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Moving from Uniform to Variable Fertilizer Rates on Iowa Corn: Effects on Rates and Returns

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This study develops a model based on the yield potential of various soil types in 12 Iowa counties to estimate the potential value of switching from uniform to variable fertilizer rates. Results indicate modest increases in the gross returns over fertilizer costs, ranging from $7.43 to $1.52 per acre. The net profitability of variable-rate technology (VRT) is sensitive to the per acre costs of moving to a VRT program. Under the assumptions of the model, applying variable rates would increase yield by 0.05 to 0.50 bushels per acre, and would reduce fertilizer costs by $1.19 to $6.83 per acre.

Key words: nitrogen fertilizer, precision farming, single-rate technology, site-specific management, variable-rate technology

Introduction

Many studies have reported that crop yields vary within fields and that the degree of variability can be substantial (Robert et al.; Carr et al.; Miller, Fiez, and Pan; Vetsch et al.; Wibawa et al.; Wolkowski and Wollenhaupt). Yield variability can be caused by a nonuniform distribution of soil properties, such as nutrient availability, soil moisture, landscape position, pest pressure, soil compaction, drainage, and rooting depth (Sawyer), or by a variable response to uniformly applied inputs.

The pervasiveness of spatial variability in yields suggests an opportunity for improving production efficiency by varying input applications within fields. Traditional input management techniques are to apply a single rate to an entire field (or group of fields). We refer to these traditional practices as single-rate technologies (SRTs). Significant research is underway to develop the knowledge and equipment needed to allow farmers to move to variable-rate technologies (VRTs) (National Research Council).

When the response of yield to applied inputs varies across a field, then using an SRT will, in general, leave part of the field undersupplied with the input, while another portion is oversupplied. The undersupplied portion experiences a reduction in yield from the lack of necessary inputs. The oversupplied portion results in wasteful input use, increasing production costs and the risk of environmental contamination.

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This excessive use of nitrogen by farmers is a major concern among agronomists, environmentalists, and the water industry (Nielsen and Lee; Office of Technology Assessment). Environmental concern about the overapplication of chemicals has grown over the years with the increasing evidence of groundwater contamination (Dao).

Babcock showed that the profit-maximizing SRT application rate occurs where the marginal yield gain on the undersupplied portions of a field is just equal to the real cost of the input, assuming that yield was not reduced by overapplication of nitrogen fertilizer. Babcock found that when the real cost of an input is inexpensive relative to its average productivity, then optimal SRT rates may result in most of a field being oversupplied. In this situation, moving to VRT, where each portion of a field receives an optimal amount of input, should lead to identical or greater output with lower input levels.

Recent empirical findings indicate that moving from SRT to VRT to control nitrogen fertilizer rates should have significant effects on input usage and possibly yield levels. Spatial variations in soil moisture within a field result in variations in the marginal product of nitrogen fertilizer, which leads to optimal nitrogen application rates that vary across a field (Dai, Fletcher, and Lee). Also, other growing conditions that vary between experimental sites alter optimal nitrogen fertilizer rates (Babcock and Blackmer), suggesting that optimal rates should vary within fields if site-specific growing conditions vary within fields. Increased variability of growing conditions tends to increase optimal SRT application rates because farmers may overapply nitrogen fertilizer to ensure against the possibility of underfertilization (Babcock; Babcock and Blackmer).

Small-scale experiments with VRT on specific fields indicate that the potential exists for small yield increases with reduced input usage (Robert et al.; Carr et al.; Miller, Fiez, and Pan; Snyder et al.; Solohub, van Kessel, and Pennock; Wibawa et al.; Wolkowski and Wollenhaupt). In these investigations, individual fields were tested and monitored extensively over a number of years. Methods also have been developed that use readily available data and decision rules to replicate the process of applying VRT (Lowenberg-DeBoer and Boehlje). The output of such models could assist local extension agents and the agricultural community in examining the private and environmental benefits from the widespread implementation of VRT.

This analysis extends the Lowenberg-DeBoer and Boehlje framework and estimates the potential value of switching from nitrogen fertilizer application based on SRT to application based on VRT in 12 Iowa counties. The economic and environmental impacts of moving from SRT to VRT depend heavily on the amount of inherent yield variability in fields (Hennessy and Babcock). An empirical contribution of this study is that a measure of potential yield variability across Iowa fields is estimated. Changes in yields, nitrogen use, and profits are estimated for individual fields and entire counties as farmers move from SRT to VRT. These estimates are based on a fertilizer decision model that is parameterized by using the results of previous studies.

The Model

There are two key issues involved in developing a model of production decisions under variable-rate fertilizer technology. The first is choosing a functional relationship between yields and fertilizer levels for a given crop. Different functional forms will give rise to different estimates of the value of VRT. Although a consensus on the appropriate functional form has not been reached, a substantial portion of the literature supports the existence of a plateau in the plant yield response to applied nitrogen (Ackello-Ogutu, Paris, and Williams; Cerrato and Blackmer; Paris). Others find the plateau in conflict with standard agronomic principles (Berck and Hefland; Frank, Beattie, and Embleton; Sinclair and Park). In this study, we adopt the Berck and Helfand approach, and assume that yield response to applied nitrogen fertilizer at the sub-field unit follows the linear response and plateau (LRP) relationship. Integration over all sub-field units gives a nonlinear relationship between expected yields and applied nitrogen.

The second key issue in development of the model is selection of a field attribute that can be used to guide fertilizer rates. Optimal fertilizer rates in a field depend on numerous factors including cropping history, whether the soil received manure, previous fertilizer practices, and inherent soil characteristics. An ideal VRT fertilizer management system would take all these factors (and others) into account.

VRT fertilizer applications are possible if variations in one or more of these attributes can be measured and used to adjust application rates across a field. The ideal field attribute would be easy to measure and would reliably predict intra-field optimal fertilizer rates. Candidate attributes are soil nitrate levels, soil organic matter levels, field slope, or field orientation. Some of these attributes may be highly correlated. For example, Chin demonstrates that on Iowa corn fields, intra-field variations in soil nitrate levels are correlated with soil organic materials, which in turn are correlated with slope, orientation, and the sand and clay content of a soil.

In this study, we abstract from the management history of a field and use yield potential in a field as the key attribute to guide fertilizer rates. This attribute is consistent with traditional fertilizer prescriptions that suggest farmers should vary fertilizer rates according to a yield goal. Yield potential can be measured in a variety of ways. For example, yield monitor data collected over many production years can be used to develop a yield potential map. For the vast majority of producers, however, yield monitors have not been available long enough for reliable yield potential maps to be developed in fields where crops are rotated.

An alternative measure, and the one used in this study, is to relate yield potential to traditional soil maps. These soil maps reflect field characteristics such as slope, hills and valleys, and clay and sand content. How well these attributes measure yield potential is open to question, but the maps do provide objective measures of the spatial variability of factors that affect a field's yield potential. We assume in the remainder of this analysis that soil maps predict yield potential accurately, and that yield potential predicts optimal fertilizer rates. To the extent that these predictions are "noisy," our results overestimate the value of moving to a VRT fertilizer program. Consideration of optimal decisions under noisy information would require development of Bayesian decision rules (Lence and Hayes; Babcock, Carriquiry, and Stern), which is beyond the scope of the present study.

Let each field consist of n different soil mapping units or soil types. Each soil type has an inherent maximum corn productivity level. Nitrogen is assumed to be the only input limiting corn productivity. All other necessary inputs are nonlimiting. For each soil type i, the maximum inherent yield (M_i) is produced by the physically optimal nitrogen application (Q_i). Nitrogen applications (N_i) greater than Q_i have no effect on yield, but applications less than Q_i reduce the soil's corn yield by a constant per unit level (b). The dummy variable D_i is equal to one if $N_i < Q_i$, and equal to zero otherwise. Under these assumptions, the ith soil type corn yield per acre response to applied nitrogen is summarized by the LRP production function:

$$Y_i = M_i - D_i b(Q_i - N_i). \tag{1}$$

With VRT, the farmer is assumed to know the exact location of the n soil types within a field. Let α_i denote the proportion of the field containing the ith soil type. Furthermore, let P_N denote the price of nitrogen fertilizer, and P_C the price of corn. The optimal per acre average yield (Y^{VRT}), nitrogen application (N^{VRT}), and profit (π^{VRT}) under VRT are specified, respectively, as follows:

$$Y^{VRT} = \sum_{i=1}^{n} \alpha_i M_i,$$

$$N^{VRT} = \sum_{i=1}^{n} \alpha_i Q_i,$$

and

$$\pi^{VRT} = P_C Y^{VRT} - P_N N^{VRT} = \sum_{i=1}^{n} \alpha_i (P_C M_i - P_N Q_i).$$

With SRT, the farmer does not know the exact location of the n soil types within a field, but knows the spatial distribution of each soil type (the α_i's). The expected per acre profit on a field from SRT is given by:

$$E(\pi^{SRT}) = \sum_{i=1}^{n} \alpha_i \left[P_C\left(M_i - D_i b(Q_i - N^{SRT})\right)\right] - P_N N^{SRT}, \tag{2}$$

where N^{SRT} is the single rate of nitrogen fertilizer applied throughout the field.

Three fertilizer application strategies have been proposed to divide the total benefit of variable-rate technology into the benefit of gathering information and the benefit of precision application (Schnitkey, Hopkins, and Tweeten). The first of these, the average strategy, assumes the producer gathers information about all the soil types in the field, so that the soil type distribution is known. The producer then assumes that the entire field is the average soil type, i.e., equal to the mean of the soil type distribution. The second approach, the information strategy, assumes that the producer has complete knowledge of the exact location of each soil type but uses a single rate of fertilizer. The difference between the information strategy and the average strategy is the benefit of information gathering. The third approach, the precision strategy, assumes the producer continues to have the same complete knowledge about the soil types, but is now able to vary the rate of fertilizer throughout the field according to the various soil types rather than being constrained to a single rate of fertilizer. The difference between the precision strategy and the information strategy is called the benefits of precision application.

Given our implied assumption of risk neutrality, the optimal N^{SRT} will happen to be the same as the optimal N rate using the information strategy. The two problems, however, are completely different, since in our SRT model the producer knows only the soil type distribution, not the exact location, and finds the single fertilizer rate which maximizes expected profits. The information strategy assumes the producer knows the exact location of each soil type and finds the single fertilizer rate that maximizes a weighted average of profits from the different soil types, where the weights are the soil type proportions in the field.

The average strategy, even though it mimics old fertilizer recommendations, is a suboptimal method of using the information under an SRT fertilizer program. Rather than using the entire soil type distribution in the SRT decision-making process, the producer treats the mean of the distribution as the one true soil type for the entire field. The benefit of information gathering is equal to the producer profit that is not obtained because of the suboptimal use of information in an SRT setting. This should not be included in the benefits of moving to a variable-rate fertilizer program from a single-rate fertilizer program.

When comparing the feasibility of moving to a VRT from an SRT fertilizer program, both programs should be used optimally. Therefore, the per acre value, V, of moving to a variable-rate technology on a field is the increase in profits when switching from SRT to VRT:

$$V = \pi^{VRT} - E(\pi^{SRT}) = \sum_{i=1}^{n} \alpha_i D_i (bP_C - P_N)(Q_i - N^{SRT}) + \sum_{i=1}^{n} \alpha_i (1 - D_i) P_N (N^{SRT} - Q_i). \tag{3}$$

With VRT, nitrogen fertilizer rates are varied according to soil type, allowing optimal rates to be applied to each type of soil. The first term in equation (3) represents the change in profits from increased yields. The term $D_i(bP_C - P_N)$ denotes the marginal profit from an additional unit of applied nitrogen when reducing the underapplication of nitrogen fertilizer, and $(Q_i - N)$ is the amount of additional fertilizer applied to these soils. The second term in equation (3) denotes the change in profits from reducing the overapplication of nitrogen fertilizer.

The value of moving to variable-rate technology is viewed in terms of correcting the misapplication of nitrogen throughout a field, rather than in terms of the overall yield increases and input savings on an entire field (Lowenberg-DeBoer and Boehlje). Such a distinction allows for both the environmental benefits and the production benefits of variable-rate technology to be revealed.

Equation (3) estimates the gross value of moving to VRT as the change in returns over fertilizer costs. The net value of VRT accounts for a number of costs associated with moving to VRT. These include the cost of acquiring knowledge about the spatial distribution of soils within a field; any additional equipment costs including new fertilizer spreaders, computer hardware and software, and global positioning systems; and any additional labor costs.

The value (gross and net) of VRT depends on the type of SRT strategy used. If the SRT strategy is to farm to the soil with the highest potential yield—that is, $N^{SRT} = \max_i(Q_i)$, so that $D_i = 0$ for all i—then the total value of VRT becomes the cost saving from reduced fertilizer application, as corn yield and production are unaffected. In this case, VRT allows farmers to produce the same output with a smaller amount of fertilizer. Only the price of nitrogen fertilizer affects the value of VRT, not the price of corn. Increases (decreases) in the price of nitrogen fertilizer increase (decrease) the value of VRT.

If the SRT strategy is to find the nitrogen application rate that maximizes expected profit, then either farming to the soil with the highest potential yield, or having $D_i = 0$ for some soil types and $D_i = 1$ for others, may be optimal. If some soil types are undersupplied and others oversupplied, then the value of VRT consists of yield increases as well as input cost savings. The value of VRT increases as the prices of nitrogen fertilizer and corn increase, as demonstrated by equations (4) and (5):

$$\frac{\partial V}{\partial P_C} = \sum_{i=1}^{n} \alpha_i D_i b\left(Q_i - N^{SRT}\right) \geq 0 \tag{4}$$

and

$$\frac{\partial V}{\partial P_N} = \sum_{i=1}^{n} \alpha_i \left[D_i\left(Q_i - N^{SRT}\right) + \left(1 - D_i\right)\left(N^{SRT} - Q_i\right)\right] \geq 0. \tag{5}$$

Equation (6) shows that as corn yields become more responsive to applied nitrogen, the value of VRT also increases:

$$\frac{\partial V}{\partial b} = \sum_{i=1}^{n} \alpha_i D_i P_C\left(Q_i - N^{SRT}\right) \geq 0. \tag{6}$$

Empirical Results

Data on the distribution and productivity of soils on 20 randomly selected fields in each of 12 randomly selected Iowa counties were obtained from the Soil Survey section of the Iowa State University's Department of Agronomy. All 99 Iowa counties had an equal chance of being selected. Each selected county was divided into grids, and the grids selected for analysis were randomly drawn. For each selected grid, numbers representing longitude and latitude were randomly drawn. If the intersection of longitude and latitude occurred in a field, the field was selected. If the intersection occurred elsewhere, a new set of longitude and latitude numbers was randomly drawn until a field was found.

Figure 1 shows the location of the 12 counties comprising our study. For each field, the spatial distribution of soil types (α_i) was estimated from digitized soil maps. Each soil type has an associated estimate of corn yield potential. The maximum yield in the LRP model [M_i from equation (1)] was set equal to this corn yield potential. The slope coefficient (b) of the LRP model was set equal to 0.56 bushels/pound, which was the average LRP slope across many site-years in a previous study (Babcock and Blackmer). The price per bushel of corn was set at \$2.50, and the price per pound of nitrogen was set at \$0.20.

How the physically optimal nitrogen applications (the rate where the kink occurs in the LRP model) change with a soil's yield potential is not a straightforward relationship. In the past, fertilizer recommendations from Iowa State University were based on the rule that $Q_i = 1.2M_i$, where the slope coefficient 1.2 is measured in pounds of fertilizer per bushel. Babcock and Blackmer found evidence that supports a positive relationship

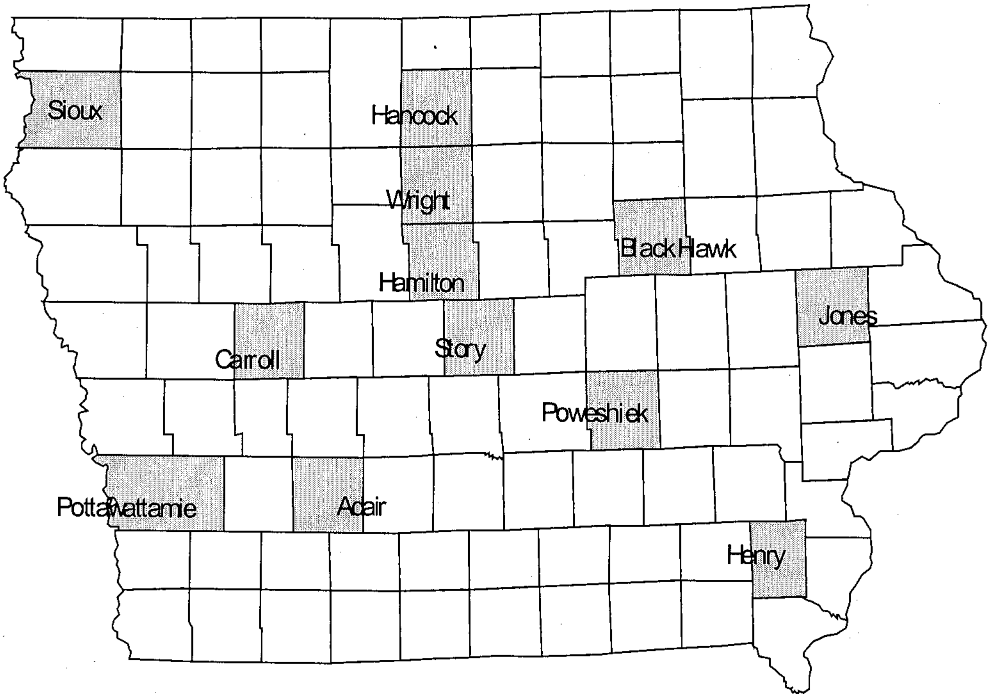

Figure 1. The 12 Iowa counties randomly selected for analysis

between Q_i and M_i across sites, but the parameters of the relationship were sensitive to the assumed functional form of the site-specific production function. To show how the effects of moving to VRT are affected by the parameters, two sets of parameters are used here (Babcock and Blackmer):

$$Q_i = 105.56 + 0.68M_i, \tag{7}$$

and

$$Q_i = -21.93 + 1.52M_i. \tag{8}$$

The two relationships are used to examine the changes in the value of VRT from altering the responsiveness of physically optimal nitrogen rates to maximum inherent yields. Equation (7) represents the situation where physically optimal nitrogen rates are relatively unresponsive to maximum yields, whereas equation (8) represents the more responsive case. Equations (7) and (8) represent different assumptions regarding the site-specific relationship between yields and nitrogen fertilizer from the Babcock and Blackmer study.

To estimate the effects of moving to VRT, we first must determine N^{SRT} for each field. This was accomplished by using a simple grid search to find the application rate that maximized equation (2). At this optimal single-application rate, portions of fields either receive too much fertilizer ($M_i < bN^{SRT}$), too little fertilizer ($M_i > bN^{SRT}$), or the optimal

Table 1. SRT Acres Oversupplied and Undersupplied with Nitrogen Fertilizer in 12 Iowa Counties

County	Total Acres	SRT Acres Over-supplied	Percent Over-supplied	SRT Acres Under-supplied	Percent Under-supplied
Adair	1,081	752	70	42	4
Black Hawk	987	567	58	27	3
Carroll	1,447	1,010	70	113	8
Henry	1,044	640	62	21	2
Hancock	1,800	1,144	64	83	5
Hamilton	1,909	1,257	66	113	6
Poweshiek	1,000	608	61	43	4
Pottawattamie	1,271	732	58	15	1
Sioux	2,024	1,470	73	115	6
Story	1,582	944	60	52	3
Jones	962	688	72	48	5
Wright	3,039	2,116	70	67	2
Total	18,146	11,929	66	738	4

(in an ex post sense) amount ($M_i = bN^{SRT}$). Table 1 presents estimates of the acreage and proportion of acreage on the fields in each of the 12 counties that are oversupplied or undersupplied with fertilizer. The acreage that receives the physically optimal amount is the residual.

If farmers fertilize according to the optimal SRT rule, and if optimal fertilizer rates and soil type are linearly related, as specified in equations (7) and (8), then 66% of acreage would be oversupplied with fertilizer, 4% would be undersupplied, and 30% of the acreage on these fields would receive the correct amount of fertilizer. The optimal single rate of fertilizer will equal the optimal VRT application for an entire field only if the field has only one soil type. In this study, all fields exhibited some soil type variability. However, on some portion of all fields, the optimal single rate is equal to the VRT rate. On these portions, there is no change in yield or fertilizer as one moves to VRT. On average, 30% of the soil in the study area would experience no change from implementing a VRT program.

Table 2 shows the per acre change in gross returns over fertilizer costs in each of the 12 Iowa counties when switching from SRT to VRT applications of nitrogen fertilizer based on soil type. The table 2 results assume that physically optimal nitrogen rates are relatively responsive to maximum yields [equation (8)]. The largest increase in gross returns ($7.43 per acre) occurred in Adair County, and the smallest increase ($3.40 per acre) occurred in Henry County. Over the entire study area, switching to VRT would increase gross returns over fertilizer costs by $4.44 per acre.

Table 2 also presents the source of the increase in gross returns when switching to VRT. In the study area, the vast majority of the increase (86%) came from reducing excess fertilizer applications. Profit maximization using SRT leads to excess applications because the payoff from reducing yield shortfalls in high-yielding portions of fields is greater than the cost savings from reducing rates on low-yielding portions. That is,

Table 2. Increase in Farmer Gross Returns Over Fertilizer Costs Using VRT in 12 Iowa Counties When Optimal Nitrogen Rates Are More Responsive to Maximum Yields

County	Gross Returns Over Fertilizer Cost[a] ($/acre)	Percent Attributable to: Eliminating SRT Overapplication of N	Percent Attributable to: Eliminating SRT Underapplication of N
Adair	7.43	93	7
Black Hawk	3.42	93	7
Carroll	4.24	70	30
Henry	3.40	93	7
Hancock	4.52	86	14
Hamilton	3.89	73	27
Poweshiek	5.65	82	18
Pottawattamie	4.27	95	5
Sioux	3.78	86	14
Story	3.55	80	20
Jones	6.68	89	11
Wright	4.34	90	10
Total	4.44	86	14

[a] These returns do not include the additional cost of moving to VRT.

when farmers cannot vary fertilizer rates across their fields, or they do not have information about the location of their best yielding soils, then they have an incentive to fertilize to those soils with the highest potential yield. In contrast, with VRT, farmers possess information about the location of their soils and the ability to vary fertilizer rates. This knowledge and ability lead to lower production costs from reduced fertilizer applications without a yield loss. In Pottawattamie County, reducing the overapplication of nitrogen fertilizer contributed 95% of the increase in profit. In Carroll County, the contribution is lowest, but still quite substantial at 70%.

Reducing the underapplication of nitrogen fertilizer represents another source of increasing profits with VRT (table 2). Applying more nitrogen fertilizer where it is needed increases corn yield and farmer profit. In the study area, only 14% of the increase in profits is attributable to increasing yields. This modest contribution reflects the large amount of land that is oversupplied with nitrogen fertilizer when using SRT. The increases in marginal returns from increasing fertilizer rates on undersupplied land are much higher than for reducing rates on oversupplied land. Adding a pound of nitrogen where it is needed generates $1.20 [$1.20 = (2.5 \times 0.56) - 0.2$] additional returns per acre, whereas removing a pound of nitrogen where it is not needed generates only $0.20 per acre. Of course, this asymmetry in returns explains why farmers have an incentive to overapply nitrogen fertilizer under SRT.

The costs of moving to variable-rate technology include the cost of data collection and increased application costs. According to the Iowa State University's Department of Agronomy, the typical producer cost in obtaining a digitized field soil map is approximately $20. This one-time cost is negligible when spread over its useful life. The charge

Table 3. VRT Environmental and Production Improvements in 12 Iowa Counties When Optimal Nitrogen Rates Are Relatively More Responsive to Maximum Yields

County	VRT Reduction in Overapplication of N (lbs.)	VRT Reduction in Overapplication of N (%)	VRT Increase in Corn Yield (bu./acre)	VRT Decrease in N Costs ($/acre)
Adair	37,401	31.8	0.24	6.83
Black Hawk	15,661	14.6	0.12	3.13
Carroll	21,427	12.1	0.60	2.75
Henry	16,583	15.4	0.11	3.14
Hancock	34,851	18.3	0.30	3.76
Hamilton	26,988	12.1	0.50	2.65
Poweshiek	23,150	21.6	0.48	4.46
Pottawattamie	25,806	21.7	0.10	4.02
Sioux	32,913	15.1	0.25	3.16
Story	22,373	12.1	0.34	2.71
Jones	28,583	25.5	0.34	5.82
Wright	59,043	15.9	0.21	3.81
Total	344,778	16.9	0.30	3.69

for variable-rate fertilizer application is $6.50 per acre (Giacchetti) versus the common $5 per acre for single-rate fertilizer application. Hence, the additional cost of moving to variable-rate technology is $1.50 per acre. This figure is much lower than the typical $3 to $10 per acre additional cost used in other studies (Hertz; Swinton and Ahmad) because of the absence of soil sampling.

Table 3 reports the environmental and production improvements when switching to VRT. As shown in table 1, about 66% of acreage received excess fertilizer over the study area. The first numeric column of table 3 identifies the amount of excess fertilizer (lbs.) applied on this acreage. This is fertilizer that is not needed by the crop and is potentially lost to the environment. The second column reports the amount as a percentage of the level applied under VRT. Over the study region, for the acreage that received excess fertilizer, 16.9% too much fertilizer was applied on average under SRT. This overapplication ranged from a high of 31.8% in Adair County to a low of 12.1% in Carroll, Hamilton, and Story counties. The reductions in excess nitrogen applications presumably yield some public environmental benefit without any loss in farmer yields.

The VRT production benefits consist of higher yields and lower production costs. Increases in yields are quite small, since gains are possible on only 4% of the acreage. Over the aggregate study area, VRT increases yield by an average of 0.30 bushels per acre, which has a value of $0.75 per acre. This small yield increase occurs with a $3.69 per acre reduction in the cost of nitrogen fertilizer (table 3). With VRT, farmers are able to modestly increase production using a smaller amount of inputs, and as a consequence they inflict less damage on the surrounding environment.

Factors Affecting the Value of VRT

As discussed below, factors that may affect the value of VRT are the responsiveness of optimal nitrogen rates to maximum yields, the variability of soil types within a field, and the overall productivity level of a field.

Responsiveness of Physically Optimal Nitrogen Rates

The SRT acres that are either oversupplied or undersupplied with nitrogen fertilizer are unaffected by the responsiveness of physically optimal nitrogen rates to changes in maximum inherent yields [as expressed in equations (7) and (8)]. The assumed linearity of the relationships between yield and applied nitrogen and between maximum inherent yield and physically optimal nitrogen rate, leaves the improperly supplied SRT acres unchanged.

Table 4 presents the increase in gross returns over fertilizer costs when switching to VRT when the response of physically optimal nitrogen application to maximum inherent yield is relatively unresponsive, as given by equation (7). As the responsiveness decreases, the increase in returns to moving to VRT becomes smaller for each county. The largest increase becomes $3.32 per acre in Adair County, while the smallest increase is $1.52 per acre in Henry County. For the entire study area, the increase is less than half the increase estimated under the more responsive relationship, falling from $4.44 per acre to $1.99 per acre. The source of the increase in gross returns from moving to VRT, however, remains at 86% due to the elimination of overapplication and 14% due to the elimination of underapplication of nitrogen (tables 2 and 4). These lower returns barely cover the increased costs of moving to variable-rate technology.

As the responsiveness of physically optimal nitrogen rates to soil productivity declines, SRT applications continue to incorrectly apply nitrogen to the same acreage, but the magnitude of the over- and underapplication becomes smaller. This reduction in the misapplication of nitrogen to a field is due to the reduced variability of optimal nitrogen rates. SRT applications of nitrogen fertilizer approach those of VRT applications. Of course, in the limit, as variability goes to zero, SRT rates converge to VRT rates.

Tables 3 and 5 provide additional evidence of this relationship by showing that the VRT environmental and production improvements are smaller when the optimal nitrogen application rate is less responsive. In the study area, the amount of nitrogen fertilizer potentially leaching into underground water supplies declines from 16.9% of VRT application rates to 7.6%. The VRT increase in corn yields also falls from 0.30 bushels per acre in the high response case to 0.13 bushels per acre in the low response case. Finally, the VRT reduction in nitrogen costs decreases from $3.69 to $1.65 per acre. A lower optimal nitrogen rate response to maximum inherent yields causes the value of VRT as well as its environmental and production improvements to decline.

Table 4. Increase in Farmer Gross Returns Over Fertilizer Costs Using VRT in 12 Iowa Counties When Optimal Nitrogen Rates Are Less Responsive to Maximum Yields

County	Gross Returns Over Fertilizer Cost[a] ($/acre)	Percent Attributable to: Eliminating SRT Overapplication of N	Percent Attributable to: Eliminating SRT Underapplication of N
Adair	3.32	93	7
Black Hawk	1.53	93	7
Carroll	1.90	70	30
Henry	1.52	93	7
Hancock	2.02	86	14
Hamilton	1.74	73	27
Poweshiek	2.53	82	18
Pottawattamie	1.91	95	5
Sioux	1.69	86	14
Story	1.59	80	20
Jones	2.99	89	11
Wright	1.94	90	10
Total	1.99	86	14

[a] These returns do not include the additional cost of moving to VRT.

Table 5. VRT Environmental and Production Improvements in 12 Iowa Counties When Optimal Nitrogen Rates Are Less Responsive to Maximum Yields

County	VRT Reduction in Overapplication of N (lbs.)	VRT Reduction in Overapplication of N (%)	VRT Increase in Corn Yield (bu./acre)	VRT Decrease in N Costs ($/acre)
Adair	16,732	14.2	0.11	3.06
Black Hawk	7,006	6.5	0.05	1.40
Carroll	9,586	5.4	0.27	1.23
Henry	7,419	6.9	0.05	1.40
Hancock	15,591	8.2	0.14	1.68
Hamilton	12,073	5.4	0.22	1.19
Poweshiek	10,357	9.7	0.21	2.00
Pottawattamie	11,545	9.7	0.04	1.80
Sioux	14,724	6.7	0.11	1.42
Story	10,009	5.4	0.15	1.21
Jones	12,787	11.4	0.15	2.60
Wright	26,414	7.1	0.09	1.70
Total	154,243	7.6	0.13	1.65

Table 6. Regression Results for the Effect of Yield Variability Within a Field on the Value of VRT

	Responsiveness of Optimal N Rates to Soil Productivity	
Variable	High Response	Low Response
Intercept	0.69*	0.31*
	(3.49)	(3.49)
Yield Variability	0.28*	0.13*
	(23.76)	(23.76)
R^2	0.69	0.69

Notes: A single asterisk (*) denotes significance at the 5% level. Numbers in parentheses are *t*-ratios.

Field Variability and Productivity

To estimate the impact of yield variability within a field, the value of VRT on a field (V) is regressed on yield variability, which is defined as the standard deviation of M_i for each field. Table 6 provides the results of the regression when the physically optimal nitrogen rate is both relatively responsive and nonresponsive to soil productivity. Not surprisingly, the variability of soil productivity significantly affects V, a result that supports the theoretical models of the effects of variability on the value of VRT (Hennessy and Babcock). As the standard deviation of soil productivity (as measured by maximum inherent yield) increases by one bushel per acre, the gross value of VRT increases by $0.13 per acre in the low response case and $0.28 per acre in the high response case.

In the 12-county study area, fields with lower overall productivity on average possess greater yield variability. The correlation coefficient between yield variability and overall field productivity is equal to –0.54. These results indicate that the value of VRT on average will be greater for less productive fields than fields with higher productivity levels.

Conclusions

There is a growing need for research that estimates the potential value to farmers of acquiring and using improved information about spatial variability within their fields. This need comes from the precision agriculture industry as it struggles to develop decision models that can take advantage of technical advances in positioning equipment and advances in data generation, and from farmers who are attempting to estimate the potential value of investing in precision agriculture equipment. This study begins to fill this need by estimating the potential value of using information about the distribution of soil productivity within fields to guide nitrogen fertilizer rates.

The spatial distribution of soils on 20 randomly selected fields in each of 12 Iowa counties is used to estimate the degree of spatial variability and determine how fertilizer rates and returns to fertilizer might be altered by moving to variable fertilizer rates. We demonstrate that the application of an optimal uniform rate on these 240 fields would result in 66% of acreage being oversupplied with nitrogen fertilizer. Only 4% of acreage would be undersupplied. The analysis is based on yield potential for various soil types. Thus, matching fertilizer rates with a soil's productivity would reduce average nitrogen fertilizer rates and increase yields by a small amount, thereby increasing gross returns over fertilizer costs. Environmental benefits would accrue because less nitrogen would be available to contaminate water supplies.

The county-level results indicate modest increases in gross returns over fertilizer costs, ranging from \$7.43 per acre to \$1.52 per acre. The county-level VRT production benefits consist of increases in yields ranging from 0.05 to 0.50 bushels per acre, and reduction in production costs ranging from \$1.19 to \$6.83 per acre. The modest increase in gross returns is due to farmers overapplying nitrogen when using SRT, thereby ensuring themselves against yield losses. The gross margin for correcting oversupplied land is minimal (\$0.20 per acre), while that for correcting undersupplied land is much larger (\$1.20 per acre). The implied VRT environmental benefit for the entire study area (240 fields) ranges from 77 to 172 tons of nitrogen.

Increases in the price of corn and nitrogen cause the value of VRT to increase. Greater yield variability at the field level also causes the value of VRT to increase. This variability may be due to either the soil types within a field (maximum inherent yields) or the best manner to treat the soil types (physically optimal nitrogen applications). Increasing the yield variability within a field by one bushel per acre increases the gross value of VRT approximately \$0.13 to \$0.28 per acre. The less productive fields in the study area were found to possess more yield variability than the more productive fields. This indicates that the value of VRT will be greater on average for less productive fields.

The gross returns over fertilizer costs estimated here cover the assumed \$1.50 per acre cost of moving to VRT. The literature, however, typically cites increased costs in the range of \$3 to \$10 per acre due to soil sampling. If a cost of \$7.50 per acre were used, then our estimated returns would not cover the total cost of moving to VRT. Because the increase in gross margins over fertilizer costs from moving to a VRT system are so small, the net profitability of VRT is quite sensitive to the per acre costs of moving to a VRT program. If a farmer is to make positive net profits by moving to a VRT system, then the cost of acquiring information about field variability must be low. Our study assumes that this knowledge can be obtained by acquisition of soil maps that do not vary from year to year. The costs of these maps are low compared to the cost of acquiring information annually with soil tests or other sensing devices.

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