Journal of Agricultural and Resource Economics 27(1):61–76

Variable-Rate Nitrogen Application Under Uncertainty: Implications for Profitability and Nitrogen Use

Murat Isik and Madhu Khanna

A micro-level model of farmer decision making is developed to examine the extent to which uncertainty about potential yields influences the value of site-specific technologies. The economic and environmental benefits of these technologies arise from two sources: information gathering and variable-rate nitrogen application. Application of the model to fields in Illinois shows the value of variable-rate nitrogen application is higher on fields with low average potential yields, high spatial variability, positively skewed potential yield distributions, responsive yield to nitrogen, and low uncertainty. Variable-rate application decreases nitrogen use by reducing the extent of overapplication. However, in the presence of uncertainty about potential yields, the incentives to overapply nitrogen irrespective of the method of application, uniform or variable rate, can reduce the economic and environmental benefits of site-specific technologies.

Key words: nitrogen overapplication, site specific, spatial variability, technology adoption, uncertainty

Introduction

Growing recognition of the spatial variability in crop yields within a field caused by variability in soil conditions, or in the responsiveness of yields to applied inputs, has drawn attention to site-specific technologies designed to vary input applications to meet location-specific needs (National Research Council). By contrast, conventional farm management practices apply inputs at a single rate uniformly across an entire field, based on the average conditions in the field. When the responsiveness of yields to applied inputs varies across a field, this average strategy can result in overapplication of inputs on some parts of the field and underapplication on other parts of the field. Thus the average strategy can lead to lower yields in undersupplied areas of the field and wasted inputs, high input costs, and high levels of residual nutrients on cropland without corresponding yield gains in the oversupplied portions of the field. Overapplication of fertilizer, particularly of nitrogen, is of significant concern in the Midwest Corn Belt, a region identified by the U.S. Department of Agriculture (USDA) as one with high residual nitrogen on cropland available for runoff to surface water or leaching to groundwater (Ribaudo, Horan, and Smith).

Murat Isik is an associate scientist with the Center for Agricultural and Rural Development, Iowa State University. Madhu Khanna is an associate professor, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign. The authors would like to thank the two anonymous reviewers for their helpful comments. This research has been supported by the Water Quality Strategic Research Initiative of the Illinois Council on Food and Agricultural Research.

Review coordinated by Gary D. Thompson.

Site-specific technologies, such as yield monitors and soil sampling, enable the detection and measurement of spatial variability in soil productivity in the field, and through use of variable-rate nitrogen technology (VRNT), nitrogen can be applied at a varying rate within the field to match the variability in soil productivity. These technologies have the potential to increase yields in the otherwise undersupplied portions of the field while reducing overapplication of nitrogen in other parts of the field and reducing input costs. Adoption of VRNT could increase farm profitability if the revenue gains and input cost savings are larger than the fixed costs of adopting site-specific technologies. VRNT can also reduce residual nitrate in the soil.

The economic and environmental benefits from site-specific technologies arise from two sources: information gathering and variable-rate nitrogen application. Farmers have a choice of gathering detailed information about soil conditions through soil sampling and mapping and using this information to identify a single rate of nitrogen application that maximizes profits. We refer to this as the information strategy. Alternatively, farmers could adopt a precision strategy in which information gathering is followed by adoption of VRNT, and the application rate is varied within the field.

In many areas, such as Illinois, soil nitrate tests have proven unsuccessful in accurately measuring and predicting the available nitrogen in the soil. Recommendations for nitrogen application are instead based on the soil type in the field that determines its maximum potential yield. However, the estimate of the potential yield for each soil type in the field is typically imprecise because it depends on uncertain weather conditions. Annual variations in rainfall and temperature can lead to variations in yield of 20% above or below the potential for the same field (Bullock and Bullock; University of Illinois). Additionally, the impact of weather varies across different parts of the field.[1] Babcock found risk-neutral farmers facing uncertainty about growing conditions tend to choose a higher uniform rate of nitrogen application (just in case plants need additional nitrogen in a good year) than farmers facing certain conditions.

In this study, we develop a micro-level model to analyze the implications of farmers' tendency to overfertilize, in the presence of uncertainty about potential yields due to weather,[2] for the nitrogen applied in the field and the profitability of the average, information, and precision strategies, as defined above. The impact of this uncertainty is then examined for potential environmental benefits through a reduction in overapplication of nitrogen, and for incentives to adopt the information and precision strategies. Additionally, the effects of the characteristics of the distribution of the potential yield in the field and the responsiveness of yield to nitrogen on the profitability of alternative strategies are analyzed. While the existence of spatial variability in potential yields within the field is fundamental to obtaining any gains from adopting site-specific technologies, the magnitude of these gains may also depend on the symmetry or skewness of the potential yield distribution which, in turn, influences the portion of the field that is overfertilized and the portion that is underfertilized under the information

[1] For example, in a wet year the productivity of the low lying areas of a field is affected more adversely than of the sloping areas of the field, while in a dry year the productivity of the low lying areas is likely to be affected less adversely than of the sloping areas because more moisture is captured and retained in lower areas.

[2] In addition to weather uncertainty, there are other types of uncertainty, such as measurement uncertainty, associated with the use of site-specific technologies. Yield monitor measurements are often subject to technical difficulties and measurement errors, which leads to errors in yield mapping (Searcy et al.). For ease of analysis, we focus only on uncertainty due to the weather.

and average strategies. This framework is applied empirically to a sample of fields in the Otter Lake Watershed in Illinois.

The literature analyzing the profitability of VRNT differs considerably in its findings, both on whether the technology is profitable and the extent of profits the technology could yield. Of the 18 studies evaluating the profitability of VRNT for corn, recently reviewed by Dayton and Lowenberg-DeBoer, 13 found VRNT profitable, one concluded it was not profitable, and four obtained mixed results. Despite the optimistic predictions of profitability reported by these studies, the currently observed adoption rates for VRNT do not reflect broad acceptance. At the national level, only 4% of farmers had adopted variable-rate technologies (for all fertilizers) by 1996, and 6% had adopted yield monitors (Daberkow and McBride). The corresponding figures for the Midwest were 12% and 10% in 1996 (Khanna, Epouhe, and Hornbaker). This last study also found adoption rates for information-gathering technologies were much larger than for variable-rate technologies.

Several simulation-based analyses have examined the profitability of VRNT relative to the information strategy. Results of these studies indicate the profitability and incentives for adoption can vary with the size of the field (Thrikawala et al.), the extent of spatial variability in the soil conditions in the field (Babcock and Pautsch; Thrikawala et al.), the average soil conditions in the field, uncertainty about output prices (Khanna, Isik, and Winter-Nelson), and the extent of rainfall (English, Mahajanashetti, and Roberts; Fixen and Reetz). Only a few studies (e.g., Schnitkey, Hopkins, and Tweeten; Isik, Khanna, and Winter-Nelson) separately evaluate the gains from the information strategy and the precision strategy relative to the average strategy.

All of the above investigations implicitly assume there is no uncertainty about the weather, and thus about the growing conditions in each part of the field. The contribution of this study is that it analyzes the impact of uncertainty about potential yields, used in many regions to determine nitrogen application rates, for the benefits of adopting site-specific technologies. By examining this impact for a broad-based sample of fields, we provide quantitative estimates of the extent to which uncertainty can mitigate these benefits and explain the low observed rates of adoption of VRNT. The benefits from adopting VRNT are also disaggregated into those arising from the information strategy and those from precision application. Additionally, we assess the extent to which skewness of the potential yield distribution and the parameters of the yield response function influence the profitability of site-specific technologies.

Pautsch, Babcock, and Breidt examine the impact of uncertainty about estimates of soil nitrate levels on the gains from switching to VRNT and the optimal amount of soil test information to be acquired for a field. Unlike uncertainty about soil nitrate levels that can be reduced through private efforts such as more intensive soil sampling, a reduction in potential yield uncertainty requires public provision of not only more complete weather information but also improved agronomic information regarding the impact of weather on crop yields.

This study provides an estimate of the extent to which provision of precise potential yield information would be valuable to farmers using alternative application strategies. Further, we demonstrate that this value should include not only the gains in profitability for farmers, but also the gain in social benefits due to a reduction in the over-application of nitrogen.

The Model

Consider a risk-neutral farmer operating a field of A acres that has $\{i = 1, \ldots, M\}$ sections, with each section representing a different soil quality or type associated with a maximum potential yield per acre of Z_i. These sections are numbered in increasing order by their potential yield levels, such that Z_1 represents the lowest potential yield, and Z_M represents the highest potential yield. The farmer may be uncertain, however, about the true potential yield Z_i in the ith section of the field, and instead consider the potential yield to be $Z_i \exp(\varepsilon_i)$. This disturbance ε_i is assumed to be normally distributed with mean zero and variance σ_ε^2. The proportion of the field having the ith level of potential yield is represented by A_i, such that $\Sigma_{i=1}^{M} A_i = 1$.

We assume the corn yield of the ith soil type is represented by a linear-plateau response function. The linear-plateau function is based on von Liebig's hypothesis that crop yield is a proportional function of the scarcest nutrient available to the plant, and increasing the availability of nonlimiting nutrients does not affect crop yield (Paris and Knapp). Many studies using multiple-year experimental data (Paris; Ackello-Ogutu, Paris, and Williams; Cerrato and Blackmer; Bullock and Bullock) have found evidence to support either a linear or a nonlinear crop response function with a plateau instead of polynomial functions such as quadratic or square-root. There is, however, no consensus on the appropriate functional form in the literature.

We use the linear-plateau response function as a convenient first approximation to represent crop responses, as employed in several earlier studies (Pautsch, Babcock, and Breidt; Babcock and Pautsch; Feinerman, Bresler, and Dagan; Lanzer and Paris; Grimm, Paris, and Williams). Agronomic recommendations for nitrogen application in several states are also based on the premise of nonsubstitution among nutrients and the existence of maximum potential yield (University of Illinois). The linear-plateau function for each section of the field, assuming nitrogen is the only input limiting the attainment of the potential yield,[3] is given by:

(1) $$Y_i = Z_i - \gamma_i D_i (T_i - N_i).$$

This function implies that a per acre nitrogen application (N_i) in excess of the physically optimal level (T_i) has no effect on yield, but applications less than T_i reduce yield by a constant per unit level, γ_i. The dummy variable D_i is equal to one if $N_i < T_i$, and zero otherwise. The slope of this response function is $\gamma_i = (Z_i - a_i)/T_i$, where a_i is its intercept, representing the amount of yield obtainable without applying any nitrogen in the ith section.

The farmer has a discrete choice among three technologies: the conventional average strategy, the information strategy, and VRNT, denoted by superscripts C, I, and V, respectively. The price of corn and nitrogen, P and w, respectively, is assumed to be known with certainty. The per acre fixed cost of moving from the average strategy to the information strategy is denoted by k^I, while the per acre cost of moving from the information strategy to VRNT is k^V. Thus, the total per acre cost of adoption of VRNT relative to the average strategy is represented by $k^I + k^V$.

[3] Because the focus of our analysis is on comparing the benefits of alternative application rates for nitrogen use, while assuming all other things remain the same across the three strategies, this assumption, although restrictive, is not likely to change the direction of the results obtained, particularly given the assumption of nonsubstitutability among inputs.

Decision Making Under Uncertainty

The average strategy assumes the farmer gathers information about potential yields in a few parts of the field and determines the average potential yield ($\bar{Z}$) for the whole field. The farmer assumes this average potential yield is then representative of the entire field and chooses a uniform nitrogen application rate. Under uncertainty about potential yields, a risk-neutral farmer[4] will choose an expected nitrogen rate per acre[5] [$E(N^C) = \bar{T}\exp(\sigma_\varepsilon^2/2)$], whereas under certainty this rate is specified as $N^C = \bar{T}$. Uncertainty increases the nitrogen application, and thus yield increases on the previously undersupplied portions of the field, raising revenues and costs, and leaving the net impact on quasi-rents (the difference between revenue and nitrogen costs) to be determined empirically.

The information strategy, on the other hand, assumes the farmer undertakes intensive soil mapping to gather detailed information about the proportions (A_i) of the field having the ith level of potential yield, and then chooses a single nitrogen rate per acre by maximizing the weighted average quasi-rents:

$$E(\pi^I) = \sum_{i=1}^{M} A_i\Big[P\big(Z_i\exp(\sigma_\varepsilon^2/2) - \gamma_i D_i(T_i - N^I)\big) - wN^I\Big]. \tag{2}$$

The expected quasi-rents realized under the average and the information strategies are given by:

$$E(\pi^j) = \sum_{i=1}^{M_1^j} A_i P Z_i + \sum_{i>M_1^j}^{M} A_i\big[-P\gamma_i(T_i - N^j)\big] - wN^j, \quad (j = C \text{ or } I), \tag{3}$$

where M_1^j denotes the number of sections (soil types) in the field that receive more nitrogen than physically optimal, under the jth strategy. The per acre difference in quasi-rents between the information and average strategy, or expected value of information strategy, $E(\Delta\pi^I)$, is:

$$\begin{aligned} E(\Delta\pi^I) &= w(N^C - N^I) \\ &\quad + P\left[\sum_{i=1}^{M_1^I} A_i Z_i - \sum_{i=1}^{M_1^C} A_i Z_i + \sum_{i>M_1^C}^{M} A_i\gamma_i(T_i - N^C) - \sum_{i>M_1^I}^{M} A_i\gamma_i(T_i - N^I)\right]. \end{aligned} \tag{4}$$

If $E(N^I) > E(N^C)$, then $M_1^I > M_1^C$. In that case, not only will the information strategy increase the costs of nitrogen use [the first term in (4)] relative to the average strategy, but it will also lead to yield gains because the undersupplied portions of the field receive more nitrogen.

Let $\alpha = M_1^C/M$ denote the proportion of the field receiving more nitrogen than T_i under the average strategy. This proportion α is related to the skewness of the distribution of potential yield within the field. If $\alpha = 0.5$, so that half of the field is overfertilized and half is underfertilized, the yield distribution is symmetric and the coefficient of skewness

---

[4] Several studies have shown uncertainty affects decision making even by a risk-neutral farmer when it affects profits nonlinearly (see Babcock and Shogren). Just and Pope illustrate how different specifications of production uncertainty affect a risk-neutral farmer's input use decision. Babcock provides an explanation for overfertilization by risk-neutral farmers under uncertainty, while studies on investment under uncertainty emphasize the impact of various sources of uncertainty on optimal timing of irreversible investment in new technologies by risk-neutral decision makers (Dixit and Pindyck).

[5] When ε is normally distributed with mean zero and variance σ_ε^2, $E(\exp(\varepsilon)) = \exp(\sigma_\varepsilon^2/2)$.

is zero. If $\alpha > 0.5$, the yield distribution is positively skewed, and it is negatively skewed if $\alpha < 0.5$. As α increases, $E(N^I)$ and $E(N^C)$ and overapplication increase. Application rate $E(N^I)$ is likely to increase more than $E(N^C)$ as long as the expected value of the additional yield is greater than the additional cost of nitrogen use. However, as skewness increases, yield gains due to an increase in nitrogen are likely to be smaller, and thus revenue is expected to increase less than cost, implying a reduction in the gain in quasi-rent from the information strategy.

An increase in uncertainty is likely to increase the application rate to achieve the higher yields which might be possible in a good weather year. While the increase in application enhances crop yields on those parts of the field previously receiving underapplication of nitrogen with the rate chosen under certainty, it also increases costs. Because the farmer is maximizing profits under certainty about true potential yield levels, any increase in N^I relative to that under certainty must lower quasi-rents more than under the average strategy, thereby decreasing the value of $E(\Delta\pi^I)$.

With adoption of VRNT, the profit-maximizing nitrogen level in each of the $\{i = 1, \ldots, M\}$ sections of the field would be T_i (as long as $\gamma_i > w/P$), if the potential yield in each part of the field were known with certainty. Under uncertainty, the expected nitrogen application on the ith soil type is $T_i \exp(\sigma_\varepsilon^2/2)$, and the expected nitrogen application averaged over the M sections is:

$$E(N^V) = \sum_{i=1}^{M} A_i T_i \exp(\sigma_\varepsilon^2/2).$$

Total nitrogen application with VRNT is equal to total nitrogen application with the average strategy because

$$E(N^V) = \sum_{i=1}^{M} A_i T_i \exp(\sigma_\varepsilon^2/2) = \bar{T} \exp(\sigma_\varepsilon^2/2) = E(N^C).$$

However, VRNT reduces nitrogen use on some portions and increases it on other portions of the field compared to the average strategy. The expected per acre quasi-rent with adoption of VRNT is written as:

$$E(\pi^V) = \sum_{i=1}^{M} A_i\left(PZ_i - wT_i \exp(\sigma_\varepsilon^2/2)\right), \tag{5}$$

which indicates that quasi-rents from VRNT decrease as uncertainty increases because increased nitrogen application increases costs [given by the second term in (5)] relative to those under certainty, while yields remain at their maximum level.

The expected value of VRNT relative to the information strategy is given by:

$$E(\Delta\pi^V) = w\left(N^I - \sum_{i=1}^{M} A_i T_i \exp(\sigma_\varepsilon^2/2)\right) + \sum_{i>M_1^I}^{M} A_i P\gamma_i (T_i - N^I). \tag{6}$$

VRNT may reduce or increase nitrogen costs because $E(N^I)$ may be greater or less than $E(N^V)$, depending on the distribution of potential yields. The first term in (6) represents the change, with the adoption of VRNT, in nitrogen costs due to a change in nitrogen use; the second term denotes the revenue gains due to an increase in crop yields on sections receiving underapplication of nitrogen under the information strategy.

Overall, an increase in σ_ε^2 reduces $E(\Delta\pi^V)$. An increase in the responsiveness of the production function, represented by an increase in γ_i, increases $E(\Delta\pi^V)$. As α increases, M_1^I increases and the magnitude of the second term in (6) falls. However, to the extent an increase in α also increases $E(N^I)$, the first term in (6) becomes larger; thus, the impact of skewness on $E(\Delta\pi^V)$ is ambiguous.

The difference in quasi-rents/acre of moving from the average strategy to VRNT is specified as:

$$(7) \qquad E(\Delta\pi^{V+I}) = E(\Delta\pi^V) + E(\Delta\pi^I) = \sum_{i>M_1}^{M} A_i P\gamma_i\left(T_i - \bar{T}\exp(\sigma_\varepsilon^2/2)\right),$$

which is obtained by summing (4) and (5). The right-hand side of (7) represents the value of the yield gain achieved on the underfertilized portions of the field due to more precise application of nitrogen. Since $E(N^C) = E(N^V)$, the price of nitrogen does not affect the difference in quasi-rents, and the value of VRNT comes entirely from the revenue gains due to an increase in crop yields. This value goes up with an increase in output price or an increase in the responsiveness of the production function.

An increase in the average potential yield leads to an increase in the application rate, which reduces yield gains and therefore the value of $E(\Delta\pi^{V+I})$. The larger the underfertilized portions of the field, the larger the potential for yield gains with VRNT—but the larger the increase in cost of nitrogen. The yield gain, and therefore the value of $E(\Delta\pi^{V+I})$, is likely to be higher for negatively skewed distributions which tend to have a larger portion of the field underfertilized with the average strategy. Increased spatial variability enlarges the divergence between T_i and $\bar{T}$, and increases $E(\Delta\pi^{V+I})$. Finally, an increase in σ_ε^2 leads to a decrease in the yield gain, and thus a decrease in $E(\Delta\pi^{V+I})$.

Adoption of information gathering followed by VRNT occurs if it leads to an increase in profits relative to the average strategy. This is the case if the difference between the gain in quasi-rents in (7) and the cost of adoption of VRNT and the information strategy is positive—i.e., if $E(\Delta\pi^{V+I}) \geq k^I + k^V$, and $E(\Delta\pi^V) \geq k^V$. Adoption of the information strategy occurs alone if $E(\Delta\pi^I) \geq k^I$ and $E(\Delta\pi^V) < k^V$. If $E(\Delta\pi^I) < k^I$ and $E(\Delta\pi^{V+I}) < k^I + k^V$, then it would be optimal to continue to use the average strategy.

Empirical Application

The empirical analysis evaluates the implications of variable-rate applications of nitrogen to continuous corn production on fields in the Otter Lake Watershed in Macoupin County, Illinois. All farmers in the watershed, which includes about 7,370 acres of cropland, were contacted to obtain information about their field boundaries. A 60% response rate enabled us to identify field boundaries for 150 fields covering 4,615 acres. The spatial distribution of soil types (A_i) within each of these 150 field boundaries was obtained using digitized soil maps for the county.

Each soil type has an associated estimate of corn yield potential (Olson and Lang). For each of the 150 fields, we calculated the average, variance, and the skewness of its potential yield distribution. Summary statistics for these characteristics over the 150 fields are presented in table 1. Fields ranged in their average potential yield from 44 bushels/acre to 162 bushels/acre. The mean of the average potential yield of the 150 fields is 130 bushels/acre. There is considerable variability in the level of spatial variability and the skewness among the 150 fields. Some fields in the sample are completely

Table 1. Parameters of Distribution of Potential Yields over the 150 Fields

	Potential Yield (bushels/acre)			
Parameter	Minimum	Mean	Std. Error	Maximum
Mean	43.6	130.0	23.7	161.8
Standard Deviation	0	9.06	5.7	44.5
Coefficient of Variation	0	7.59	5.8	34.9
Skewness	-25.3	-0.99	4.38	21.6

Notes: Number of observations = 150. Total acreage of the 150 fields = 4,615 acres.

uniform (i.e., zero standard deviation), while the standard deviation of the most variable field is 44.5. The coefficient of skewness of the fields also ranged from being highly negative (-25.3) to very positive (21.6).

For continuous corn, the *Illinois Agronomy Handbook* (University of Illinois) recommends the optimal level of nitrogen application should be $T_i = 1.2Z_i$. The slope coefficient of the production function (γ_i) depends on the intercept (a_i), since $\gamma_i = (Z_i - a_i)/(1.2Z_i)$ and determines the responsiveness of yield to nitrogen. For simplicity, we assume a_i is the same for all i. Five alternative values for a_i are considered, depending on whether it is possible to obtain 0%, 20%, 40%, 60%, or 80% of the maximum potential yield without nitrogen application. The values of γ_i corresponding to these values of a_i are 0.83, 0.66, 0.50, 0.33, and 0.17, respectively. An estimate of the uncertainty in potential yields (σ_ε^2) is obtained from the annual variations in logarithm of corn yield[6] for Illinois between 1950 and 2000, which is 0.10. Similar estimates for each of the 112 counties in Illinois show that σ_ε^2 ranges from 0.06 to 0.24. Hence, three alternative levels[7] of σ_ε^2 are considered: 0.05, 0.10, and 0.20.

The prices of corn and nitrogen are assumed to be at their 10-year average level of \$2.50/bushel and \$0.20/pound, respectively (as in Babcock and Pautch; Pautsch, Babcock, and Breidt). It is also assumed that the cost of moving from the average strategy to VRNT is \$6.6/acre, which includes the cost of soil mapping (\$1.6/acre) and variable-rate application (\$5/acre).[8] This value falls within the range of \$3/acre and \$10/acre typically cited for the cost of VRNT (Swinton and Lowenberg-DeBoer).

Results

As the slope of the production function decreases, crop yields and quasi-rents with the average strategy increase but nitrogen use does not change (table 2). Average per acre quasi-rents with the average strategy range between \$272.9 with $\gamma_i = 0.83$ and \$286.0 with $\gamma_i = 0.17$. Nitrogen use and quasi-rents per acre are higher under the information strategy than under the average strategy. The average per acre quasi-rents of the

[6] We hypothesize that the observed corn yield Y is a function of the true potential yield Z. This can be represented as $Y = Z\exp(\varepsilon)$, which implies $\ln(Y) = \ln(Z) + \varepsilon$. The variance of ε, σ_ε^2, can be obtained from the variance of $\ln(Y)$ with a linear trend ($\ln(Y) = a + bt + \varepsilon$). Data on state- and county-level yields for Illinois are obtained from the USDA's *Agricultural Statistics* (1950–2000).

[7] A value of $\sigma_\varepsilon^2 = 0.05$ implies that for a field (or a section of the field) with a true average potential yield of 130 bushels/acre (which is unknown to the farmer), the farmer would consider the yield to lie, with a 68.26% probability, between 104 and 163 bushels/acre (representing one-standard-deviation levels on either side of the true level).

[8] The cost of soil mapping and VRNT is obtained from Illini FS, Inc., Agricultural Cooperative (available online at http://www.illinifs.com).

Table 2. Impact of Responsiveness of Yield-Response Function on Profitability of the Information Strategy and VRNT

Description	Slope of Production Function (γ_i): Mean Levels and (Standard Deviations)				
	$\gamma_i = 0.83$	$\gamma_i = 0.66$	$\gamma_i = 0.50$	$\gamma_i = 0.33$	$\gamma_i = 0.17$
Average Strategy:					
Nitrogen Use (lbs./acre)	153.6	153.6	153.6	153.6	153.6
	(28.5)	(28.5)	(18.5)	(28.5)	(28.5)
Crop Yields (bu./acre)	121.5	122.8	124.1	125.4	126.7
	(25.1)	(24.7)	(24.4)	(24.2)	(23.9)
Quasi-Rents ($/acre)	272.9	276.2	279.5	282.8	286.0
	(57.0)	(56.2)	(55.5)	(54.7)	(54.1)
Information Strategy:					
Nitrogen Use (lbs./acre)	164.5	163.8	163.3	162.6	154.7
	(26.2)	(27.1)	(27.4)	(28.5)	(30.2)
Crop Yields (bu./acre)	125.5	126.0	126.5	126.9	127.1
	(24.3)	(23.7)	(23.5)	(24.0)	(23.9)
Quasi-Rents ($/acre)	280.9	282.2	283.5	284.7	286.5
	(55.6)	(55.2)	(54.5)	(54.1)	(53.3)
Difference in Quasi-Rents ($/acre) w/Adoption of:					
Information Strategy relative to Average Strategy	7.94 (5.53)	5.96 (4.24)	3.97 (2.97)	1.99 (1.74)	0.32 (0.44)
VRNT relative to Information Strategy	8.35 (7.17)	7.08 (5.88)	5.80 (4.61)	4.51 (3.35)	2.74 (1.92)
VRNT relative to Average Strategy	16.29 (10.36)	13.03 (8.29)	9.77 (6.22)	6.52 (4.15)	3.26 (2.07)
Adoption Rates (%):					
Information Strategy[a]	22.0	25.3	23.0	32.7	7.0
VRNT[b]	63.3	58.0	53.0	33.3	6.0
Average Strategy[c]	14.7	16.7	24.0	34.0	87.0

[a]Represents the percentage of the 150 fields that would switch from the average strategy to the information strategy only after taking into account the costs of soil mapping.

[b] Represents the percentage of the 150 fields that would switch from the average strategy to VRNT after taking into account the costs of adopting VRNT.

[c]Represents the percentage of the 150 fields that continue to use the average strategy.

information strategy vary between $280.9 and $286.5 with $\gamma_i = 0.83$ and $\gamma_i = 0.17$, respectively. As yield becomes less responsive to nitrogen (its slope γ_i falls), crop yields rise because of an upward shift in the intercept of the production function. This leads to an increase in quasi-rents with the average and information strategies and a fall in the gain in quasi-rents with a switch to the information strategy and VRNT from the average strategy. With $\gamma_i = 0.83$, 22% of the fields would adopt the information strategy only (because the difference in quasi-rents exceeds the additional costs of adoption), while 63% would adopt VRNT. These rates decrease to 7% and 6%, respectively, with $\gamma_i = 0.17$.

Impact of Uncertainty on Crop Yields, Variable Costs, and Quasi-Rents

We compare the impact of adoption of the information strategy and VRNT on quasi-rents under varying levels of uncertainty about potential yields. The results presented in table 3 are obtained by setting γ_i equal to 0.5 because 40% of the potential corn yield

Table 3. Impact of Uncertainty About Potential Yields on the Gains from the Information Strategy and VRNT

	Degree of Uncertainty (σ_ε^2): Means and (Standard Deviations)			
Description	$\sigma_\varepsilon^2 = 0.0$	$\sigma_\varepsilon^2 = 0.05$	$\sigma_\varepsilon^2 = 0.1$	$\sigma_\varepsilon^2 = 0.2$
Quasi-Rents ($/acre):				
Average Strategy	279.5	280.8	281.8	282.6
	(55.5)	(55.8)	(56.1)	(56.3)
Information Strategy	283.5	283.4	283.2	283.0
	(54.5)	(54.45)	(54.41)	(54.36)
VRNT	289.3	288.4	287.5	285.6
	(57.6)	(57.0)	(56.7)	(56.5)
Information Strategy Relative to Average Strategy:				
Yield Gains (bu./acre)	2.38	1.52	0.74	-0.31
	(1.57)	(1.35)	(1.80)	(1.08)
Cost Savings ($/acre)	-1.98	-1.22	-0.44	1.19
	(1.31)	(1.34)	(1.39)	(1.51)
Difference in Quasi-Rents ($/acre)	3.97	2.57	1.40	0.44
	(2.97)	(2.33)	(1.87)	(1.71)
VRNT Relative to Information Strategy:				
Yield Gains (bu./acre)	1.53	1.54	1.53	1.52
	(1.57)	(1.57)	(1.57)	(1.57)
Cost Savings ($/acre)	1.98	1.22	0.44	-1.19
	(1.31)	(1.34)	(1.39)	(1.56)
Difference in Quasi-Rents ($/acre)	5.80	5.04	4.26	2.62
	(4.61)	(4.63)	(4.65)	(4.75)
VRNT Relative to Average Strategy: [a]				
Yield Gains (bu./acre)	3.91	3.00	2.25	1.22
	(2.48)	(2.41)	(2.28)	(1.87)
Difference in Quasi-Rents ($/acre)	9.77	7.61	5.66	3.06
	(6.22)	(6.00)	(5.71)	(4.68)
Adoption Rates (%):				
Information Strategy [b]	23.0	31.3	26.0	20.7
VRNT [c]	53.0	12.0	6.7	2.0
Average Strategy [d]	24.0	56.7	67.3	77.3

Note: The slope parameter is set to 0.5.
[a] There is no cost savings with adoption of VRNT relative to the average strategy.
[b] Represents the percentage of the 150 fields that would switch from the average strategy to the information strategy only after taking into account the costs of soil mapping.
[c] Represents the percentage of the 150 fields that would switch from the average strategy to VRNT after taking into account the costs of adopting VRNT.
[d] Represents the percentage of the 150 fields that continue to use the average strategy.

can typically be obtained without applying nitrogen (University of Illinois). As observed in table 3, an increase in σ_ε^2 increases quasi-rent per acre with the average strategy,[9] but reduces it with the information strategy, for reasons discussed above. The private value of increased information about potential yields to farmers using the information strategy would, however, be negligible. For farmers using VRNT, improved information could increase quasi-rent from $0.9/acre to $3.7/acre.

[9] As σ_ε^2 increases beyond the level of 0.2, profits with the average strategy would start falling relative to the level under certainty.

The value of VRNT relative to the information strategy decreases as σ_ε^2 increases because it is profitable to increase nitrogen applications more under VRNT than under the information strategy as σ_ε^2 increases. Under the information strategy, the gain in expected yield from increasing nitrogen application uniformly over the whole field (as uncertainty increases) and overapplying across larger portions of the field decreases as applications increase. Under VRNT, however, an increase in uncertainty leads to an expectation of higher yields at each point in the field by increasing applications. As a result, input costs under VRNT rise faster than under the information strategy, and the average per acre difference in quasi-rents with VRNT relative to the information strategy decreases from \$5.80 with certainty to \$2.62 with $\sigma_\varepsilon^2 = 0.2$.[10] The corresponding decrease in the average per acre difference in quasi-rents with the information strategy relative to the average strategy is from \$3.97 to \$0.44 (table 3).

Incorporating uncertainty reduces the percentage of fields that would adopt the information strategy and VRNT. With certainty, incentives to shift from the average strategy to the information strategy alone exist for 23% of the fields, and to shift from the average strategy to VRNT for 53% of the fields (table 3). Under uncertainty ($\sigma_\varepsilon^2 = 0.05$), adoption rates of the information strategy alone increase to 31%, while for VRNT they fall to 12%. Thus, uncertainty has differential effects on the incentives to adopt the information and precision strategies. With higher uncertainty, adoption rates for VRNT would fall even further.

Determinants of Value of Information and Precision Strategies

We now examine the extent to which differences in the parameters of the distribution of potential yields—the mean, variability, and skewness of the distribution—and the responsiveness of the production function explain differences in the value of the information strategy and VRNT across fields. The dependent variable (value of the information strategy and of VRNT) is generated under certainty for the 150 fields with the five different slope parameters identified in the "empirical application" section. Because there are repeated observations for these 150 fields (giving 750 observations), the Lagrange multiplier test is used to determine if panel data methods are more appropriate than ordinary least squares (OLS). The LM test statistic reported in table 4 indicates the validity of the random-effects model relative to OLS. The estimated coefficients with the random-effects model are very close to those with OLS, but their standard errors are smaller.

From table 4, the values of the information strategy and of VRNT relative to the average strategy are both positively related to the variability of the potential yields and the slope of the production function. Fields with lower average potential yield are likely to gain more from adopting the information and precision strategies. This could be

---

[10] We also examined the sensitivity of the value of VRNT to output and input prices. As shown in the theoretical model, an increase in input price does not affect the value of VRNT relative to the average strategy, but it does affect the difference in quasi-rents relative to the information strategy. We find that (with $\gamma_i = 0.5$) an increase in the price of fertilizer from \$0.2/pound to \$0.3/pound leads to an increase in the per acre average difference in quasi-rents from \$5.8 to \$6.7 with VRNT relative to the information strategy. A decrease in corn price from \$2.5/bushel to \$2.0/bushel leads to a decrease in the value of VRNT relative to both the average and the information strategies. The average difference in quasi-rents with VRNT decreased from \$9.8/acre to \$7.8/acre relative to the average strategy, and from \$5.8/acre to \$5.0/acre relative to the information strategy. Although the differences in quasi-rents with VRNT relative to the information strategy are always positive under certainty, under uncertainty they do become negative for a few fields.

Table 4. Determinants of the Value of the Information Strategy and VRNT Under Certainty

Description	Dependent Variable: Per Acre Gains in Quasi-Rents w/Adoption of: Information Strategy Relative to Average Strategy[b]	VRNT Relative to Information Strategy	VRNT Relative to Average Strategy
Intercept	-3.107***	-0.177	-3.661***
	(0.685)	(1.667)	(1.121)
Average Potential Yield	-0.011***	-0.021**	-0.032***
	(0.004)	(0.011)	(0.006)
Potential Yield Variability	0.290***	0.547***	0.838***
	(0.019)	(0.025)	(0.031)
Skewness of Potential Yield	-0.177***	0.122**	-0.059
	(0.024)	(0.063)	(0.071)
Slope of Production Function (γ_i)	11.581***	7.674***	19.632***
	(0.448)	(0.308)	(0.498)
R^2	0.75	0.50	0.68
LM Statistic[a]	—	725.68	402.29
{p-value}		{0.0}	{0.0}
N	750	750	750

Notes: Single, double, and triple asterisks (*) denote significance at the 10%, 5%, and 1% levels, respectively. Numbers in parentheses are standard errors.

[a] LM test statistic is obtained by a Breusch-Pagan Lagrange multiplier test for testing the random-effects model against the classical regression without a field-specific intercept.

[b] OLS results are reported here because the random-effects model did not find positive estimates of the components of the variance.

because fields with lower quality soils and a lower average potential yield also have greater variability in soil types, as reported by Babcock and Pautsch for fields in Iowa.

As observed in table 4, the impact of skewness of potential yields on the values of the information strategy and of VRNT differs. Positively skewed fields were less likely to gain by adopting the information strategy; of those fields adopting the information strategy, however, the positively skewed fields were more likely to find it profitable to adopt VRNT. The net effect of the coefficient of skewness on the value of VRNT under certainty relative to the average strategy is negative, as predicted by the theoretical model, but not statistically significant. The extent to which the information strategy leads to overapplication of nitrogen is relatively higher for positively skewed distributions, and while this increases yields, it also increases costs. Gains from adoption of the information strategy on positively skewed distributions are therefore low. It is on these fields, however, that precision application can keep nitrogen costs from escalating too much, without sacrificing yield. Thus, gains from VRNT are higher on positively skewed fields.

As the variability of potential yield increases by one bushel, the per acre value of the information strategy increases by $0.29 while that of VRNT increases by $0.55. As the coefficient of skewness increases by 0.1, the per acre value of the information strategy decreases by $1.8. In contrast, the VRNT per acre value increases by $1.2 (table 4). The value of the information strategy is more responsive to changes in the slope of the production function than the value of VRNT.

Table 5. Determinants of the Value of the Information Strategy and VRNT Under Uncertainty About Potential Yield

	Dependent Variable: Per Acre Gains in Quasi-Rents w/Adoption of:		
Description	Information Strategy Relative to Average Strategy	VRNT Relative to Information Strategy [b]	VRNT Relative to Average Strategy
Intercept	6.302***	5.163***	10.983***
	(0.911)	(0.837)	(1.678)
Average Potential Yield	-0.032***	-0.032***	-0.061***
	(0.006)	(0.006)	(0.012)
Potential Yield Variability	0.0371*	0.542***	0.687***
	(0.1553)	(0.024)	(0.027)
Skewness of Potential Yield	-0.047	0.122***	0.048
	(0.031)	(0.031)	(0.064)
Degree of Uncertainty (σ_ε^2)	-19.402***	-15.966***	-33.019***
	(3.146)	(1.809)	(0.899)
R^2	0.64	0.54	0.66
LM Statistic [a]	159.10	—	533.58
{p-value}	{0.0}		{0.0}
N	600	600	600

Notes: Single, double, and triple asterisks (*) denote significance at the 10%, 5%, and 1% levels, respectively. Numbers in parentheses are standard errors.

[a] LM test statistic is obtained by a Breusch-Pagan Lagrange multiplier test for testing the random-effects model against the classical regression without a field-specific intercept.

[b] OLS results are reported here because the random-effects model did not find positive estimates of the components of the variance.

The impact of uncertainty on the value of the information strategy and VRNT with $\gamma_i = 0.5$ is estimated by running a random-effects regression using 600 values generated for $\sigma_\varepsilon^2 = 0, 0.05, 0.1$, and 0.2 (table 5). As σ_ε^2 increases by 0.1, the per acre value of the information strategy decreases by $2.0, while the value of VRNT relative to the information strategy decreases by $1.6.

Impact of VRNT on Nitrogen Use

Table 6 presents the impact of the information strategy and VRNT on improving the precision with which nitrogen is applied. Under certainty, the average strategy provides the exact amount of nitrogen on only 1% of the total acreage, while the information strategy provides the precise amount on 2% of the acreage. Over 51% of the total acreage receives more nitrogen than necessary under the average strategy, and over 64% receives overapplication under the information strategy. The information strategy tends to overapply nitrogen to reduce potential yield loss; at the existing high price of corn relative to the price of nitrogen, preventing yield loss is worth more than the cost savings. The information strategy leads to higher nitrogen use (by 9.1 pounds under certainty) and more overapplication of nitrogen compared to the average strategy.

We next estimate the reduction in overapplication of nitrogen that could be achieved by adopting VRNT as a percentage of the level applied under VRNT (table 6). Under certainty, VRNT reduces overapplication of nitrogen relative to the average strategy by

Table 6. Environmental Improvements with Information Strategy and VRNT Under Alternative Levels of Uncertainty About Potential Yield

	Degree of Uncertainty (σ_ε^2)			
Description	$\sigma_\varepsilon^2 = 0.0$	$\sigma_\varepsilon^2 = 0.05$	$\sigma_\varepsilon^2 = 0.1$	$\sigma_\varepsilon^2 = 0.2$
Average Strategy:				
Acres receiving exact amount (%)	1.1	0.0	0.0	0.0
Acres receiving overapplication (%)	51.3	60.8	68.1	82.1
Acres receiving underapplication (%)	47.6	39.2	31.9	17.9
Information Strategy:				
Acres receiving exact amount (%)	2.0	2.0	2.0	2.0
Acres receiving overapplication (%)	64.6	64.6	65.2	65.3
Acres receiving underapplication (%)	33.4	33.4	32.8	32.7
Per Acre Nitrogen Reductions w/Adoption of: [a]				
Information Strategy relative to Average Strategy (lbs.) [b]	-9.1	-5.0	-0.8	7.0
VRNT relative to Information Strategy (lbs.) [b]	9.1	5.0	0.8	-7.0
Percentage Reductions in Overapplication w/Adoption of:				
VRNT relative to Information Strategy (%)	12.6	9.8	7.0	2.0
VRNT relative to Average Strategy (%)	9.6	7.8	6.3	3.5

Note: The results in this table are obtained by setting the slope of the production function at 0.5.
[a] Adoption of VRNT relative to the average strategy does not reduce per acre nitrogen use.
[b] Negative numbers imply an increase in per acre nitrogen use.

9.6%, and relative to the information strategy by 12.6%. While adoption of VRNT relative to the average strategy does not lead to a decrease in the total nitrogen use relative to the average strategy, adoption of VRNT relative to the information strategy does reduce total nitrogen use by about nine pounds/acre. As uncertainty increases, the percentage of acreage receiving excess nitrogen with the average strategy increases compared to the level under certainty.

From table 6, with $\sigma_\varepsilon^2 = 0.2$, adoption of the information strategy would reduce nitrogen use relative to the average strategy by seven pounds/acre. The extent to which adoption of VRNT can prevent excess nitrogen use relative to the average and information strategies decreases as uncertainty increases. With $\sigma_\varepsilon^2 = 0.2$, VRNT reduces the overapplication of nitrogen by 3.5% relative to the average strategy and by 2% relative to the information strategy, as compared to 9.6% and 12.6%, respectively, under the certainty case.

Conclusions

There is widespread concern about levels of nitrogen use in agriculture, which, in several regions in the United States, are determined on the basis of the potential maximum yield of the soil. Information about crop yield is quite imprecise because of uncertainty about weather patterns during the growing season. This analysis shows that a high degree of uncertainty about potential yields can decrease the per acre gain in quasi-rents with VRNT, with a typical production function ranging from \$9.8 to as low as \$3.1 relative to the average strategy. The loss in quasi-rents due to uncertainty is higher for farmers switching from the information strategy to VRNT than for those switching from the average strategy to the information strategy.

Adoption rates of VRNT obtained under some uncertainty appear to be closer to the actual observed adoption rates than those obtained under complete certainty. The gain in quasi-rents from the information and precision strategies is higher on fields with low potential yield and high spatial variability. While fields with negatively skewed distributions gain more from the information strategy, fields with positively skewed distributions are more likely to gain from VRNT.

Based on the results obtained in this study, VRNT does have the potential to reduce nitrogen use by reducing the extent of overapplication relative to the average strategy. Yet, in the presence of a high degree of uncertainty about potential yields in the field, the incentives to overapply nitrogen irrespective of the method of application can reduce the environmental gains from VRNT considerably. Hence, improved information about weather patterns and their impact on crop yields would enable better realization of the potential benefits of VRNT. Such information is found to be more valuable for farmers switching to VRNT than for those switching to the information strategy. While the feasibility of reducing this uncertainty and its costs are not examined here, the potential benefits of reducing this uncertainty should include both the private benefits for farmers and the social benefits of reduced nitrate run-off.

[*Received April 2001; final revision received November 2001.*]

References

Ackello-Ogutu, C., Q. Paris, and W. A. Williams. "Testing a von Liebig Crop Response Function Against Polynomial Specification." *Amer. J. Agr. Econ.* 67(1985):873–80.

Babcock, B. A. "The Effects of Uncertainty on Optimal Nitrogen Applications." *Rev. Agr. Econ.* 14(1992): 271–80.

Babcock, B. A., and G. R. Pautsch. "Moving from Uniform to Variable Fertilizer Rates on Iowa Corn: Effects on Rates and Returns." *J. Agr. and Resour. Econ.* 23(1998):385–400.

Babcock, B. A., and J. F. Shogren. "The Cost of Agricultural Production Risk." *Agr. Econ.* 12(1995): 141–50.

Bullock, D. G., and D. S. Bullock. "Quadratic and Quadratic-Plus-Plateau Models for Predicting Optimal Nitrogen Rate of Corn: A Comparison?" *Agronomy J.* 86(1994):191–95.

Cerrato, M. E., and A. M. Blackmer. "Comparison of Models for Describing Corn Yield Response to Nitrogen Fertilizer." *Agronomy J.* 82(1990):138–43.

Daberkow, S. G., and W. D. McBride. "Adoption of Precision Agriculture Technologies by U.S. Corn Producers." *J. Agribus.* 16(1998):151–68.

Dayton, L., and J. Lowenberg-DeBoer. "Precision Agriculture Profitability Review." Work. Pap., Site-Specific Management Center, School of Agriculture, Purdue University, 2000.

Dixit, A. K., and R. S. Pindyck. *Investment Under Uncertainty.* Princeton NJ: Princeton University Press, 1994.

English, B. C., S. B. Mahajanashetti, and R. K. Roberts. "Economic and Environmental Benefits of Variable Rate Application of Nitrogen to Corn Fields: Role of Variability and Weather." Selected paper presented at the annual meetings of the American Agricultural Economics Association, Nashville TN, 8–11 August 1999.

Feinerman, E., E. Besler, and G. Dagan. "Optimization of a Spatially Variable Resource: An Illustration for Irrigated Crops." *Water Res. Resour.* 21(1985):793–800.

Fixen, P. E., and H. F. Reetz. "Site-Specific Soil Test Interpretation Incorporating Soil and Farmer Characteristics." In proceedings of the ASA/CSSA/SSSA 2nd International Conference, pp. 731–43. Madison WI: Soil Science Society of America, 1995.

Grimm, S. S., Q. Paris, and W. A. Williams. "A von Liebig Model for Water and Nitrogen Crop Response." *West. J. Agr. Econ.* 12(1987):182–92.

Isik, M., M. Khanna, and A. Winter-Nelson. "Sequential Investment in Site-Specific Crop Management Under Output Price Uncertainty." *J. Agr. and Resour. Econ.* 26(2001):212–29.

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

Khanna, M., O. F. Epouhe, and R. Hornbaker. "Site-Specific Crop Management: Adoption Patterns and Trends." *Rev. Agr. Econ.* 21(1999):455–72.

Khanna, M., M. Isik, and A. Winter-Nelson. "Investment in Site-Specific Crop Management Under Uncertainty: Implications for Nitrogen Pollution Control and Environmental Policy." *Agr. Econ.* 24(2000):9–21.

Lanzer, E. A., and Q. Paris. "A New Analytical Framework for the Fertilizer Problem." *Amer. J. Agr. Econ.* 63(1981):93–103.

National Research Council. "Precision Agriculture in the 21st Century." Committee on Assessing Crop Yield: Site-Specific Farming, Information Systems, and Research Opportunities, Board on Agriculture, Washington DC, 1997.

Olson, K. R., and J. M. Lang. "Productivity of Newly Established Illinois Soils, 1978–1994." Supplement to *Soil Productivity in Illinois.* Dept. of Agronomy, University of Illinois at Urbana-Champaign, 1994.

Paris, Q. "The Return of von Liebig's Law of the Minimum." *Agronomy J.* 84(1992):1040–46.

Paris, Q., and K. Knapp. "Estimation of von Liebig Response Functions." *Amer. J. Agr. Econ.* 77(1989): 178–86.

Pautsch, G. R., B. A. Babcock, and F. J. Breidt. "Optimal Information Acquisition Under a Geostatistical Model." *J. Agr. and Resour. Econ.* 24(1999):342–66.

Ribaudo, M. O., R. D. Horan, and M. E. Smith. "Economics of Water Quality Protection from Nonpoint Sources." Agr. Econ. Rep. No. 782, USDA/Economic Research Service, Washington DC, 2000.

Schnitkey, G. D., J. W. Hopkins, and L. G. Tweeten. "An Economic Evaluation of Precision Fertilizer Applications on Corn-Soybean Fields." In *Proceedings of the Third International Conference on Precision Agriculture*, eds., P. C. Robert, R. H. Rust, and W. E. Larson, pp. 977–87. Madison WI: American Society of Agronomy, 1996.

Searcy, S. W., J. K. Schueller, Y. H. Bae, S. C. Borgelt, and B. A. Stout. "Mapping of Spatially-Variable Yield During Grain Combining." *Trans. ASAE* 32(1989):826–29.

Swinton, S. M., and J. Lowenberg-DeBoer. "Evaluating the Profitability of Site-Specific Farming." *J. Production Agr.* 11(1998):439–46.

Thrikawala, S., A. Weersink, G. Kachnoski, and G. Fox. "Economic Feasibility of Variable Rate Technology for Nitrogen on Corn." *Amer. J. Agr. Econ.* 81(1999):914–27.

University of Illinois. *Illinois Agronomy Handbook.* Coop. Ext. Ser., Dept. of Crop Sciences, University of Illinois, Urbana-Champaign, 1998.

U.S. Department of Agriculture. *Agricultural Statistics.* USDA/National Agricultural Statistics Service, Washington DC. Annual issues, 1950–2000. Online. Available at http://www.nass.usda.gov:81/ipedb/.

———. *Soils of Illinois.* Bull. No. 778, Agr. Exp. Sta., University of Illinois at Urbana-Champaign College of Agriculture, in cooperation with USDA/Soil Conservation Service, 1984.