application or not is \$19.66 (the upper bound of inequality (18)). By implementing risk sharing (pooling) among participating farmers, the insurance company may be able to reduce the insurance premium from \$19.66 to an actuarially fair premium of \$11.96 ($p = 1$), assuming that the risk for an individual farmer is independent of the risk for other farmers. This is the minimum sustainable insurance premium to the farmer, representing a saving of \$12.88 to the farmer.¹⁰ If this saving is added to the CE net return (\$302.55), there will be an increase in the farmer's CE net return to \$315.43, which is \$7.70 greater than the CE net return (of \$307.73) of a BP-only application. The farmer, therefore, after paying the minimum insurance premium of \$11.96 for the insurance coverage, will realize a \$7.70 increase of CE net return. This is the maximum the farmer would gain from adopting the GS-only N fertilizer application. If an insurance company incurs some administrative cost, the administrative cost A must be less than \$7.70 for the insurance program to be sustainable. Thus a sustainable insurance premium will have to be between \$11.96 and \$19.66 for full-yield coverage insurance.

Similarly, a sustainable insurance program also can be designed for $p = 0.15$ that would provide farmers an incentive to adopt a GS-only N fertilizer application. In this case the gain from an insurance program for the adoption of a GS-only application is relatively small (\$1.76), if the farmer pays an actuarially fair insurance premium of \$17.93. The estimated range for a sustainable insurance premium for full-yield coverage is between \$17.93 and \$19.66.

Table 4 summarizes the potential benefits of the adoption insurance for a GS-only N fer-

⁹ $I = [Z_s] - [Z_f] = [\text{yield of a successful GS-only N fertilizer application (141.25 bu/ac)} \times \$2.45/\text{bu} - \text{fertilizer used (60.05 lbs/ac)} \times \$0.2/\text{lb} - \text{field operation cost } (\$6.65/\text{ac})] - [\text{yield associated with failing to apply the GS-only (84.80 bu/ac)} \times \$2.45/\text{bu}] = [\$327.40/\text{ac}] - [\$207.76/\text{ac}] = \$119.64/\text{ac}$.

¹⁰ The reduction (\$12.88/ac) in the insurance premium also can be realized by the farmer if the insurance company is risk-neutral and able to absorb all the risk transferred from farmers.

Table 4. Benefits of Adoption Insurance to a Risk-averse Farmer Changing N Fertilizer Application Timing on Continuous Corn from a BP-Only (baseline) to a GS Only

Scenarios	$p = 0.10$ Change in		$p = 0.15$ Change in	
	Premium	CE Return	Premium	CE Net Return
No insurance	0 (302.55) ^a	-5.18	0 (291.21)	-16.52
Maximum insurance premium that a farmer is willing to pay for full coverage of yield loss (\$/ac)	24.85 (302.55)	-5.18	36.20 (291.21)	-16.52
Maximum insurance premium that a farmer is willing to pay while still having an incentive to adopt (\$/ac)	19.67 (307.73)	0	19.67 (307.73)	0
Minimum insurance premium (actuarially fair premium) that a farmer pays for the adoption insurance (\$/ac)	11.96 (315.43)	7.70	17.93 (309.49)	1.76

^a Number in the parentheses is the CE net return after subtracting the insurance premium.

tilizer. Figures inside the parentheses are the farmer's CE net returns of adopting the GS-only N fertilizer application for each insurance premium. With an insurance program, the farmer may be able to increase his or her certain net return. As p increases from 0.10 to 0.15, the potential maximum economic benefit to the farmer decreases from \$7.70 to \$1.76 per acre.

Reduction in Residual Nitrogen

Residual N (RN) indicates the potential environmental impact of N fertilizer applications.

RN from the current crop production is susceptible to loss to the environment before the next crop season. A farmer who switches N fertilizer application timing from a BP-only to a GS-only can reduce the amount of N fertilizer applied by as much as 114.43 pounds for $p = 0.10$ and by as much as 128.17 pounds for $p = 0.10$ (Table 5). The large savings in RN is the result of the high application rate (173.56 pounds) in the BP-only application and the low average application rate, 54.04 pounds, in the GS-only application for $p = 0.10$ and 51.04 pounds for $p = 0.15$. The av-

Table 5. Reduction of Residual N from Changing the N Fertilizer Application Timing from a BP-Only (baseline) to a GS-Only, Continuous Corn

	$p = 0.15$	$p = 0.10$	Survey Average
	pounds/acre		
BP-only application			
(1) N applied	173.56	173.56	154.00
(2) N removed	127.13	127.13	122.04
(3) Residual N ((1)-(2))	46.43	46.43	31.95
GS-only application			
(4) Average N Applied ^a	54.04	51.04	108.80
(5) Average N removed ^b	122.04	132.78	95.76
(6) Average N mined ((4)-(5))	-68.00	-81.74	13.04
Total Residual N reduced ((3)-(6))	114.43	128.17	18.90

Note:

^a Average application rate = (successful application of N) (1- p).

^b Average N removed = {(Yield of successful application of N) * (1- p) + (yield of failing to apply N) * p } * 0.9, where 0.9 is the amount of N in one bushel of corn harvested (Meisinger).

Table 6. Comparison of Alternative Yield Functions Used

	Quadratic (QD)	Linear plateau (LP)	Mitsch-Baule (MB)
$P = 0.10$			
Optimal N application timing	SN ^a	BP-only	SN
Before planting (lbs/acre)	92.41	173.56	68.21
After planting (lbs/acre)	62.31	0	67.21
CE net return (\$/acre)	309.88	307.73	292.51
Risk premium (\$/acre)	14.90	12.88	14.35
Potential gain (\$/acre)	15.55	7.70	13.28
RN Reduction (lbs./acre)	140.31	114.43	99.40
$P = 0.15$			
Optimal N application timing	SN	BP-only	SN
Before planting (lbs/acre)	112.65	173.56	86.35
After planting (lbs/acre)	51.30	0	61.14
CE net return (\$/acre)	307.73	307.73	290.36
Risk premium (\$/acre) ^b	21.10	18.25	20.33
Potential gain (\$/acre) ^c	9.12	1.76	6.96
RN Reduction (lbs./acre) ^d	142.29	128.173	105.26

^a SN = split N-fertilizer application applying some fertilizer before-planting and some fertilizer in the growing season. BP-only = fertilizer application only before planting.

^b Risk premium, as the farmer switches from a BP-only application to a GS-only application.

^c Potential gain in CE net return when the insured farmer pays actuarially fair insurance premium, as the farmer switches from a BP-only application to a GS-only application.

^d Reduction in residual N, as the farmer switches from a BP-only application to a GS-only application.

erage application rate per year is the product of a successful GS-only application rate (60.05 in Table 2) and probability of a successful GS-only application ($1-p$). The reduction of RN is quite large compared with the reduction in RN computed from the survey data. The average reduction in RN from the survey data is about 19 pounds per acre, which is only about one sixth of the model's result (Table 5). Most of the reductions are from the mining of soil-N carried over from previous years. For example, when $p = 0.1$, 68 out of 114.43 pounds of N are mined from soil-N. Iowa soil generally contains a large amount of soil-N, and mining of such a large amount of soil-N may be possible for a few years (Voss and Shradler), but it may not be possible for over a long-period.

Sensitivity Analyses

Two sensitivity analyses were conducted. The first analysis investigated the sensitivity of the results to the yield function used. The second

analysis investigated the sensitivity of the results to the estimate of N-efficiency (d).

The results from the three alternative yield functions are presented in Table 6. The optimal application timing for the LP function is BP-only, while for the QD and MB functions it is SN. The potential gains from an adoption insurance program for the GS-only adoption (\$7.70 for $p = 0.1$ and \$1.76 for $p = 0.15$) are much smaller for the LP function than for the QD and MB functions. As the value of p increases, the difference becomes larger. However, the risk premiums and CE net returns from these three functions are comparable. The results from the QD function and the MB function in general are comparable.

The potential economic gains (the differences between the CE net return of the GS-only and CE net return of the BP-only application) were estimated under three levels of efficiency (d) of N-fertilizer being applied before planting: 0.231 ($0.346 \div 1.5$), 0.346 and 0.519 (0.346×1.5). The potential gain in CE net return to the farmer was estimated assum-

Table 7. Effects of Efficiency of N Fertilizer Applied before Planting on CE Net Returns from Continuous Corn and on Reduction of Residual N When Farmers Have GS-only Adoption Insurance

N-Efficiency (d)	CE Net Returns		Residual Nitrogen	
	$p = 0.10$	$p = 0.15$	$p = 0.10$	$p = 0.15$
	Dollars/acre		Pounds/acre	
0.231	24.99	15.39	200.85	214.59
0.346	7.70	1.76	114.43	128.17
0.519	-3.86	-13.46	56.58	69.58

ing that the farmer pays the actuarially fair insurance premiums. The gain in CE net return is sensitive to changes in the efficiency of N-fertilizer applied before planting (Table 7). The gain diminishes as the N-efficiency (d) and the probability (p) of not applying N during the growing season increases. When d is greater than 0.50, the gain becomes negative, implying that insurance will not help the farmer improve his or her CE net return in adopting a GS-only N application. Similarly, when p is greater than 0.15 and d is greater than 0.346, insurance may not be helpful to the farmer. The farmer will be better off by staying with the BP-only application. The potential reduction of residual N nitrogen as the farmer switches from the BP-only application to the insured GS-only application reduces 200 pounds to less than 100 pounds as the value of N-efficiency increases. These results imply that adoption insurance is most useful to the farmer with the sandy-soil cropland where N loss is large (d is small) and where the probability of not being able to apply N fertilizer during the growing season is small because of good drainage.

Concluding Remarks

The potential economic and environmental benefits of using insurance to help a risk-averse farmer adopt a better nitrogen management practice of timing N fertilizer application to reduce N loss to the environment were analytically and empirically investigated. The empirical results presented here are general because of the limitations of data and the as-

sumptions used in this study. Adoption insurance is very farm-specific just as life insurance is specific to individuals. The design of insurance program must be based on long-run pooled cross-sectional (for estimating N-efficiency) and time series (for estimating expected net returns) data on N-fertilizer and crop yields. Site-specific information, such as soil type and weather conditions, are required to estimate the production function. Nevertheless, this paper demonstrates that there is a potential for insurance to provide a farmer incentive to adopt a GS-only application.

Other considerations must also be addressed. One key consideration is the cropping pattern. This study focuses only on farmers who plant continuous corn. Farmers can reduce their risk cost of adopting a GS-only N fertilizer application by diversifying the crops they grow. For example, soybeans can leave a substantial amount of N to soil for the subsequent production of corn. A risk-averse farmer can reduce the production risk by growing corn after soybeans. The carry-over N fixed by soybeans will reduce the yield loss that would otherwise occur if the farmer fails to apply N during the growing season. Thus an insurance program may not be useful for a corn-soybean rotation.

The problems of moral hazard and adverse selection can also be serious. Moral hazard and adverse selection problems are often observed and well documented in crop insurance (Skees, Black, and Barnett). An insurance program for the adoption of a GS-only application is likely to confront these same problems. Moral hazard occurs when insurance reduces

the farmer's incentive to complete N-fertilizer application during the growing season when weather is favorable for the farmer to comply with the GS-only practice and the application of N fertilizer at the optimal rate, as required by the adoption insurance. Unlike the current crop insurance, the adoption insurance would need inexpensive ways to monitor the compliance and to determine indemnity payments to avoid high administration cost that may cause the adoption insurance market to fail.

Adverse selection occurs when the insurance company cannot separate better risks from poor risks. This has been a serious problem for crop insurance (Skees, Black, and Barnett 1997). The self-insurance problem such as the one addressed by Babcock could be a particularly serious barrier for adoption insurance. Strategies (Nelson and Loehman; Newbery and Stiglitz) that have been employed to mitigate the problems of moral hazard and adverse selection in crop insurance also need to be explored with regard to N fertilizer timing.

One strategy to reduce the cost of the program might be to piggyback the adoption insurance on the current crop insurance. The "additional" (or Buy Up) coverage under the current crop insurance could be modified to include an adoption insurance program. Such a strategy may allow the adoption insurance to share the risk cost and the program administration with the current crop insurance program. Pilot studies would be needed to explore the feasibility of this alternative. Farmers in the area where nitrate leaching is severe could be offered an insurance option to foster adoption of a better application timing.

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Appendix: Derivation of the First-order Conditions (14) and (15)

When constraint (8) (in the main text) is not binding ($\lambda = 0$), the Lagrangean of the model is $L = U|V|$. By taking the partial derivative of L with respect to N_b and to N_g , the first-order conditions become:

$$\begin{aligned}
 &(\partial U(V_s)/\partial N_b) (1 - p) (\partial V_s/\partial N_b) + p(\partial U(V_f)/\partial N_b) \\
 &(\partial V_f/\partial N_b) = 0, \text{ and} \\
 &(\partial U(V_s)/\partial N_g) (1 - p) (\partial V_s/\partial N_g) + p(\partial U(V_f)/\partial N_g) \\
 &(\partial V_f/\partial N_g) = 0.
 \end{aligned}$$

Since $V_s = Z_s - (1 + \alpha) p (Z_s - Z_f)$ and $V_f = Z_f + [(1 - (1 + \alpha) p) (Z_s - Z_f)]$, and also $V_s = V_f = Z_s - (1 + \alpha) p (Z_s - Z_f)$, thus $\partial U(V_s)/\partial N_g = \partial U(V_f)/\partial N_g$ and $\partial U(V_s)/\partial N_b = \partial U(V_f)/\partial N_b$. Using

these two relations, the first-order conditions become:

$$(1 - p) (\partial V_s / \partial N_b) + p (\partial V_f / \partial N_b) = 0, \text{ and}$$

$$(1 - p) (\partial V_s / \partial N_g) + p (\partial V_f / \partial N_g) = 0.$$

Substituting $Z_s = p_c Y(N_t) - p_f N_g - p_f N_b - C(N_g) - C(N_b)$ and $Z_f = p_c Y(N_t | N_g = 0) - p_f N_b - C(N_b)$ for computing V_s and V_f and assuming $C(N_g)$ and

$C(N_b)$ are fixed costs, the first-order conditions become:

$$(1 - (1 + \alpha) p) (p_c \partial Y(N_t) / \partial N_t - p_f) + (1 + \alpha) p (p_c \partial Y(N_t | N_g = 0) / \partial N_t - p_f) = 0,$$

$$p_c \partial Y(N_t) / \partial N_t - p_f = 0.$$