MSABR 99-04

Morrison School of Agribusiness and Resource Management

Faculty Working Paper Series

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June 15, 1999

This report is also available online at http://agb.east.asu.edu/workingpapers/9904.pdf

INVESTING IN PRECISION AGRICULTURE*

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*The authors would like to thank Andrew Schmitz and two anonymous reviewers for their comments on earlier drafts of the manuscript.

ABSTRACT

This paper provides a methodology that can be used to weigh the costs and benefits of precision agriculture in the measurement and application of variable-rate production technology. Empirical estimates of the economic value of precision farming in the form of variable-rate fertilizer application to corn fields in the mid-western United States are calculated and compared to the current cost of investing in this technology. The results of this study indicate that the use of precision technology in the application of fertilizer for corn production in the United States is not profitable over a relatively wide range of corn prices, nitrogen prices, and agronomic differences in soil characteristics.

INVESTING IN PRECISION AGRICULTURE

I. INTRODUCTION

For some observers, site-specific crop management, using the latest technology such as yield counters, ground-based monitors, computers, satellites, and variable-rate application technologies for spatially-variable field operations, represents the potential for a new scientific revolution in agriculture. This emerging technology is known collectively as precision agriculture. Schueller states, “Spatially-variable field operations are unquestionably the wave of the future. Both researchers and farmers are invariably enthused when they understand the concept.” However, while many farmers are excited about the future prospects for precision agriculture, they are typically not as enthusiastic about investing in the technology. Most farmers are interested in the bottom line. They will adopt the new technology only if it is expected to be a profitable investment. While the costs associated with various types of precision technology are not difficult to calculate, the benefits are. For example, measurement of the potential productivity gains associated with variable-rate application technologies requires knowledge of underlying agronomic conditions, such as the distribution of soil characteristics across a field, and the way in which changes in input use affect productivity.

There are a number of studies that have attempted to measure the benefits from the use of precision technology in agriculture. Many agronomists have recognized that there are agronomic benefits associated with precision farming, some of which extend beyond the benefits from increased productivity.[1] However, they are still working to "prove the benefits economically" (Dunn). Schnitkey, Hopkins, and Tweeten state that precision farming is "economically attractive when a field's soil characteristics vary so

that varying input rates across a field based on soil characteristics results in more efficient input use." Swinton and Ahmad found that while many groups within the agribusiness sector have an intense interest in precision technologies, those experienced with these technologies found a number of unexpected costs, as well as a few unexpected benefits associated with adoption of precision agriculture equipment and services. They conclude that evaluating the returns to investment in site-specific crop management requires more information than the yield and cash cost data that are typically available. Lowenberg-DeBoer and Boehlje found that out of 11 case studies of operations that adopted precision technology, only two showed conclusive evidence of increased profitability. Factors contributing to profitability were high initial soil fertility and higher valued crops. They conclude that, "The available economic analysis cannot dispel the possibility that precision farming is a technological dead-end."

The purpose of this paper is to estimate the economic benefits of precision agriculture by analyzing the costs and benefits associated with variable-rate production and monitoring technology. Empirical estimates of the profitability of precision farming are obtained for variable-rate nitrogen application for corn production in several mid-western states. The value of precision farming is compared to the current costs of investing in precision technology in order to determine the profitability of the variable-rate application of nitrogen over a period of five years. In addition, we examine the sensitivity of the results to differences in: (1) functional form; (2) input and output prices; (3) dispersion of soil types; and (4) the accuracy of precision technology.

II. THE VALUE OF PRECISION FARMING

The value of precision in the use of inputs applied to a particular field can be measured by comparing the gross benefit from the allocation of inputs in the absence of precision information and technology, with the gross benefit from the optimal application of inputs, given precision information and technology. In the absence of precision technology, the farmer does not have the ability to apply variable inputs to different sub-plots within a field, nor does he have the ability to accurately determine the relative productivity of those different portions. However, a particular farmer usually has knowledge concerning the average productivity across a (larger) parcel of land. In this case, profit maximization will result in the uniform application of inputs across the entire field. On the other hand, if precision technology is available, the farmer can vary the application of inputs across different sub-plots of the field, resulting in higher productivity, and larger gross benefits. The additional gain from precision technology is driven by an increase in the information available to the farmer. For example, as Dunn illustrates, with current grid sampling technology, a 150-acre field can be divided into sub-plots as small as 2.5 acres. A different optimal input mix can be used on each 2.5 acre sub-plot. If the distribution of the underlying productivity of the soil is more variable, the gross benefits from precision agriculture will be larger.

We proceed by determining the input mix for a farmer who is constrained to treating the entire field as one production unit. This outcome is compared to the input mix for a farmer who has access to variable-rate technology that allows him to apply a different input mix across each sub-plot of the field. The difference in gross benefits between these two cases provides a measure of the value of precision farming.

In many cases, each field in which a farmer operates possesses soil characteristics that can vary greatly from one sub-plot to another. Hence, the aggregate production function of a particular field is actually comprised of a number of small production units. Let F(V) be the aggregate primal production function of a particular field, then:

$$(1) \quad F(V) = \sum_{s=1}^{S} f_s(v_s)$$

where S is the number of sub-plots, V is a 1xS vector of inputs applied to each sub-plot, and $f_s(v_s)$ represents the primal production function for sub-plot s, given an amount v_s applied to sub-plot s.

1. Gross Benefits in the absence of Precision Technology

Consider a farmer that does not have access to variable-rate application and monitoring technology. He must treat each sub-plot in a uniform manner. Hence, his objective function is to maximize profits in the presence of the (implicit) constraint that v = v_i and that all the v_i's are equal. This objective function can be written as:

$$(2) \quad \underset{v}{MAX} \quad p\sum_{s=1}^{S} f_s(v) - Swv$$

where p is the price of the output, w is the cost of the input, and v is the amount of the input uniformly applied to each sub-plot. The solution to maximization problem (2) provides the optimal input mix in the absence of precision technology. The first order condition for this problem is:

$$(3) \quad \frac{Sw}{p} = \sum_{s=1}^{S} \frac{\partial f_s(v)}{\partial v} \equiv \frac{\partial F(V)}{\partial v} \quad where\ V = (v, v, ..., v)$$

Intuitively, solution (3) is identical to maximizing profit along the average production function (F/S). The solution (v^{NP}) obtained by solving (3) provides the gross benefits from farming in the absence of precision technology, which equals

$$(4) \quad B^{NP} = p\sum_{s=1}^{S} f_s\left(v^{NP}\right) - Swv^{NP}$$

2. Gross Benefits with Precision Technologies

Consider the gross benefits accruing to a farmer that has access to precision classification equipment, and has access to equipment that can mechanize the variable application of these inputs. Retaining the notation from the last section, the producer's maximization problem becomes

$$(5) \quad \underset{v_1,\ldots,v_S}{MAX} \quad p\sum_{s=1}^{S} f_s(v_s) - w\sum_{s=1}^{S} v_s$$

with precision technologies, the farmer will apply different amounts of inputs across different portions of a field. The solution to maximization problem (5) provides the optimal input mix with precision technology. There are S first order conditions associated with this problem. The first order conditions for the quantity of applied inputs are:

$$(6) \quad \frac{w}{p} = \frac{\partial f_s(v_s)}{\partial v_s} \quad \forall\, s = \{1,\ldots,S\}$$

The solution set to (6) $\{v_1^{PR},\ldots,v_S^{PR}\}$ provides the gross benefit from the use of precision technology, which equals

$$(7) \quad B^{PR} = \sum_{s=1}^{S} B_s^{PR} = \sum_{s=1}^{S}\left[pf_s(v_s^{PR}) - wv_s^{PR}\right]$$

The value of precision farming is calculated as the difference between the gross benefits determined by maximization problem (7), which differentiates among sub-plots through precision technology, and the gross benefits associated with maximization problem (4), which does not differentiate among sub-plots. Mathematically, the value of variable-rate application technology for a single input becomes:

$$(8) \quad \Lambda = B^{PR} - B^{NP} = p\sum_{s=1}^{S}\left[f_s(v_s^{PR}) - f_s(v^{NP})\right] - w\sum_{s=1}^{S}\left[v_s^{PR} - v^{NP}\right]$$

3. Empirical Implementation

The value of precision agriculture in equation (8) is heavily dependent upon the exact form of the primal production function. We are interested in obtaining empirical estimates of the benefits of the variable-rate application of fertilizer in corn production. The three major components of fertilizer are potassium, nitrogen, and phosphorus. In the mid-western United States, nitrogen is the main ingredient, but potassium and phosphorus are also applied in smaller quantities. Even though the analysis focuses on nitrogen, potassium and phosphorus must be taken into account.

As a first approximation of the value of variable-rate fertilizer application, we assume a functional form that possesses all three stages of production.[2] The following functional form proposed by Zellner possesses each stage of production, and can be easily manipulated to differentiate among land types. This functional form is

$$\phi(v_1, v_2) = \frac{a v_1^3}{Exp\left[b\dfrac{v_1}{v_2}\right] - 1} \quad (9)$$

where v_1 and v_2 are inputs and a and b are parameters. For this application, v_1 is set equal to the level of nitrogen (the dominant variable input controlled by precision technology)

and v_2 is a latent factor of production that controls the overall productivity of land.[3] It is assumed that v_2 incorporates potassium, phosphorus, and any other controlled or uncertain variables that influence the productivity of the soil. This approach has the advantage of reducing notational complexity while still preserving the model's capacity to underscore the economic incentives at work.[4]

We restrict our analysis by assuming that all corn production in the mid-western states in 1995 used 100% conventional tillage and that the actual amount of fertilizer applied by each farmer was optimal given the restriction of uniform application implied by maximization problem (2). Under these assumptions, we work backwards in order to derive the parameters a and b, assuming a univariate Zellner production function using the semiparametric procedure developed by Moss (1999). Moss suggests removing the effect of the other inputs using a nonparametric kernel estimator:

$$y_i - \left[\sum_{j=1}^{N} k\left(x_{1i}, x_{2i}, x_{3i}, x_{1j}, x_{2j}, x_{3j}, \omega\right) y_j - \sum_{j=1}^{N} k\left(x_{1i}, \bar{x}_2, \bar{x}_3, x_{1j}, x_{2j}, x_{3j}, \omega\right) y_j \right] = \frac{a\, x_{1i}^3}{Exp[b\, x_{1i}] - 1} \tag{10}$$

where y_i is the observed level of corn production at observation i, $k(.)$ is a Gaussian kernel, x_{1i} is the level of nitrogen applied for observation i, x_{2i} is the observed level of phosphorus, x_{3i} is the observed level of potassium, and ω is the bandwidth for the nonparametric kernel. The i subscript denotes the observed input and output levels at the point of estimation while the j subscripts denotes the observed level of inputs and output for the rest of the sample. The two remaining variables on the left-hand side, $\bar{x}_2$ and $\bar{x}_3$, are the sample average levels of phosphorous and potassium, respectively. The left-hand side of equation (9) has the effect of normalizing the sample around the mean level of

phosphorous and potassium. Given this normalization, the coefficients *a* and *b* can be estimated using nonlinear least squares.

Once the functional form has been specified, the dispersion of soil types across each individual farmer's field must be introduced into the system. While the authors were able to obtain micro-level data regarding the individual amount of fertilizer applied by a sample of corn producers from various states, we were not able to obtain (sub) micro-level data regarding individual sub-plots contained within a farmer's field. To make the model tractable, each field is divided up into two sub-plots of the same size. One sub-plot is considered "lower quality land" while the other sub-plot is considered "higher quality land". As a proxy for the dispersion of soil types across an individual field, we turn to previous research. Specifically, Wollenhaupt, Mulla, and Crawford found that corn yields have a coefficient of variation between 8 and 29 percent. Hence, we compute estimates of the benefits of variable-rate fertilizer application for corn production, by choosing coefficients of variation between 8 and 29 percent.

At first glance, dividing a farmer's field into only two different types and assuming that there is exactly 50% of each type seems unrealistic. However, this process actually generates the maximum estimate of the benefits from variable-rate fertilizer application, given a specific coefficient of variation. For example, consider a field that has a particular coefficient of variation, but is instead divided up into two unequal halves. As the amount of high quality land increases beyond 50%, the field becomes closer and closer to being uniformly high quality, implying that the value of precision agriculture approaches zero. Alternatively, as the relative quantity of high quality land decreases below 50%, the field approaches uniformity in low quality land and the benefits from

variable-rate application also approach zero. Finally, consider a field with a certain coefficient of variation that is divided up into several sub-plots of land that differ in quality. As long as the distribution of land types are mean-variance equivalent (i.e. the first and second moments of the distribution are equal to the first and second moments of the simple distribution defined by two sub-plots of equal size) the estimates obtained in both cases will be approximately equal.[5]

The specification of the Zellner production function in equation (9) is dependent on two input levels and two parameter values. Focusing on v_1 in our development of the value of precision agriculture, we let v_2 equal $1-\mu/2$ for low quality land and $1+\mu/2$ for high quality land. This specification offers two advantages. First, we can select μ to yield specific coefficients of variation subject to optimizing behavior for v_1. Second, assuming that the percentage of low quality land is 0.5 yields an average production function that is approximately equal to the Zellner function with v_2 equal to 1.00. Applying this normalization leaves us with one variable, v_1, and two parameters (*a* and *b*) to estimate.

4. Empirical Results

Estimates of *a* and *b* were derived from a sample of farm level data provided by the USDA/NASS *Agricultural Chemical Usage Survey, 1995 Field Crops Summary*. Only six states, Illinois, Indiana, Iowa, Michigan, Minnesota, and Ohio were included in the analysis because the sample sizes for the other states were not large enough. The estimated values of *a* and *b* for this specification are presented in Table 1 along with the

number of observations and the bandwidth parameter resulting from the kernel estimation.

Empirical estimates of the value of precision farming by state are presented in Table 2. Column 1 shows the various values of μ that are calibrated to a 0.2 coefficient of variation. This value was chosen because it is the approximate midpoint of the range provided by Wollenhaupt, Mulla, and Crawford. The next three columns show the results from the "average function" that can be interpreted as the optimal values revealed through the estimation procedure in the absence of precision farming. For example, the optimal nitrogen application rate in Illinois for 1995 was 155.98 pounds/acre using the average price of corn received by farmers in 1995 of $3.09/bushel, and the average price of nitrogen in 1995 of $0.109/pound. The average yield in 1995 was 134.80 bushels per acre generating a return above fertilizer cost of $399.54/acre. The next column provides the gross benefits from farming in the absence of precision technology by farmers in each state (corresponding to B^{NP} from equation (4)).

The optimal quantities of nitrogen and corresponding yields that would have been realized had farmers used variable-rate fertilizer application in 1995 are provided in the next few columns of Table 2. These values were generated by first obtaining estimates for individual farmers, and then aggregating. The optimal quantity of nitrogen applied to the low quality land ranges from 109.94 lbs/acre in Minnesota to 161.39 lbs/acre in Ohio, whereas the optimal quantity of nitrogen applied to the high quality land ranges from 126.34 lbs/acre in Minnesota to 185.76 lbs/acre in Ohio. These values are different from those that existed in the absence of precision technology. The next column provides the

gross benefits to producers in each state from farming using variable-rate precision technology (corresponding to B^{PR} from equation (7)).

The intuition behind the disparity in nitrogen application to the different types of land in Table 2 is illustrated in Figure 1, which compares corn yield as a function of optimal nitrogen use under the average production function, the production function for high-quality sub-plots, and the production function for low-quality sub-plots of land. At the average level of nitrogen in the absence of precision technology (N=155.98 pounds/acre), the marginal physical product of nitrogen along the average Illinois production function is equal to the price ratio. This is the optimal allocation applied by the farmer in the absence of information on land quality within the field. In the absence of this detailed information, the farmer applies the same level of nitrogen to both the low and high quality sub-plots. When this level of nitrogen is applied to the lower quality land, the marginal physical product is actually negative. Hence, applying the same rate of nitrogen as the average production function represents operating the lower quality land in stage III. Similarly, if this level of nitrogen is applied to the high-quality land, the marginal physical product of nitrogen becomes higher than the price ratio. Given additional information regarding the underlying quality of land, the farmer would optimally increase the nitrogen applied to the high quality land and decrease the nitrogen applied to the low quality land.

The increase in revenue that can be attributed to the reallocation of nitrogen across the field due to the availability of precision technology is provided in the last column of Table 2. The values in this column correspond to Λ from equation (8). They indicate the difference in gross benefits between producing corn using variable-rate

technology and producing corn in the absence of variable-rate technology. The value of precision technology under 1995 nitrogen and corn prices ranges from $2.14 per acre in Minnesota to $2.78 per acre in Indiana.

III. The Profitability of Precision Agriculture

The above analysis clearly shows that spatially variable field operations have value because of the more efficient use of inputs in the presence of precision technology. However, the additional value must be weighed against the additional costs associated with investing in the new technology. The use of grid-sampling based variable-rate application technology requires (1) sampling of the soil in a grid pattern to determine the nutrient status of different sub-plots of the field; (2) the chemical assay of the soil; (3) the analysis of the chemical assay; and (4) the cost of the variable-rate application technologies. From a management perspective, the typical approach would involve soil sampling, assay of the sample, and analysis of the assay once every five years. However, the additional cost of variable-rate application technology must be incurred every year.

The typical costs associated with investing in precision technology for fertilizer application to corn production in the mid-west are presented in Table 3. The amortized annual costs range from $5.71 to $7.69 per acre. These estimates imply that, under 1995 nitrogen and corn prices, and assuming an average coefficient of dispersion of 0.2, the use of precision technology for application of nitrogen would not have been profitable in the mid-western states in 1995. Referring back to Table 2, the average value of precision technology ranges from $2.14/acre in Minnesota to $2.78/acre in Indiana. This is much lower than the estimated associated costs.

Our analysis has been highly stylized and is dependent on the range of soil dispersion based on previously published research. Specifically, it represents an upper estimate of the value of precision technology, given an average coefficient of dispersion of 0.2. In order to provide evidence that these results are robust, we examine the sensitivity of our results to the following factors: (1) functional form; (2) input and output prices; (3) dispersion of soil types; and (4) the accuracy of precision technology.

1. Sensitivity to the Choice of Functional Form

The results of the forgoing analysis depend on the functional form of the primal production function. For our purposes, we used the Zellner function, which has the traditional shape associated with a three-stage production function. There are a plethora of applied production functions that we could have chosen instead of the Zellner specification. In order to provide evidence of robustness to functional form, we re-estimated the entire model using the Cobb-Douglas production function:

$$f(x_1, x_2, x_3) = x_1^{\alpha} x_2^{\beta} x_3^{\gamma}$$

where x_1 is nitrogen in pounds per acre, x_2 is phosphorous, x_3 is potassium and α, β, and γ are estimated parameters. We further simplify the analysis by assuming that the levels of phosphorous and potassium are held constant, so that:

$$f(x_1) = Ax_1^{\alpha}$$

We then solved for the parameters A and α which approximate the Zellner function at the optimizing level of nitrogen. As with the Zellner production function, we then construct two production functions

$$f_1(x_1) = A\left(1 - \mu/2\right)x_1^{\alpha\left(1-\mu/2\right)}$$
$$f_2(x_2) = A\left(1 + \mu/2\right)x_1^{\alpha\left(1+\mu/2\right)}$$

where μ is selected to yield a coefficient of variation for yields of 20 percent. The parameters are estimated simultaneously and it is again assumed that the field is divided into two sub-plots of equal size.

The value of the parameters *A* and α for the Cobb-Douglas approximation are provided in Table 4. Also included in Table 4 are the μ required to generate a coefficient of variation in yields of 0.2, the optimal levels of nitrogen for each land type, the gross benefit of variable-rate fertilizer application, and the value of precision agriculture. Comparing these results with those provided in Table 2, indicates that precision agriculture would be even less profitable if the underlying production functions were more closely approximated by the Cobb-Douglas specification. On average, the value of precision agriculture for the Cobb-Douglas specification is 45 percent of the value under the original Zellner function. The smaller value of precision agriculture can be attributed to the relative flatness of the Cobb-Douglas function and lack of a stage III.

The linear response plateau production function is another alternative functional form. This function has a constant marginal product of nitrogen below some plateau level of production, and a constant level of total physical product above the plateau. The optimal decision under this production function would be to apply nitrogen at a rate sufficient to obtain the plateau if the marginal physical product of nitrogen along the linear response path is greater than the ratio of the price of nitrogen to the price of corn. Parameterization of this production function within our current formulation would

depend on the determination of the linear response coefficient and the production plateau. It is expected that the value of precision farming under the linear response plateau function would be somewhat higher than the value generated by continuously differentiable functions typically used in production analysis.

2. Input and Output Prices

The value of precision farming is sensitive to the relative price of the output with respect to the price of the input. For this reason, precision technology would be much more promising when applied to higher-valued crops. Of course, if the price of corn were high enough when compared to the price of nitrogen, variable-rate fertilizer application would become profitable. Evidence regarding the sensitivity of the value of precision technology to changes in relative prices are provided in Table 5.

The values of precision agriculture presented in Table 5 are derived assuming that the price of nitrogen remains constant, while the price of corn changes. The value of precision agriculture increases with an increase in the price of corn. This result is driven by the fact that the allocation of the marginal unit of nitrogen between land types becomes more important as the value of higher yields increases. This result also implies that the value of precision agriculture declines as the price of nitrogen increases with the price of corn. The value of precision farming is asymmetric around the point of maximum physical product in the lower quality land. This result begs the question as to whether precision farming would lead to less input use. In this case, the use of nitrogen will be lower under precision farming so that additional benefits from the reduction in non-point pollution will be realized.[6]

3. Dispersion of Soil Types

The value of variable rate application of fertilizer is affected by the observed variability in yield. Within our framework, variability in yield arises from the variability in soil quality through v_2 in equation (9). Wollenhaupt, Mulla, and Crawford suggested that the range of variability in yields among different sub-plots of a field range from between 8 and 29 percent for corn producers. The sensitivity of the estimates of the value of precision agriculture to a wide range of soil variation in each state are presented in Table 6. Consistent with intuition, the value of precision agriculture increases with the dispersion of soil types. At the highest realistic level of soil dispersion (0.29 coefficient of variation) the value of precision for a farmer in Indiana is $5.77 per acre which is slightly higher than the lowest estimate of the additional annual cost attributed to variable-rate application of fertilizer in corn production ($5.71 per acre from Table 3).

Another dimension of the dispersion of soil types can be observed by varying the percent of low productivity land. The variance of yields across land types is a quadratic function of the percentage of low quality land. Figure 2 depicts the value of variable rate technology for Illinois for different percentages of low quality land. As would be expected given the results in Table 6, the value of precision agriculture takes on a quadratic shape consistent with the quadratic shape of the variance. This reiterates the point that if the percentage of low quality land is small, the gain to differential application of fertilizer on the low quality land is small. Similarly, if the percent of high quality land is small, the gain to applying more fertilizer on the high quality land is small.

4. Accuracy of Precision Technology

The forgoing analysis assumes that precision technology can provide perfect information regarding the composition of the underlying quality of the land. However, in practice this is not the case. The soil sampling and classification process can generate inaccurate results. The machinery used for variable-rate application of the inputs may also be inaccurate. There are several ways that one could potentially incorporate erroneous classification and erroneous variable-rate application into the analysis. Intuitively, however, any inaccuracies inherent in the technology would simply reduce the estimates of the value of precision farming provided in Tables 2 through 6. Considering that none of the previous results show a significant positive value of variable-rate fertilizer application to corn fields in the mid-western U.S., the introduction of technological inaccuracies would only serve to decrease these values further.

IV. CONCLUSIONS AND LIMITATIONS

This paper provides a methodology that can be used to weigh the costs and benefits of precision agriculture in the measurement and application of variable-rate production technology. Empirical estimates of the economic value of precision farming in the form of variable-rate fertilizer application to corn fields in the mid-western United States were calculated and compared to the current cost of investing in this technology. The results of this study indicate that the use of precision technology in the application of nitrogen for corn production in the United States has an associated average value ranging anywhere from $1.02 per acre to $5.77 per acre. The costs associated with investing in this technology range from $5.71 per acre to $7.69 per acre. Hence, for the average farm

in the mid-western United States, investing in precision technology for the sole purpose of variable-rate fertilizer application in corn production is not profitable over a relatively wide range of corn prices, nitrogen prices, and agronomic differences in soil characteristics.

Schnitkey, Hopkins, and Tweeten found that the value of precision fertilizer application to corn-soybean fields is approximately $3.28 per acre. In our analysis, a coefficient of variation of between 20 and 25 percent, associated with differences in the underlying soil characteristics of a particular field, would generate a value close to that found by Schnitkey, Hopkins, and Tweeten (assuming that the technology is 100% accurate). Wollenhaupt, Mulla, and Crawford found that crop yields have a coefficient of variation in the range of 8 to 29 percent across different portions of fields in the United States. Our estimates, though slightly lower than Schnitkey et al. on average, are reasonably consistent with these previous findings.

The economic analysis of any precision technology is sensitive to many factors. These include the specification of functional form for the production functions associated with the underlying land types, the prices of inputs and outputs, the distribution of soil types, relative differences in soil productivity, and the degree of accuracy associated with classification and variable-input application. Moreover, random natural events, particularly weather, have a significant effect on the reliability of estimates associated with any empirical study that approximates an underlying production process. In the future, the method of analysis used in this study could be expanded by formulating a number of different probability distributions around a number of different factors and incorporating them into the analysis. However, the results of the analysis in this paper

provide strong evidence that the use of precision agriculture solely for the purpose of variable-rate fertilizer application to corn production in the mid-western United States is not economically viable.

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Table 1. Semiparametric Estimates of the Zellner Production Function

State	Observations	Bandwidth	a	b
Illinois	142	.4674	.0005433	.01794
			(.0008681)*	(.009046)
Indiana	82	.4017	.001029	.02162
			(.002217)	(.01419)
Iowa	282	3.1033	.0008637	.02093
			(.001828)	(.01458)
Michigan	42	6.1303	.0006728	.01918
			(.001019)	(.009507)
Minnesota	102	13.3870	.001214	.02356
			(.002207)	(.01359)
Ohio	56	1.6869	.0004016	.01597
			(.0007015)	(.008978)

*Numbers in parenthesis denote standard deviations

Note: all estimates assume a coefficient of variation of 0.2

Table 2. Value of Precision Farming by State[a]

					Precision Agriculture					
		Average Function			Low Quality Land		High Quality Land			Value of Precision Ag
	μ	Nitrogen	Yield	Gross Benefit	Nitrogen	Yield	Nitrogen	Yield	Gross Benefit	
Illinois	0.1355	155.98	134.80	399.54	143.82	108.31	165.48	161.77	401.99	2.44
Indiana	0.1350	130.05	145.89	471.64	120.04	117.34	137.86	175.07	474.42	2.78
Iowa	0.1353	133.93	134.96	384.88	123.54	108.48	142.05	161.96	387.21	2.32
Michigan	0.1355	145.99	136.61	389.81	134.63	109.78	154.87	163.93	392.19	2.37
Minnesota	0.1352	119.15	133.00	358.80	109.94	106.93	126.34	159.60	360.94	2.14
Ohio	0.1356	175.07	141.25	425.86	161.39	113.48	185.76	169.51	428.49	2.62

[a]Corn prices from the USDA's *Agricultural Prices* (1998) were $3.09/bushel for Illinois, $3.33/bushel for Indiana, $2.96/bushel in Iowa, $2.97/bushel in Michigan, $2.79/bushel in Minnesota, and $3.15/bushel in Ohio. The price of Nitrogen was $218/ton for all states except Minnesota which was $206/ton.

Table 3. Marginal Cost of Variable Rate Nitrogen Application[a]

Additional Cost	Amount per Acre	Cost Amortized over 5 Years[b]
Grid Sampling	$3.00-$10.00	$.79-$2.64
Soil Assay	$3.00	$.79
Computer Mapping	$.50-$1.00	$.13-$.26
Variable Rate Application	$4.00	$4.00
Annual Cost of VRT		$5.71-$7.69

[a]The estimated cost of precision agriculture were obtained from Nyle Wollenhaupt at Ag-Chem Equipment Company.
[b]The annual cost for grid sampling, soil assay, and computer mapping assume a five year use of a single map and a .10 interest rate.

Table 4: Value of Precision Agriculture Under Cobb-Douglas Specification

	A	α	μ	N_1	N_2	Gross Benefits	Value
Illinois	109.69	0.0408	0.33312	103.232	223.474	403.358	1.186
Indiana	126.57	0.0292	0.35145	85.313	186.612	474.956	1.024
Iowa	112.84	0.0365	0.34064	88.303	192.053	388.189	1.034
Michigan	112.36	0.0392	0.33603	96.476	209.239	393.406	1.117
Minnesota	113.55	0.0331	0.34666	78.321	170.970	361.589	0.879
Ohio	113.18	0.0429	0.32899	116.117	250.668	430.153	1.320

Table 5. Value of Precision Agriculture Under Differing Corn Prices

	Corn Price ($/bushel)									
	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50
Illinois	1.07	1.26	1.45	1.63	1.82	2.01	2.20	2.40	2.59	2.79
Indiana	1.12	1.32	1.52	1.72	1.92	2.12	2.32	2.53	2.73	2.94
Iowa	1.05	1.24	1.42	1.61	1.80	1.99	2.18	2.37	2.56	2.75
Michigan	1.08	1.26	1.45	1.64	1.83	2.02	2.22	2.41	2.61	2.81
Minnesota	1.02	1.20	1.38	1.56	1.75	1.93	2.12	2.31	2.49	2.68
Ohio	1.14	1.33	1.53	1.72	1.92	2.12	2.33	2.53	2.74	2.94

Table 6. Value of Precision Agriculture at Various Coefficients of Variation

	Coefficients of Variation				
	0.08	0.15	0.20	0.25	0.29
Illinois	0.39	1.38	2.44	3.80	5.08
Indiana	0.45	1.57	2.78	4.32	5.77
Iowa	0.38	1.31	2.32	3.61	4.83
Michigan	0.38	1.34	2.37	3.69	4.93
Minnesota	0.35	1.21	2.14	3.33	4.45
Ohio	0.42	1.48	2.62	4.07	5.45

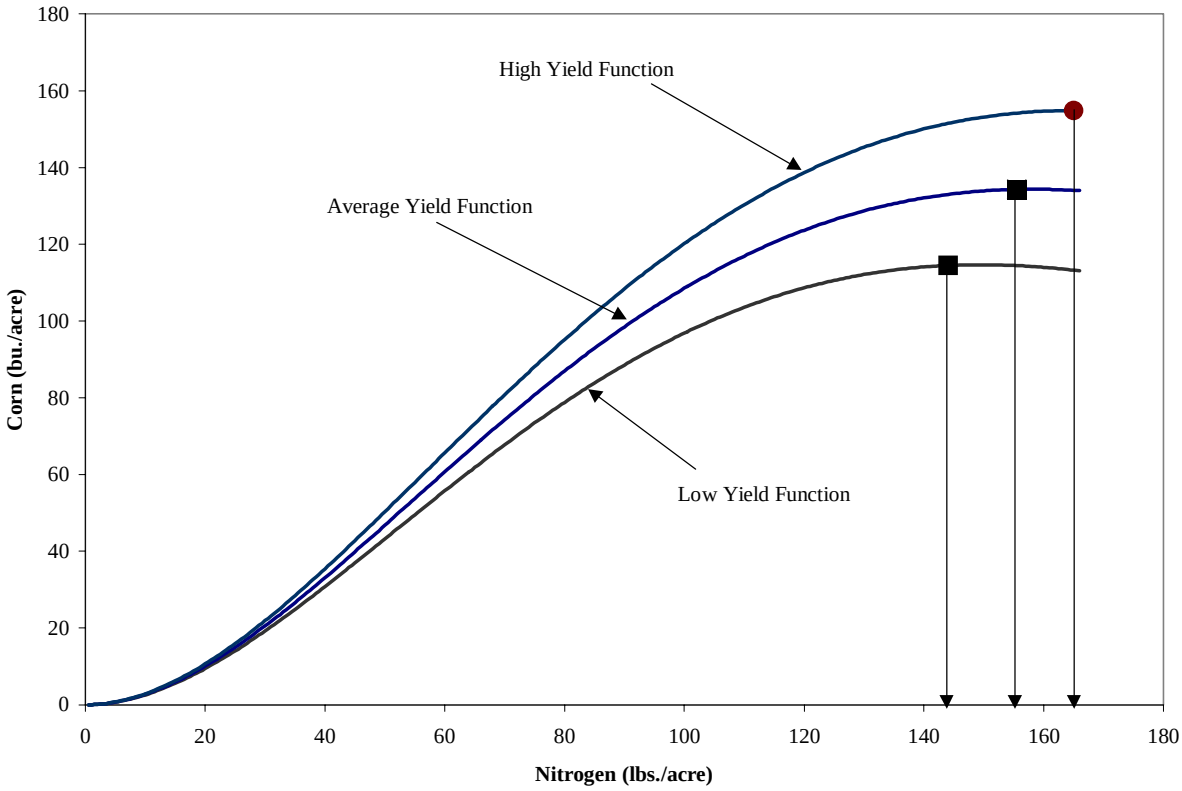

Figure 1. Corn Yield as a Function of Nitrogen for Different Land Types

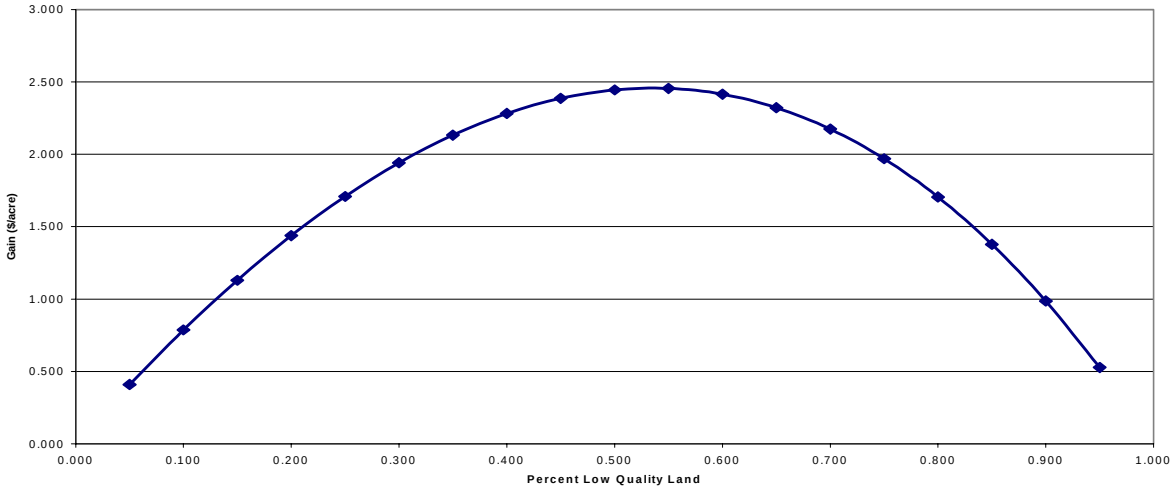

Figure 2. Gains to Variable Rate Nitrogen Application for Alternative Shares of Low Quality Land

ENDNOTES

[1] Nonpoint pollution control is among the list of non-economic benefits associated with the variable-rate application of chemical inputs. Examples include contaminated water supplies from chemical run-offs and the externalities associated with air-borne herbicides and pesticides. However, these issues are beyond the scope of this paper. We refer the interested reader to Khanna and Zilberman.

[2] Some empirical studies of nitrogen application suggest that stage 3 does not exist. While stage 3 is usually not reached in practice due to economic considerations, it is still technologically feasible. Moreover, in section 3.1 we provide empirical results for the Cobb-Douglas specification, a function that has only 2 stages.

[3] It can be shown that the marginal product of v_2 is positive and that the marginal product of v_1 is increasing in v_2 across the relevant range of production. Further, the total physical product with respect to v_1 yields all three stages of production.

[4] Schueller develops five considerations that could significantly alter the value of precision farming: Weather effects, crop production management, time demands, agronomy, and operational accuracy. With regard to weather he states: "It must be remembered that weather is almost the overriding factor in crop production. Time history of rainfall and temperature will affect the production more than anything which can be controlled in a spatially-variable manner."

[5] In order to test this hypothesis, a limited number of simulations were conducted that involved dividing a field up into an increasing number of sub-plots and re-estimating

the model. The fields were divided up so that they were all mean-variance equivalent distributions. In all of the cases we tested, the largest difference between the estimated value of precision agriculture obtained by dividing the field in half, and using mean-variance equivalent distributions was under .01 percent.

[6] In general, the concavity of the production function around the point of optimality is sufficient to guarantee that the overall level of nitrogen applied to the entire field under precision farming will be lower than the overall level of nitrogen in the absence of precision farming.