Journal of Agricultural and Resource Economics 25(2):468–484

Contract Incentives and Excessive Nitrogen Use in Agriculture

Paul V. Preckel, Gerald E. Shively, Timothy G. Baker, Mei-Chin Chu, and Jessica Eide Burrell

This study examines incentives for input use under tournament contracts. We analyze implications of contract design for nitrate-based environmental externalities generated by agricultural producers. Outcomes are compared from contracts awarded by tournament to those from fixed-payment contracts. Our findings show contract insecurity can distort input use. The model developed in this analysis is applied to a region of the U.S. where tournament-based production is prevalent and groundwater contamination is a problem. We find contract insecurity increases nitrogen use by about 12%, resulting in a 17% increase in nitrate leaching. Implications for contract modification to reduce environmental externalities while maintaining contract incentives are discussed.

Key words: agriculture, environmental externalities, nitrogen use, tournament contracts

Introduction

The costs of water degradation in the U.S. due to agriculture have been estimated at \$2–\$8 billion annually (Ribaudo). Contamination of drinking water supplies by elevated nitrate levels in subsurface water is a particular concern. Nitrate is the most widespread agricultural contaminant and poses a potential risk to human health in some locations. Recent data suggest that as many as 4.5 million Americans are exposed to nitrate concentrations above the maximum level recommended by the U.S. Environmental Protection Agency (EPA). The most significant environmental releases of inorganic sources of nitrates originate in the use of fertilizers.[1] In many cases, elevated nitrate levels can be traced to high rates of nitrogen fertilizer application by agricultural producers. When nitrogen is applied in excess of crop uptake, nitrate leaching occurs below the crop root zone leading to contamination of subsurface water supplies.

Preckel is professor, Shively is associate professor, and Baker is professor, all in the Department of Agricultural Economics, Purdue University; Chu is graduate assistant, Department of Agricultural Economics, Michigan State University; and Burrell is graduate assistant, Department of Agricultural Economics, Purdue University.

The authors are grateful to Otto Doering, Craig Dobbins, Sandra Batie, and John Cranfield for access to data and helpful comments and suggestions. Special thanks to Brian Baer for providing invaluable assistance in validating the yield simulation model that served as the basis for the empirical section of this article. This material is based on work supported in part by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture, under Agreement No. 94-37102-0839. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the U.S. Department of Agriculture. This article is Purdue University Agricultural Research Program Journal Paper No. 16,339.

[1] For example, according to the EPA's Toxics Release Inventory, releases of fertilizer to water and land totaled over 112 million pounds from 1991 through 1993.

In this study, we demonstrate both theoretically and empirically how excessive use of nitrogen fertilizer can be traced to the incentives associated with insecure tournament contracts.[2] A stochastic dynamic principal-agent model is used to compare specific incentives for input use under fixed-payment and insecure tournament contracts. The behavioral implications of the model are then examined and the magnitude of excess nitrogen use is measured for a region in the Midwestern U.S. where groundwater is highly susceptible to nitrate contamination. We show how the perceived lack of contract security on the part of producers can lead to overapplication of variable inputs relative to the case where it is known a priori whether the contract will be renewed. We also show how contract rules could be modified to reduce or eliminate socially suboptimal applications of nitrogen.

Tournament Contracts in Agriculture

The contract of interest in this study is a tournament-based principal-agent contract. The structure of principal-agent contracts in agriculture is of perennial interest among applied economists due to underlying and difficult-to-observe differences in efficiency, risk aversion, and double-sided moral hazards. Salanie provides a modern treatment of contracting models, many of which build upon principal-agent theory (e.g., Holmstrom and Milgrom 1987, 1992). Chu et al. provide an extensive treatment of the static principal-agent problem in an agricultural setting, and Agrawal analyzes the links between producer efficiency and contract choice in a principal-agent model applied to agriculture.

In the principal-agent framework, the principal has the power to design the contract, while the agent responds to the contract in a self-serving way. The principal's goal is to design the contract so as to achieve her goals, given that the agent will respond to the contract by optimizing his goals. A major difficulty in contract design in agriculture is that the principal (e.g., a landlord or contractor) is frequently unable to observe some of the characteristics or actions taken by contracting agents.

In response, tournament contracts have arisen in agriculture as a way to encourage incentive compatibility among contract participants. Outside of agriculture, tournament contracts are widely used for employee compensation, especially at top management levels (Gibbons and Murphy; Jensen and Murphy). The primary goal of a tournament contract is to foster competition between agents by basing rewards from the principal on some measure of agent performance (Nalebuff and Stiglitz). Typically, this goal is achieved by designing a system of payoffs that reward those who perform better than average and penalize, at least in relative terms, those who perform less well.[3] Although many principal-agent models are constructed using a risk-averse agent and a less risk-averse (or risk-neutral) principal, the assumption of risk aversion is not required to explain either the emergence of contracts or their persistence (e.g., Eswaran and Kotwal;

---

[2] As noted by one of the reviewers, tournament contracts do not necessarily lead to increases in input use any more than contracts based on fixed performance standards. (See Tsoulouhas and Vukina for a discussion of the various types of contracts used in livestock production.) Rather, it is the combination of dependence of the compensation scheme and the future access to the contract on current yield performance that can lead to excessive input use.

[3] Our formulation leads to behavioral predictions for the agent that share some features of models of ratchet effects, i.e., contracts in which performance standards increase over time conditional on past performance. However, the current analysis assumes the conditional probability distribution for contract renewal is fixed over time. Allen and Lueck study share contracts in agriculture and find only limited evidence of ratchet effects.

Nalebuff and Stiglitz). For simplicity in the model developed below, we assume risk neutrality on the part of both principal and agent.

One difficulty associated with optimal contract design is that the principal's optimization problem includes optimal behavior of the agent as part of the constraint set. Thus, the problem falls into the class of bilevel programming problems (Bard and Moore; Candler and Townsley). These problems can prove difficult to solve via traditional numerical techniques because, in general, the constraint set for such problems need not be convex. In the present case, we are concerned with the nature of the agent's response to an existing tournament contract. Thus, we focus our attention on the agent's problem, which is a convex optimization problem.

In the agricultural sector, tournament contracts are common in livestock and seed corn production (e.g., Knoeber; Knoeber and Thurman 1994, 1995; Swinton, Chu, and Batie; Tsoulouhas and Vukina). In the case of broiler production, contract termination provisions are rarely connected to tournament outcomes. In contrast, performance and contract renewal are closely wedded in the case of seed corn production. Shaw, Howard, and Martin provide a survey of contracts in the seed corn industry.

Contract seed production, wherein an agricultural producer grows a crop expressly to provide seed for a supplier, is characterized by a lack of relationship-specific assets. Producers typically provide machinery, land, and management skills that could be used in other ways. Furthermore, significant and unobserved heterogeneity may exist with respect to land and management skills. Because of this heterogeneity, the contracting relationship between the seed corn company and the seed producer does not necessarily develop as a long-term agreement. Unlike poultry contracts, which typically span several years, seed corn contracts tend to be renewed annually. Moreover, because there are essentially no fixed assets specific to seed corn production, there is no strong barrier to short-term contracting. Instead, seed corn producers are paid for use of land and for providing services such as land preparation, planting, and crop management. Payments to seed producers are comprised of a fixed payment plus a bonus or penalty. The fixed payment is typically not linked to seed corn production, but is instead based on per acre revenues realized in the commodity corn sector. To this fixed payment, which is clearly independent of variable input use on the seed corn, a bonus is added. An individual producer receives a bonus if his yield exceeds the average for all producers under contract. The producer may be penalized if his yield falls below the average.

Typically the number of producers seeking such contracts exceeds the number of contracts available. In response, seed companies allocate contracts to preferred producers, usually on the basis of high yields. As a result, a producer has two incentives to seek a high yield: the bonus payment and the increased likelihood of future contract allocations.

The first issue we address in this article is whether the features of insecure tournament contracts encourage greater application of inputs such as fertilizers than would be the case under an allocation of contract by lottery, combined with a straight payment for yield. Using a stylized model of the producer's problem, we demonstrate that the insecure tournament contract can create an incentive to overapply fertilizer. Our second concern is empirical and focuses on measuring the magnitude of this increase in input use. A third issue taken up below is how one might modify the payment and contract allocation schemes so as to reduce or eliminate the incentives for increased application, while maintaining farmer incentives to maximize yields.

The Model

To begin, we develop a model to compare fertilizer use under fixed-price and insecure tournament contracts. For simplicity, we assume a single-input, stochastic yield function, in which output per acre is a function of nitrogen application (the representative variable input), a weather index, and an error term. The production function is assumed to take a linear response and plateau form. The slope of the linear portion is constant with respect to nitrogen and is independent of weather. The plateau level is an increasing function of weather. The production function for the individual producer is:

$$y(n, w) = \min(\alpha n, \beta w) + \varepsilon,$$

where α and β are fixed positive parameters, $y(\cdot)$ denotes output as a function of input (nitrogen) level n and the disturbances w and ε. The disturbances reflect the imperfect relationship between weather and output. Throughout the exposition, we use W (upper case) to denote the weather random variable and w (lower case) to denote a realization of the weather random variable. When functions of random variables are defined, they will be defined in terms of realizations. When the arguments of these functions include W, the function should be understood to indicate a random variable whose randomness is driven by its arguments.

Following Nalebuff and Stiglitz, we assume the first disturbance is covariate, i.e., shared by all producers in the contest, and that the second disturbance is idiosyncratic, i.e., specific to individual producers. The weather index ranges between zero and one, with one indicating ideal conditions and zero indicating conditions resulting in zero yield. For convenience, we assume in the theoretical model that weather (W) and the idiosyncratic disturbance (ε) are uniformly distributed on $[0, 1]$ and $[-d - en, d + en]$, respectively, where d and e are constants. With this formulation, the support of the distribution that is not explained by weather has the potential to grow or shrink with the level of nitrogen use. The question of whether this support should grow, shrink, or remain unchanged in response to changes in nitrogen use is an empirical one. We address this in a subsequent section.

For simplicity, we rule out the possibility that farmers might base nitrogen application rates on the expected impact of current-period nitrogen application on future soil productivity. Whether such an assumption is appropriate is arguable, but the literature on nitrogen carryover in the humid Midwest is largely inconclusive. Several studies (e.g., Brown, Rice, and Hoette; Leclerc) have found little or no nitrogen carryover in years of normal or high precipitation. Other studies (e.g., Bundy and Malone) have indicated substantial overwinter retention of nitrogen in years when precipitation was sufficiently limited that residual nitrogen did not leach beyond the root zone. Vanotti and Bundy argue that while carryover is likely in most years at commonly recommended application rates, the amount of nitrogen carryover is largely weather driven, and that "accurate predictions of N carryover based only on the amounts of N previously applied are not possible" (p. 885).

We assume, therefore, that a producer lacks the ability to accurately assess the extent of nitrogen carryover in any given year. We also note that, in the region of study for the empirical analysis of input use distortion (described in a later section), soils are sandy and irrigation is used. Both of these factors contribute to a reduction in nitrogen carryover and add support to our decision to ignore nitrogen carryover. Given this assumption, the dynamics of the farmer's problem are reduced to assessing the impact of current-period input decisions on subsequent bonus payments and probability of contract renewal.

A Fixed-Payment Scheme

We examine first the incentives associated with a fixed-payment contract.[4] With free access to contracts and a fixed price per unit of output produced, the expected per acre contribution from production is:

$$\begin{aligned} E[\pi(n, W, \varepsilon)] &= \int_0^1 \int_{-d-en}^{d+en} [p\min(\beta w, \alpha n) + p\varepsilon - cn] \frac{1}{2(d+en)}\, d\varepsilon\, dw \\ &= \int_0^{\alpha n/\beta} (p\beta w - cn)\, dw + \int_{\alpha n/\beta}^1 (p\alpha n - cn)\, dw \\ &= p\alpha n \left[1 - \frac{\alpha n}{2\beta}\right] - cn, \end{aligned}$$

where p denotes output price and c denotes nitrogen price. The expected profit-maximizing level of nitrogen under the fixed-price scheme is:

$$n^F = \max\left[\frac{\beta}{p\alpha^2}(p\alpha - c),\ 0\right].$$

The nitrogen level is strictly positive as long as the net marginal value product of nitrogen is positive in some weather state of nature. Henceforth we assume $p\alpha - c > 0$, because otherwise nitrogen application would be zero. The expected profit-maximizing level of nitrogen application under the fixed-payment contract is that which equates the marginal value product of nitrogen application to its marginal cost.

The Tournament Contract

We now compare the fixed-payment scheme to a tournament contract. Let "tournament average" refer to the average yield realized by producers participating in the tournment. We denote this by $\overline{Y}$. Now consider the case in which each producer receives a fixed payment R plus a bonus. The bonus is a linear function of the deviation of producer yield from the tournament average. Let the bonus be described by $\gamma(y(n, w) - \overline{Y})$, where γ is a constant ($ per bushel). Note that the bonus payment is conditional on realized weather. Thus, it is an ex post payment. The producer's yield is a function of nitrogen use on the farm, a weather realization, and the producer's idiosyncratic shock. The tournament average is a function of nitrogen use on all farms in the tournament and the same weather realization. As formulated, the bonus parameter γ fills a role similar to price in determining the optimal nitrogen application level. Expected profit under this scheme is:

---

[4] In the context of the model, the phrase "fixed payment" indicates a rate, like a price, that multiplies output. This is in contrast to the "fixed performance standard" type of compensation as described by Tsoulouhas and Vukina, where the payment is a constant plus a fixed rate that multiplies output.

$$E[\pi(n, W, \varepsilon)] = \int_0^1 \int_{-d-en}^{d+en} \left[R + \gamma\left(\min(\alpha n, \beta w) + \varepsilon - \overline{Y}\right) - cn\right] \frac{1}{2(d+en)}\, d\varepsilon\, dw$$
$$= R + \gamma \alpha n \left[1 - \frac{\alpha n}{2\beta}\right] - \gamma E[\overline{Y}] - cn.$$

If the individual producer believes that other producers will not alter rates of nitrogen application in response to the individual's choice, the optimal level of input use under the bonus scheme is:

$$n^B = \frac{\beta}{\gamma \alpha^2}(\gamma\alpha - c).$$

This expression is analogous to the free-market, fixed-payment solution, with the bonus rate γ playing the role of the market price p. Observe that the optimal nitrogen level under this contract will be greater than the optimal free-market rate when the bonus rate exceeds the market price (i.e., $\gamma > p$). It also will be less than the free-market rate when the bonus rate falls below the market price. In other words, the effect of this type of contract on nitrogen use is, in theory, ambiguous.

If producers have free access to the tournament contract and there is a noncontract market for seed corn, participants and nonparticipants will apply the same rate of nitrogen, provided the market price of the product and the bonus rate for yield are equal.[5] But if a farmer has an incentive to participate in the tournament and believes his contract is insecure, he may respond by increasing nitrogen application to avoid falling into the lower tail of the yield distribution, and thereby risking contract loss.

Behavior of Producers Under the Optimal Contract

To assess the behavioral implications of our model, consider the case where a producer begins with access to the contract and $\gamma = p$. Assume that the producer's best production alternative produces a return of S.[6] Assume further that the producer's access to the contract will be terminated if his output falls below the tournament mean by more than the constant amount $\varphi(d + en)$.[7] Finally, assume that the producer discounts future contributions to profits at the rate δ and seeks to maximize the discounted sum of returns. In this case, the producer's problem can be represented by a Markov chain with two states—a transient state (with the contract), and an absorbing state (without the contract).[8] In the style of Bellman, the value function is defined by the following recursive relationship:

---

[5] In this case, the marginal revenue associated with nitrogen is identical for participants and nonparticipants.

[6] We assume $S < E[\pi]$ because otherwise, producers would have an alternative that pays as well or better than seed corn production with certainty. Thus, no producer would want the seed corn contract.

[7] The perception of the critical level for contract termination will vary by individual. Some agents may perceive that contracts will be terminated if yields fall below the tournament average ($\varphi = 0$). Here, however, we examine a general threshold and sensitivity with respect to it.

[8] The underlying assumption here is that once access to the contract is lost, it is lost forever. If the population of potential agents is fixed, this implies that eventually no one has access to the contract. This outcome does not occur in reality because the pool of contract seekers is not fixed. Even so, this assumption is probably a bit extreme. But to eliminate the assumption, we would require an estimate of the transition probability between "no contract" and "contract" states. We have neither data nor anecdotal evidence to suggest a value for this probability.

$$(1)\quad V_T(j) = \begin{cases} \sum_{t=T}^{\infty} \delta^{t-T} S & \text{if } j = 0, \\ \max\limits_{n_T} \left\{ E\left[\pi_T(n_T, W, \varepsilon) + \delta((1 - q(n_T, W))V_{T+1}(1) + q(n_T, W)V_T(0))\right]\right\} & \text{if } j = 1, \end{cases}$$

where j denotes the contracting state, $\pi_T(n_T, W, \varepsilon)$ is a random variable denoting the current return from seed corn production, and $q(n_T, W)$ is a random variable denoting the probability that the contract will not be renewed. Note that the probability of contract loss is conditional on nitrogen use and weather. The value function expresses the current value in period T of the expected discounted future stream of profit flows, conditional on the current state, where $j = 0$ indicates that no contract is available and $j = 1$ indicates the contract is available.

In order to derive the individual producer's probability of losing the contract for a given weather realization ($q(n_T, w)$) and establish its dependence on n_T and w, it is necessary to distinguish mean yield, conditional on weather, for the individual producer and for all tournament participants. Payoffs under the contract, as well as the probability of losing the contract for the individual, depend on the tournament average yield.

This tournament average yield is reasoned as follows. First, we assume that because individuals behave independently, the tournament may be viewed as a game. Second, to facilitate the analysis of this game, we assume that all tournament participants have access to the same technology, resources, and information as the other participants. Third, in the interest of simplicity, we take a Nash perspective of the tournament—the individual producer chooses his nitrogen level assuming that the other producers do not change their nitrogen levels. Finally, because of symmetry of this game, we reason that the equilibrium occurs when all tournament participants have chosen the same level of nitrogen use. The chosen level is such that there is no incentive to change, given that the other participants do not change.

Thus, all participants use the same level of nitrogen, but the individual producer controls only his own. To keep this distinction clear, we denote the individual's level by n and the level applied by each of the other participants by N, noting that in equilibrium, these levels will be equal. Thus, the individual producer's mean yield conditional on weather is:

$$\bar{y}(n, w) = \int_{-d-en}^{d+en} [\min(\beta w, \alpha n) + \varepsilon] \frac{d\varepsilon}{2(d + en)} = \min(\beta w, \alpha n).$$

The tournament mean yield is expressed in analogous form as $\overline{Y}(N, w)$, with the regional nitrogen level N replacing the individual nitrogen level n. Note this means that $\overline{Y}(N, w) = \bar{y}(N, w)$.

The producer's probability of losing the contract, conditional on the state of weather and the level of nitrogen application, is found by integrating the density of the individual producer's yield disturbance (ε) over the range of ε that would result in loss of contract. This integral is:

$$(2)\quad \begin{aligned} q(n, w) &= \int_{\bar{y}(n,w)-d-en}^{\overline{Y}(N,w)-\varphi(d+eN)} \frac{1}{2(d + en)}\, d\varepsilon \\ &= \frac{1}{2} + \frac{1}{2(d + en)} \left[\overline{Y}(N, w) - \varphi(d + eN) - \bar{y}(n, w)\right]. \end{aligned}$$

We are now in a position to derive the conditions under which a producer tries to reduce his subjective probability of contract loss by increasing nitrogen use. If the tournament and individual nitrogen levels are equal, the expression for the probability of contract loss in equation (2) reduces to $(1 - \varphi)/2$. However, the farmer knows that the rate of nitrogen application affects his mean yield. Hence, the marginal effect of nitrogen application on the individual producer's probability is:

$$\frac{\partial q(n,w)}{\partial n} = \frac{1}{2(d+en)}\left[-\frac{\partial \bar{y}(n,w)}{\partial n} - \frac{e}{(d+en)}\left(\overline{Y}(N,w) - \varphi(d+eN) - \bar{y}(n,w)\right)\right]. \tag{3}$$

The right-hand side of equation (3) is negative as long as the term in square brackets is negative.[9]

Consider the optimization problem in the recursive relationship. The first-order condition for the optimal nitrogen level is:

$$E\left\{\frac{\partial \pi(n_T, W, \varepsilon)}{\partial n_T} + \delta\,\frac{\partial q(n_T, W)}{\partial n_T}\left[V_{T+1}(0) - V_{T+1}(1)\right]\right\} = 0. \tag{4}$$

Equation (4) reflects our assumption that the optimal expected value function in the subsequent period does not depend on the current-period nitrogen level (i.e., nitrogen carryover is ignored). Taking advantage of the fact that the optimal expected value function is stationary [i.e., that $V_T(j) = V_{T+1}(j)$], along with the fact that the optimal expected value function has known value in the state without the contract [i.e., $V_T(0) = S/(1 - \delta)$], we can define a relationship that implicitly identifies the optimal nitrogen level. This is:

$$E\left[\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n}\right] = \frac{\delta\left(E\left[\pi_T(n^*, W, \varepsilon)\right] - S\right)}{\left(1 - \delta(1 - E[q(n^*, W)])\right)}\, E\left[\frac{\partial q(n^*, W)}{\partial n}\right]. \tag{5}$$

Equation (5) simply states that the current expected marginal profit from nitrogen application should equal the expected difference in the discounted income streams with and without the contract, multiplied by the expected marginal change in the probability of contract loss due to the effects of nitrogen changes. We derive equation (5) formally in appendix A. For current purposes, the most important implication of equation (5) is that the effect of contract insecurity on input use (hereafter referred to as the input distortion) is in general ambiguous. Incentives for input distortion, if any, depend on the relative values (and in some cases signs) of parameters in the problem. Thus, to measure the direction and magnitude of any input distortion associated with the terms of an insecure tournament contract, we must examine a particular case. The next section provides a numerical analysis of our model, as applied to seed corn contract farming in a region of the Midwestern U.S.

---

[9] The first term in the square brackets is nonpositive because the marginal product of nitrogen is nonnegative in each state of nature. If the regional and individual nitrogen levels are equal, then the sign of the second term depends upon the sign of $-e\varphi(d + eN)$. The sign of this expression cannot be determined without knowledge of the sign of e, which must be evaluated empirically.

Empirical Evaluation of Input Use Distortion

Data

We evaluate our model empirically for St. Joseph County, in southern Michigan. We selected this region for the empirical study due to the prevalence of seed corn production and the high incidence of elevated nitrate levels in groundwater (Weight). St. Joseph County exhibited the highest levels of nitrate presence in the U.S., with 19.5% of well samples in a 1989 survey exceeding the maximum contaminant level set by the U.S. EPA (Martin). Complete details regarding production costs for seed corn in this region are available from the lead author upon request. In brief, seed corn is produced under irrigated conditions, and total variable operating costs excluding nitrogen are \$133 per acre. For a representative farm, we analyze a contract of the form:

$$(6) \qquad payment = 1.1(P_{cbot} - 0.12)\left[2\left(y_i - \bar{y}(N, w)\right) + 185\right],$$

where P_{cbot} denotes an agreed-upon price, y_i is the individual producer's realized yield, and 185 is the regional average yield for non-seed-corn production. As is common in contracts of this form, we peg the price to the Chicago Board of Trade futures price for commercial corn, using a delivery date near harvest for the current year. In the simulations reported here, we use a value of $P_{cbot} = 2.70$. As equation (6) states, we adjust the pegged price downward by \$0.12 to reflect the cost of transportation, and scale up the payment by 10% to reflect the bonus the principal uses to make the contract desirable. We assume yield depends upon both the realization of weather and random factors unrelated to weather. As noted above, we set base yield for non-seed corn (the reference crop for the fixed payment) to 185 bushels per acre. A payment bonus for above-average yield equals twice the difference between farm-level yields and average yield across other tournament participants. These figures are broadly representative of both the form and magnitude of existing contracts in the industry.

The biophysical relationship between nitrogen and seed corn yield is based on a widely used crop simulation model called DSSAT (Tsuji, Uehara, and Balas). For this study, the model was calibrated to track the growth of hybrid seed corn in St. Joseph County, Michigan (Ritchie et al.). Weather risk in the model is based on actual weather data for the years 1953–92. We generated yields for each of the 40 years using 21 discrete nitrogen application rates. These ranged from zero pounds per acre to 178 pounds per acre in 8.9-pound (10 kilograms per hectare) increments.[10] Table 1 presents the estimated parameter values for the DSSAT production relationship. (Further details regarding the yield computations are presented in appendix B.) Based on the fitted model of yield response, and a nitrogen rate of 86 pounds per acre, we obtain an average yield of 78.3 bushels per acre for seed corn.[11] Based on the payoff function and farm budgets, this yields a net return of \$504 per acre.[12] Net return to the next best alternative to seed corn production (*S* in the model) is \$150 per acre. This corresponds to the median cash rental rate for agricultural land in St. Joseph County during 1995 (King).

---

[10] The DSSAT model takes as input data daily maximum and minimum temperatures, precipitation, and solar radiation. While the model accounts for potential nitrogen carryover, we ignore any impact of nitrogen carryover in the analysis.

[11] Note that the average yield of 78.3 bushels per acre corresponds to seed corn production, which is intensive in its use of land. The base yield used to set the fixed payment, 185 bushels per acre, corresponds to #2 dent corn, the alternative crop for the producer.

[12] *Net return* in this context refers to gross revenues less variable costs.

Table 1. Estimated Parameter Values for DSSAT Production Relationship

Year (t)	Intercept (ψ)	Plateau (β)	Year (t)	Intercept (ψ)	Plateau (β)
1953	22.712	77.155	1973	21.176	76.313
1954	14.562	74.425	1974	29.786	86.557
1955	23.863	78.852	1975	29.765	90.014
1956	13.287	69.080	1976	13.550	62.140
1957	30.919	91.150	1977	30.790	86.200
1958	28.133	81.837	1978	23.883	75.344
1959	13.953	65.227	1979	21.644	78.278
1960	12.613	68.378	1980	11.888	71.861
1961	24.010	77.614	1981	27.896	86.583
1962	28.732	82.016	1982	17.473	76.517
1963	11.110	58.351	1983	19.616	73.303
1964	36.442	83.814	1984	24.687	86.162
1965	33.026	87.323	1985	24.913	76.173
1966	33.844	89.542	1986	26.737	87.157
1967	4.824	60.660	1987	28.767	83.700
1968	24.369	83.011	1988	30.665	95.781
1969	30.970	83.598	1989	17.826	81.467
1970	26.053	85.281	1990	17.529	72.805
1971	27.558	77.614	1991	29.437	88.535
1972	22.749	67.217	1992	11.386	54.511

Note: The common slope with respect to nitrogen for all years is $\alpha = 0.51242$.

Empirical Results

The optimum level of nitrogen use can be computed by evaluating expression (5). Based on the economic conditions assumed for this analysis, we computed an optimum level of applied nitrogen of 98 pounds per acre for the case in which the producer is certain he will retain his contract in the subsequent period.[13] We arrived at this result by conducting a grid search across nitrogen values ranging from 93 to 113 pounds per acre.[14]

As we stated at the outset, however, producers cannot be certain of contract renewal. Therefore we consider the case in which some of the producers lose access to the contract in the next period. We examine a range of scenarios. These are defined by the density in the lower tail of the yield distribution for tournament participants corresponding to contract suspension in the subsequent period. Optimal nitrogen application rates for

---

[13] This also is the optimum when the agent is certain that he will *lose* the contract next period. The reason is that the derivative of the probability of retaining the contract with respect to the nitrogen application rate is zero in both cases.

[14] Derivatives of expected yield with respect to nitrogen application rate were evaluated by difference approximation. The optimum is identified by the interval in which the sign of the expression (4) changes. If this sign does not change, then the optimum nitrogen application rate is the lowest rate at which the expected marginal product of nitrogen becomes zero, which occurs when the marginal product of nitrogen is zero in all 40 weather states (years). Clearly, this is the greatest rate that would ever be applied in the presence of a positive nitrogen cost. In the present case, this maximum application rate is 110 pounds per acre.

Table 2. Optimal Nitrogen Application Rates by Contract Cutoff Probability

Perceived Percentage of Lower Tail of Regional Yield Distribution That Loses the Contract (%)	Optimal Nitrogen Application Rate (lbs./acre)	Nitrate Loading Rate (lbs./acre)
0	98	34.7
1–36	110	40.5
37	108	39.3
38–50	106	38.2
51–60	104	37.2
61–67	102	36.5
68–76	100	35.6
77–80	98	34.7
81–100	97	34.4

these simulations are reported in table 2. Results show that if the cutoff percentage is small (even 1%), then the optimal producer strategy is to apply nitrogen at the maximum rate of 110 pounds per acre.[15] The reason is that the individual can effectively eliminate the probability of falling into the range of the yield distribution that triggers loss of access to the contract by applying a bit more nitrogen than others in the tournament. However, because all participants have identical incentives, and because we assume they do not collude, each increases his use of nitrogen to the point where, in equilibrium, he cannot affect the probability of contract loss in the subsequent period.

This phenomenon persists up to the point where the percentage of the lower tail corresponding to contract suspension is 36%. As the data in table 2 indicate, at this point nitrogen application has been distorted by over 12%. Above the 36% level, nitrogen application drops gradually to the contract certainty level of 98 pounds per acre at the 77% level. When 100% of the lower tail loses the contract, the nature of contract security is again certain. As a result, the incentive for excessive application disappears, and the optimal application rate is again 98 pounds per acre.

In addition to predicting yields, the DSSAT model predicts nitrate leaching below the crop root zone. These predictions are presented in figure 1. Importantly, the change in the rate of nitrate leaching below the crop root zone is even greater than the rate of increase in nitrogen application. The highest levels of leaching (and hence the greatest risk of groundwater contamination) occur when the cutoff percentage is in the 1–36% range. Here the nitrate loading rate is approximately 40.5 pounds/acre, about 17% higher than with certain contract loss or certain contract renewal. In other words, when producers believe that one-third or less of the contract holders will lose their contracts due to low yield, the increase in nitrate leaching is approximately 17%. This by-product of the tournament contract system is a direct source of an increased risk of groundwater contamination. In the next section, we examine modifications to the contract that would reduce or eliminate these distortions in input use.

---

[15] Note that beyond 110 pounds per acre, there is no yield response to nitrogen in any of the weather states.

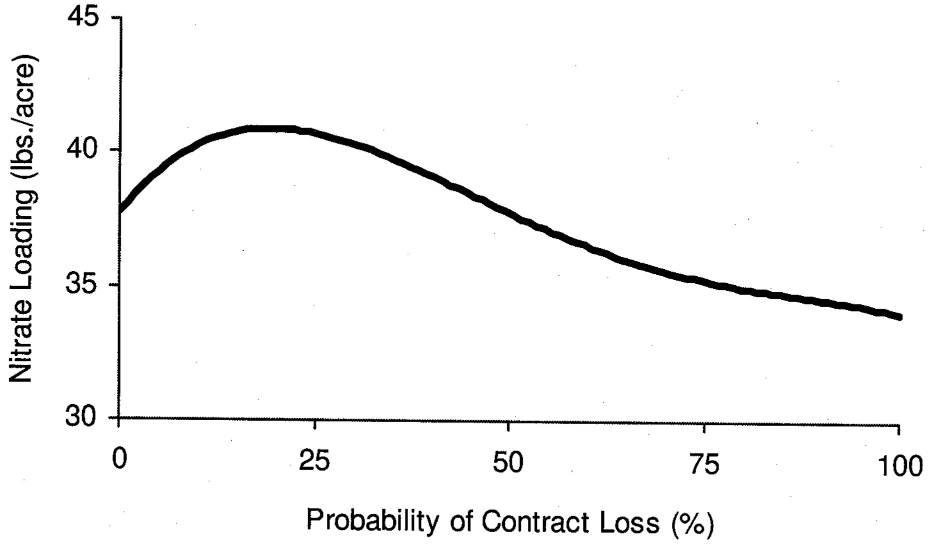

Figure 1. Predicted nitrate loading rates (pounds/acre)

Implications for Contract Design

Our theoretical model demonstrates that, under plausible stylized circumstances, the nature of insecure tournament contracts in the seed corn industry may lead to excessive nitrogen application (and conceivably distortion in the use of other inputs). One cause of this increase in input use is lack of security in the contract and the perception by agents that if yield falls too low relative to the tournament average, the principal may suspend the contract. Importantly, this result was derived under an assumption of risk-neutrality on the part of both principal and agent.[16] From a theoretical perspective, the potential for a contract-induced externality serves to undermine some of the desirable properties of relative performance compensation schemes in economies with imperfect information.

The principal may desire to mitigate the externality induced by a tournament contract in the interest of being perceived as a good corporate citizen. One way to achieve this goal would be to award the contracts on the basis of random lotteries. However, in the presence of real differences among agents with respect to yields, this approach probably would not be acceptable to the principal without modification of the payment system. This is because a greater amount of land under contract would be required to produce the same amount of seed. Of course, the fixed portion of the payment could be reduced to compensate the principal for the increased area under contract. But if the decrease in the fixed payment were too large, some producers might seek alternatives to the contract, thus raising the specter of adverse selection among participants.

However, there remains the important case where the principal may not perceive a need to mitigate the externality. In this case, the market fails, and any solution will

---

[16] It is beyond the scope of this investigation to confront the problem of contract incentives when agents and/or the principal are risk-averse. Such effort is warranted, however.

likely involve government intervention. This intervention could take the form of regulating and monitoring nitrogen levels of tournament participants or limiting the geographic region where the tournament contracts can be employed to those where the environmental risks of input distortions are relatively low. None of these solutions are particularly attractive from a practical perspective, and further research is needed to identify additional alternatives.

Concluding Remarks

As the trend toward increased industrialization of agriculture proceeds (e.g., Barry; Boehlje and Schrader), a number of observers have speculated that the role of contracts as a means of coordinating links between agricultural firms will expand and strengthen (e.g., Boehlje; Schrader). In the case of seed corn production, this analysis shows that the use of insecure tournament contracts has the potential to distort input use. We found insecure tournament contracts, in which the probability of contract renewal depends on yield performance, encourage excess use of nitrogen fertilizer, and as a result lead to increased nitrate leaching below the crop root zone. Levels of nitrogen application and leaching were found to exceed those in the case in which it was known a priori whether the contract would be renewed by up to 12% and 17%, respectively.

Given the significant environmental and public health risks associated with nitrate contamination of groundwater in the U.S. and elsewhere, this analysis calls into question the ability of insecure tournament contracts to achieve socially optimal outcomes. However, we have shown that the negative effects do not lie in the use of the tournament contract, per se, and that input distortions could be mitigated by either awarding contracts by lottery, or possibly by modifying the contract payment function.

[*Received January 2000; final revision received August 2000.*]

References

Agrawal, P. "Contractual Structure in Agriculture." *J. Econ. Behavior and Organization* 39,3(1999): 293–325.

Allen, D. W., and D. Lueck. "Searching for Ratchet Effects in Agricultural Contracts." *J. Agr. and Resour. Econ.* 24,2(1999):536–52.

Bard, J. F., and J. T. Moore. "A Branch and Bound Algorithm for the Bilevel Programming Problem." *SIAM J. on Scientific and Statis. Computing* 11(1990):281–92.

Barry, P. J. "Industrialization of U.S. Agriculture: Policy, Research, and Education Needs." *Agr. and Resour. Econ. Rev.* 24(1995):128–35.

Bellman, R. *Dynamic Programming.* Princeton NJ: Princeton University Press, 1957.

Boehlje, M. "Industrialization of Agriculture: What Are the Implications?" *Choices* (1st Quarter 1996): 30–33.

Boehlje, M., and L. F. Schrader. "The Industrialization of Agriculture: Questions of Coordination." Staff Pap. No. 94-13, Dept. of Agr. Econ., Purdue University, West Lafayette IN, 1994.

Brown, J. R., W. C. Rice, and G. W. Hoette. "Soil Nitrate Measurements for Prediction of N Response by Corn in a Udollic Ochraqualf." *Communications in Soil Sci. and Plant Anal.* 15(1984):239–51.

Bundy, L. G., and E. S. Malone. "Effect of Residual Profile Nitrate on Corn Response to Applied Nitrogen." *Soil Sci. Soc. of Amer. J.* 52(1988):1377–83.

Candler, W., and R. Townsley. "A Linear Two-Level Programming Problem." *Computers and Operations Res.* 9(1982):59–76.

Chu, M., S. M. Swinton, S. S. Batie, and C. Dobbins. "Designing Contracts to Reduce Agricultural Non-point Source Pollution." *Taiwanese Agr. Econ. Rev.* 2,2(1997):187–209.

Eswaran, M., and A. Kotwal. "A Theory of Contractual Structure in Agriculture." *Amer. Econ. Rev.* 75,3 (1985):352–67.

Gibbons, R., and K. J. Murphy. "Relative Performance Evaluation for Chief Executive Officers." *Industrial Labor Relations Rev.* 43(February 1990):30S–51S.

Holmstrom, B., and P. Milgrom. "Aggregation and Linearity in the Provision of Intertemporal Incentives." *Econometrica* 55,2(1987):303–28.

———. "Multitask Principal-Agent Analyses: Incentive Contracts, Asset Ownership, and Job Design." *J. Law, Econ., and Organization* 7(1992):24–52.

Jensen, M. C., and K. J. Murphy. "Performance Pay and Top-Management Incentives." *J. Polit. Econ.* 91(June 1990):349–65.

Just, R. E., and R. Pope. "Stochastic Specifications of Production Functions and Economic Implications." *J. Econometrics* 7(1979):67–86.

King, R. County Extension Director, St. Joseph's County. Coop. Ext. Ser., Michigan State University, East Lansing. Personal communication, 1996.

Knoeber, C. R. "A Real Game of Chicken: Contracts, Tournaments, and the Production of Broilers." *J. Law, Econ., and Organization* 5,2(1989):271–92.

Knoeber, C. R., and W. N. Thurman. "Testing the Theory of Tournaments: An Empirical Analysis of Broiler Production." *J. Labor Econ.* 12,2(1994):155–79.

———. "'Don't Count Your Chickens ...': Risk and Risk Shifting in the Broiler Industry." *Amer. J. Agr. Econ.* 77,3(1995):486–96.

Leclerc, S. "Effects of Residual Profile Nitrate Accumulation and Retention on Corn Response to Applied N." Unpub. M.S. thesis, Dept. of Agron., University of Wisconsin-Madison, 1987.

Martin, E. C. "Management Strategies to Minimize Nitrate Leaching in Seed Corn Production." Unpub. Ph.D. diss., Dept. of Agr. Engineering, Michigan State University, East Lansing, 1992.

Nalebuff, B. J., and J. E. Stiglitz. "Prizes and Incentives: Toward a General Theory of Compensation and Competition." *Bell J. Econ.* 14(Spring 1983):21–43.

Ribaudo, M. "Agriculture's Impact on Water Quality." In *Cropland, Water, and Conservation: Situation and Outlook.* USDA/Economic Research Service, Washington DC, 1987.

Ritchie, J. T., T. Loudon, E. C. Martin, K. Klambach, J. Lightner, S. Lupkes, and R. Peterson. "Irrigation Water and Nitrogen Management Project for Hybrid Seed Corn Production at Constantine, Michigan." Research report prepared for Pioneer Hi-Bred International, Inc., by Dept. of Agronomy, Michigan State University, East Lansing, 1993.

Salanie, B. *The Economics of Contracts.* Cambridge MA: The MIT Press, 1997.

Schrader, L. F. "Responses to Forces Shaping Agricultural Marketing: Contracting." *Amer. J. Agr. Econ.* 68,5(1986):1161–66.

Shaw, D. J., W. H. Howard, and L. J. Martin. "Costs, Prices, and Contracts in the U.S. and Canadian Seed Corn Industries." Pub. No. AEB 89/8, Dept. of Agr. Econ. and Bus., University of Guelph, Guelph, Ontario, August 1989.

Swinton, S. M., M. Chu, and S. S. Batie. "Agricultural Production Contracts to Reduce Water Pollution." In *Flexible Incentives of Adoption of Environmental Technologies in Agriculture*, eds., F. Casey, A. Schmitz, S. M. Swinton, and D. Zilberman, pp. 273–83. Boston: Kluwer Academic Publishers, 1997.

Tsoulouhas, T., and T. Vukina. "Integrator Contracts with Many Agents and Bankruptcy." *Amer. J. Agr. Econ.* 81,1(1999):61–74.

Tsuji, G. Y., G. Uehara, and S. Balas. *DSSAT Version 3: A Decision Support System for Agrotechnology Transfer*, Vols. 1–3. Dept. of Agronomy and Soil Sci., University of Hawaii, Honolulu, 1994.

U.S. Environmental Protection Agency. "Environmental Indicators of Water Quality in the United States." Pub. No. 841-R-96-002, EPA/Office of Water, Washington DC, June 1996.

Vanotti, M. B., and L. G. Bundy. "Frequency of Nitrogen Fertilizer Carryover in the Humid Midwest." *Agronomy J.* 86(1994):881–86.

Weight, D. "Nitrates, Geohydrology, and Land Use in Michigan." Work. pap., Dept. of Agr. Econ., Michigan State University, East Lansing, 1996.

Appendix A:
Derivation of Optimality Condition for Nitrogen Level

Here we derive the optimality condition for nitrogen levels based on the theoretical choice model. From the first half of the recursive relationship in text equation (1), we know that

$$V_T(0) = \sum_{t=0}^{\infty} \delta^t S = \frac{S}{1-\delta}. \tag{A1}$$

From the second half of the recursive relationship, we know that

$$V_T(1) = \max_n E\left\{\pi_T(n, W, \varepsilon) + \delta[1 - q(n, W)]V_{T+1}(1) + \delta q(n, W)V_{T+1}(0)\right\}. \tag{A2}$$

The first-order condition with respect to n is:

$$\begin{aligned} 0 &= E\left\{\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n} + \delta \frac{\partial q(n^*, W)}{\partial n}\left[V_{T+1}(0) - V_{T+1}(1)\right]\right\} \\ &= E\left[\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n}\right] + \delta E\left[\frac{\partial q(n^*, W)}{\partial n}\right]\left[V_{T+1}(0) - V_{T+1}(1)\right], \end{aligned} \tag{A3}$$

where n^* denotes the optimal level of nitrogen. Assuming the expectation of the marginal effect of nitrogen on the probability of contract loss is not zero, this expression may be rearranged to express the value function in the state with the contract as a function of the marginal effects of nitrogen on current profits, the probability of contract loss, and the value of returns to the alternative to seed corn production as

$$\begin{aligned} V_{T+1}(1) &= E\left[\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n}\right]\left\{\delta E\left[\frac{\partial q(n^*, W)}{\partial n}\right]\right\}^{-1} + V_{T+1}(0) \\ &= E\left[\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n}\right]\left\{\delta E\left[\frac{\partial q(n^*, W)}{\partial n}\right]\right\}^{-1} + \frac{S}{1-\delta}. \end{aligned} \tag{A4}$$

Note that if the marginal effect of nitrogen on the probability of contract loss is zero, the first-order condition for the nitrogen level is satisfied at the more usual point where the marginal profit of nitrogen is equal to zero. The value function is stationary [$V_T(0) = V(0)$ and $V_T(1) = V(1)$], so we can rewrite the recursion for the state with the contract as

$$V(1) = E\left\{\pi_T(n^*, W, \varepsilon) + \delta[1 - q(n^*, W)]V(1) + \delta q(n^*, W)V(0)\right\}. \tag{A5}$$

Eliminating the expected optimal value function by substituting the expression derived from the first-order condition for nitrogen for the state with the contract, and for the previously noted expression of the expected optimal value function for the state without the contract, results in the following expression:

$$\begin{aligned} &\frac{S}{1-\delta} + E\left[\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n}\right]E\left[\frac{\partial q(n^*, W)}{\partial n}\right]^{-1}\delta^{-1} \\ &= E\left\{\pi_T(n^*, W, \varepsilon) + \delta\left[1 - q(n^*, W)\right]\left(\frac{S}{1-\delta} + E\left[\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n}\right]E\left[\frac{\partial q(n^*, W)}{\partial n}\right]^{-1}\delta^{-1}\right)\right. \\ &\qquad \left. + \delta q(n^*, W)\frac{S}{1-\delta}\right\}, \end{aligned} \tag{A6}$$

which can be rearranged to obtain:

$$\text{(A7)}\qquad \left(S - E\left[\pi_T(n^*, W, \varepsilon)\right]\right)E\left[\frac{\partial q(n^*, W)}{\partial n}\right]\delta + \left(1 - \delta(1 - E[q(n^*, W)])\right)E\left[\frac{\partial \pi_T(n^*, W, \varepsilon)}{\partial n}\right] = 0.$$

This expression defines the optimal level of n^*. The expressions for expected current-period profits and expected marginal current-period profits are derived in the text. The expected probability of contract loss and the marginal effect of nitrogen on the probability of contract loss are:

$$\begin{aligned}\text{(A8)}\qquad E[q(n^*, W)] &= \int_0^1 \left(\frac{1}{2} + \frac{\overline{Y}(N, w) - \varphi(d + en) - \bar{y}(n^*, w)}{2(d + en^*)}\right)dw \\ &= \frac{1 - \varphi}{2} + \frac{1}{2(d + en^*)}\left[\int_0^{\alpha N/\beta} \alpha N\, dw + \int_{\alpha N/\beta}^1 \beta w\, dw - \int_0^{\alpha n^*/\beta} \alpha n^*\, dw - \int_{\alpha n^*/\beta}^1 \beta w\, dw\right] \\ &= \frac{1 - \varphi}{2} + \frac{1}{2(d + en^*)}\left[\frac{(\alpha N)^2}{2\beta} - \frac{(\alpha n^*)^2}{2\beta}\right]\end{aligned}$$

and

$$\text{(A9)}\qquad E\left[\frac{\partial q(n^*, W)}{\partial n}\right] = -\frac{e}{2(d + en^*)^2}\left[\frac{(\alpha N)^2}{2\beta} - \frac{(\alpha n^*)^2}{2\beta}\right] - \frac{\alpha^2 n^*}{2(d + en^*)\beta}.$$

We assume that in equilibrium $N = n^*$. Taking account of this fact and combining expressions, we obtain a restatement of the condition satisfied by the optimal nitrogen level:

$$\begin{aligned}\text{(A10)}\qquad S + \left(1 - \delta + \frac{1 - \varphi}{2}\right)\gamma\alpha\left[1 - \frac{\alpha n^*}{\beta} - c\right]\left[\frac{-\alpha^2 2(d + en^*)\beta + e\beta\alpha^2 n^*}{(d + en^*)^2\beta}\right]^{-1}\delta^{-1} \\ = \left[R + \gamma\alpha n^*\left(1 - \frac{\alpha n^*}{2\beta}\right) - \gamma\left(\alpha n^* - \frac{(\alpha n^*)^2}{2\beta}\right) - cn^*\right].\end{aligned}$$

This simplifies to a cubic equation in n^*. While a closed-form expression exists for the single real root of this expression, it is cumbersome and not amenable to straightforward interpretation. Thus, we proceed on a numerical basis.

Appendix B:
Description of Estimation Procedure for Yield Distributions

This appendix describes the estimation procedure employed to generate the yield distributions used in the simulations reported in the "Empirical Evaluation of Input Use Distortion" section of the text. Conceptually, the model of yield which is roughly consistent with the DSSAT biophysical model is:

$$\text{(A11)}\qquad \min\left[\alpha(n + n_0(w)),\ \beta(w)\right],$$

where $n_0(w)$ denotes the amount of nitrogen available from natural sources. To obtain yield estimates for values of nitrogen which are intermediate to the 8.9-pound increments, we solved the following least squares problem:

$$\text{(A12)}\qquad \min_{\alpha_t, \gamma_t \geq 0} \sum_{t=1}^{40} \sum_{i=1}^{21} \left(y_{ti} - \min\left[\psi_t + \alpha n_i,\ \beta_t\right]\right)^2.$$

Thus, there are year-specific intercepts (ψ_t) and plateaus (β_t), and there is a common slope (α) across years. The parameters β_t were fixed at the previously mentioned levels observed in the data. Due to the source of the data, this model-fitting exercise should not be viewed as a proper statistical regression. However, it may be useful to note that the estimated model fits the DSSAT data quite well with an explained variation in the model data (R^2) of 99.99%. Parameter values for the estimation are listed in text table 1.

As part of the process of calibration of the DSSAT model used to simulate seed corn yields in southern Michigan, Ritchie et al. employed experimental plot data and published the actual yields versus the yields predicted by DSSAT. This information served as the basis for developing a distribution of the variability in yields that is not explained by weather. These data include four alternative nitrogen application programs and replications across three years, and suggest that the variance of the distribution of unexplained variability is not constant with respect to the nitrogen application rates. These variances were transformed into supports for a uniform distribution of yield variation unexplained by weather (and the DSSAT model), and a linear regression of the support of the distribution of unexplained variability on nitrogen application rate was performed to obtain the following relationship: $d + en = 24.838 - 0.055n$, where n is applied nitrogen in pounds, and yield is measured in bushels per acre. This relationship implies that the *unexplained variation* declines as nitrogen application increases.

This does not necessarily imply that nitrogen is a variance-decreasing input (in the sense of Just and Pope). The reason is that, over a range of nitrogen applications, the variation which is explained by weather is *increasing* in nitrogen application. The total variation in output is a combination of variation from these two sources. For simplicity, the distribution of the unexplained variation is assumed to be uniform with mean equal to the sample mean of the residuals from the calibration and variance depending upon the level of nitrogen application as described. Ideally we would elicit the distribution of the yield variation not explained by weather from the data rather than imposing a uniform distribution. However, in the present context, insufficient experimental plot data were available to discriminate among alternative distributional assumptions.