Kapitel 9

Chapter 9

Ökonomie und Betriebsorganisation

Economy and company organization

9.1 A Test of within Field Variation of Corn Response to Nitrogen in Central Minnesota

Terrance M. Hurley, Assistant Professor, Department of Applied Economics
Gary Malzer, Professor, Department of Soil, Water and Climate University of Minnesota
Bernard Kilian, University Hohenheim, Germany

9.1.1 Abstract

The purpose of this paper is to test within field variation in corn response to nitrogen for two fields in south central Minnesota in 1995. After confirming within field variation, the implications of this variation are estimated. The results suggest that variable rate nitrogen applications would have resulted in an increase in net returns ranging from 25 $/ha to 68 $/ha when compared to a uniform nitrogen application rate based on university recommendations. However, the average amount of nitrogen applied would also be higher. The environmental implications of higher average nitrogen applications are unclear because for some regions of the field the university recommendation exceeds the estimated optimal variable rate.

9.1.2 Introduction

The precision agriculture paradigm is based on the premise that there is within field variation in crop response that can be managed to the benefit of farmers or the environment. The inherent difficulties of collecting, analyzing, and interpreting appropriate data make support for this assertion tenuous.

Two approaches for testing the premise of precision agriculture in crop production dominate the literature. The first seeks to make direct comparisons between fields managed uniformly with those managed variably in response to factors such as soil properties, past yields, or current crop condition (Mulla et al., 1992; Ferguson et al., 1997; Haahr et al., 1999; Welsh et al., 1999; and Schawarz et al., 2001). The results in general do not indicate a substantial benefit to managing within field variability. However, the results depend on the management rules used to respond to within field variation. To the extent that these management rules are not optimal, the results can mask the potential benefits of precision agriculture.

The second approach addresses the concern of comparing sub-optimal within field management to uniform management by estimating crop response functions for different regions within a field (Bruulsema et al., 1996; Davis et al., 1996; Malzer et al. 1996; Peters et al., 1999; and Gooding et al., 1999). These crop response functions can be used to find the optimal within field management strategy ex post. The predicted outcome of this optimal within field management strategy can then be compared to an optimal or typical uniform management strategy in order to assess the potential benefit of precision agriculture. If this potential benefit is small, implementing precision agriculture will likely be cost prohibitive.

The purpose of this paper is to test for within field variation in corn response to nitrogen for two fields in south central Minnesota in 1995. After confirming the presence of within field variation, the potential value of managing this variation is calculated by comparing optimal within field management to an optimal and typical uniform management strategy. The value of within field management is compared based on net economic returns and the average, under, and over supply of nitrogen when compared to the estimated optimal variable application rate.

We find that managing the variation in corn response to nitrogen would result in an estimated increase in net returns ranging from about 25 $/ha to 68 $/ha when compared to managing the fields uniformly following university recommendations. Average nitrogen applications would be lower under university recommendations, but would exceed the estimated optimal variable rate application for some parts of the field, so the environmental implications of this result are unclear.

9.1.3 Methods

Experimental

Data was collected in 1995 at fields in Hanska and Morgan, Minnesota. The section of field used for each experiment was 164.2 meters in width and 274 meters in length. Each field was first divided into six approximately 27 meter wide blocks that ran the length of the field (s. Fig. 9.1-1). Each block was further divided into six approximately 4.6 meter wide strips that also ran the length of the field (s. Fig. 9.1-2). One of six nitrogen treatment rates (0, 68, 102, 136, 170 and 204 kg/ha) was applied to each strip in a block in random order, such that each treatment was replicated six times, once in each block. Blocks and strips were divided into 17 segments of approximately 16 meters in length (s. Fig. 9.1-1). Yield measurements were taken for each segment and strip combination resulting 612 observations per field or 1224 total observations for the experiment. The layout of blocks, strips, and segments was identical for both fields. Complete details of the experimental design are reported in Dikici (2000).

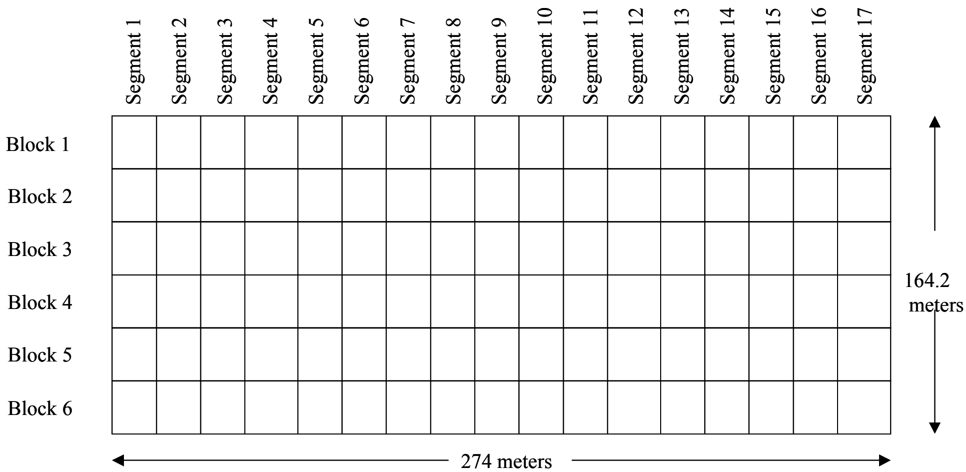

Fig. 9.1-1: Layout of blocks and segments in a field.

Strip 1	**Nitrogen = 170 kg/ha**
Strip 2	**Nitrogen = 0 kg/ha**
Strip 3	**Nitrogen = 136 kg/ha**
Strip 4	**Nitrogen = 68 kg/ha**
Strip 5	**Nitrogen = 204 kg/ha**
Strip 6	**Nitrogen = 102 kg/ha**

Note: 6 blocks × 6 strips = 36 strips in total. Strip treatments were randomized by block.

Fig. 9.1-2: Example of the layout of treatment strips within a block.

Empirical

A quadratic yield response function is used for the analysis based on a second order Taylor series approximation to the general relationship between yield and applied nitrogen. Specifically,

(1) $$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + \varepsilon_i$$

where y_i is the ith observed yield normalized by subtracting the field mean and dividing by the field standard deviation; x_i is the amount of nitrogen applied; ε_i is a mean 0 and variance σ^2 error; and β_0, β_1, and β_2 are the constant, linear, and quadratic response coefficients.

Consider a partition of the observations into R subsets, such that equation (1) is now:

(2) $$y_{ir} = \beta_{0r} + \beta_{1r} x_{ir} + \beta_{2r} x_{ir}^2 + \varepsilon_{ir}$$

for $r \in \{1,\ldots,R\}$. While equation (1) is used to estimate yield response to nitrogen for all observations taken as a whole, equation (2) is used to estimate a potentially different yield response to nitrogen for each subset of observations in R. Consider the hypothesis $\beta_0 = \beta_{0r}$, $\beta_1 = \beta_{1r}$, $\beta_2 = \beta_{2r}$, and $\sigma^2 = \sigma_r^2$ for all $r \in \{1,\ldots,R\}$, which implies equation (1) is identical to equation (2). This hypothesis can be tested by estimating equations (1) and (2) using maximum likelihood and comparing the maximized value of the likelihood functions with the likelihood ratio statistic. If the distribution of error is appropriately specified, this statistic will be distributed χ^2 with the degrees of freedom equal to the difference in the number of parameters estimated for each model.

This procedure can be generalized by partitioning r into subsets for all $r \in \{1,\ldots,R\}$ resulting in R' ($> R$) subsets of the observations and

(3) $$y_{ir'} = \beta_{0r'} + \beta_{1r} x_{ir'} + \beta_{2r} x_{ir'}^2 + \varepsilon_{ir'}$$

for $r' \in \{1,\ldots,R'\}$. The hypothesis of interest is now $\beta_{0r} = \beta_{0r'}$, $\beta_{1r} = \beta_{1r'}$, $\beta_{2r} = \beta_{2r'}$, and $\sigma_r^2 = \sigma_{r'}^2$ for all $r' \in r$ and $r \in \{1,\ldots,R\}$, which implies equation (2) is identical to equation (3). Again, the likelihood ratio statistic can be used to test the significance of this hypothesis.

To test for between field and within field variation in yield response to nitrogen, we first estimated equation (1). We then partition observations by field and estimate equation (2). Next, we estimated equation (3) with partitions of each field into 6, 12, and 48 subsets. These partitions are nested as described above so they can be compared using the likelihood ratio statistic. Partitions were constructed spatially, by dividing the observations from the field into smaller and smaller contiguous regions of similar length and width.

Before estimating equations (1) - (3) using maximum likelihood, an appropriate distribution for the error needs to be specified. Two important issues emerge when specifying this distribution. First, differences in soil type, landscape, climate, and other factors can result in correlation between errors. However, under the null hypothesis of no within region variation, this correlation should be of little concern. So if we cannot reject our hypothesis, we should not be too concerned about correlation in the errors.

Second, the experimental design did not randomize treatments within strips. Therefore, observations within a strip are always adjacent to observations that had the same treatment applied. For example, in Figure 2, observations from strip 3 are always next to the 0 and 66 kg/ha treatments. This raises a concern that the experimental design could influence the distribution of errors. Having the identical experimental design at Hanska and Morgan, afford us the opportunity to address this concern by we incorporating strip effects into equations (1)-(3). Specifically, for equation (1) we treat the error as normally distributed with mean 0 and variance equal to $\sigma^2\sigma_s^2$ where s indicates the strip from which the yield is observed. For equations (2) and (3), the variance is $\sigma_r^2\sigma_s^2$ and $\sigma_{r'}^2\sigma_s^2$. We can test for the presence of strip effects by using the likelihood ratio statistic to compare models with and without ($\sigma_s^2 = 1$) these effects.

The expected net return is defined as

(5) $$\pi = P_y(\sigma_y(\beta_0' + \beta_1'x + \beta_2'x^2) - \mu_y) - P_x x$$

where P_y is the price of corn; σ_y is the standard deviation of yield; β_0', β_1', and β_2' are estimated response coefficients from equations (1) – (3); x is applied nitrogen; μ_y is average yield; and P_x is the price of nitrogen. Given the estimated response coefficients, the expected net return is maximized when

(6) $$x = \frac{\dfrac{P_x}{P_y\sigma_y} - \beta_1'}{2\beta_2'}$$

assuming $\beta_2' < 0$. We use equation (6) to calculate the optimal nitrogen rate when $\beta_2' < 0$ with the caveat that it is constrained between 0 and 204 kg/ha to avoid predicting outside the range of the treatment variable. When $\beta_2' < 0$, the optimal rate is set to either 0 or 204 kg/ha depending on which results in the highest net return.

For the optimal uniform management strategy, we use equation (6) with the coefficient estimates from equation (1). For the optimal within field management strategy, we use the coefficient estimates from equation (3) using the partition that fits the data the best. In both instances, net returns are predicted using equation (5) and coefficient estimates from equation (3) using the partition that fits the data the best.

9.1.4 Results

Table 9.1-1 reports the maximized log-likelihood and number of parameters estimated for five different models with and without strip effects.[1] The likelihood ratio statistic for comparing various models is also reported along with the degrees of freedom.

[1] Due to the proliferation of parameters in the various models, individual parameter estimates are not reported. The authors will gladly make all unreported regression results available to interested parties on request.

Tab. 9.1-1: Test of within field variation and strip effects.

Partitions		**No Strip Effects**	**Strip Effects**		**Test For Strip Effects:**
					χ^2 *Degrees of Freedom*
1[a]	Log-Likelihood	-1490.34	-1329.69		321.30[f]
	Parameters	3	38		35
2[b]	Log-Likelihood	-1446.98	-1305.89		282.18[f]
	Parameters	7	42		35
12[c]	Log-Likelihood	-1212.23	-1100.78		222.90[f]
	Parameters	47	81		34
24[d]	Log-Likelihood	-1025.15	-959.28		131.75[f]
	Parameters	95	128		33
96[e]	Log-Likelihood	-601.53	-524.82		153.42[f]
	Parameters	383	413		30
	Comparison	**Test of Homogeneity Within Regions**			
	1 vs 2	86.72[f]	47.60[f]		
		4	4		
	2 vs 12	469.50[f]	410.22[f]		
		40	39		
	12 vs 24	374.16[f]	283.01[f]		
		48	47		
	24 vs 96	847.25[f]	868.92[f]		
		288	285		

[a]Yield response to nitrogen estimated for Hanska and Morgan fields combined. [b]Yield response to nitrogen estimated for Hanska and Morgan fields separately. [c]Yield response to nitrogen estimated for 6 different regions within Hanska and Morgan fields. [d]Yield response to nitrogen estimated for 12 different regions within Hanska and Morgan fields. [e]Yield response to nitrogen estimated for 48 different regions within Hanska and Morgan fields. [f]Significant at one-percent.

The first model with one partition estimates yield response to nitrogen pooling the data from both fields together. Comparing the model with and without strip effects results in the likelihood ratio statistic χ^2 = 321.30 with 35 degrees of freedom, which is significant at one-percent. A similar result is found when comparing each of the five models with and without strip effects. Therefore, we can reject the hypothesis of no strip effects. The experimental design did have a significant influence on the variance of the errors. Failing to account for this influence can result in less efficient parameter estimates.

The second model with 2 partitions estimates separate yield response functions for Hanska and Morgan. Comparing this model to the first model both with strip effects results in the likelihood ratio statistic χ^2 = 47.60 with 4 degrees of freedom, which is significant at one-percent. Therefore, we can reject the hypothesis that yield response to nitrogen was the same in the Hanska and Morgan fields.

The third model divides each field into 6 contiguous and similar sized regions resulting in a total of 12 different partitions. The fourth divides each field into 12 contiguous and similar sized regions resulting in 24 partitions, while the fifth divides each field into 48 contiguous and similar sized regions resulting in 96 partitions. Again, these partitions are appropriately nested, so we can use the likelihood ratio statistic to compare any two models. The likelihood ratio statistics comparing the second and third, third and fourth, and fourth and fifth

models are all significant at one-percent. Therefore, we can reject the hypothesis that the 6 and 12 regions in each field are homogeneous for the third and fourth model. That is, there is statistically significant within field variation in yield response to nitrogen.
The limited number of observations in the data set does not allow the model with strip effects to be estimated when each field is divided into more than 48 contiguous regions. Since the hypothesis cannot be rejected when comparing the fourth and fifth model, there is reason to be concerned with correlation in the errors. To explore this concern, semi-variograms were estimated using the models' residual errors. With 1 partition the semi-variograms indicated strong spatial correlation in the residual errors. As the number of partitions increased, the degree spatial correlation decreased, but was not completely eliminated, which suggests there is significant variation even within the 96 partitions. It also suggests that the estimates could be improved by modeling the errors as being spatially correlated.

To understand the economic and environmental significance of this within field variation, Table 9.1-2 reports a comparison of optimal within field management calculated using selected models and the University of Minnesota recommendation for a uniform application rate (125 kg/ha). The price of corn used for the analysis is 2.10 $/bu, while the price of nitrogen is 0.44 $/kg. In all cases, yields are calculated using the model with 96 partitions and strip effects since it fits the data the best. In addition to reporting average net returns, we also report the average nitrogen application and the average nitrogen application under and over of the optimum nitrogen application calculated using the best fitting model.

Tab. 9.1-2:

Nitrogen Recommendation	**Net Return**	**Average**	**Nitrogen Under**[a]	**Over**[b]
	$/ha	*kg/ha*		
Both Fields				
University	707.34	124.7	41.5	5.1
1 (Strip Effects)	726.88	169.9	12.5	21.3
2 (Strip Effects)	733.49	170.2	10.5	19.6
12 (Strip Effects)	741.07	172.9	7.1	18.9
24 (Strip Effects)	745.18	167.8	7.4	14.0
96 (No Strip Effects)	749.87	162.8	6.5	8.1
96 (Strip Effects)	753.03	161.1	0.0	0.0
Hanska				
University	689.40	124.7	27.7	5.1
1 (Strip Effects)	690.90	165.4	9.3	21.3
2 (Strip Effects)	692.71	136.4	21.1	19.6
12 (Strip Effects)	703.17	152.6	11.0	18.9
24 (Strip Effects)	708.43	144.8	11.6	14.0
96 (No Strip Effects)	712.66	146.7	5.4	8.1
96 (Strip Effects)	714.53	148.7	0.0	0.0
Morgan				
University	732.75	124.74	55.4	6.5
1 (Strip Effects)	770.71	174.40	15.8	16.6
2 (Strip Effects)	782.19	204.12	0.0	30.5
12 (Strip Effects)	786.97	193.19	3.3	22.9
24 (Strip Effects)	789.96	190.78	3.2	20.4
96 (No Strip Effects)	795.13	178.83	7.6	12.8
96 (Strip Effects)	799.60	173.63	0.0	0.0

Note: Yields for all recommendations were predicted using the model with 96 partitions and strip effects.
[a]Average kg/ha of nitrogen under the optimum with 96 partitions and strip effects.
[b]Average kg/ha of nitrogen over the optimum with 96 partitions and strip effects.

Compared to the University recommendation, our best estimate indicates the potential for a 45.69 $/ha higher return from varying nitrogen applications within a field. For Hanska, a 25.13 $/ha higher return is found, while a 60.85 $/ha higher return is found for Morgan. Compared to the optimum uniform rate (1 partition with strip effects), the net return for the best estimate of the optimum variable rate is 26.15 $/ha higher overall, 23.63 $/ha higher for Hanska, and 28.89 $/ha higher for Morgan.

Figure 9.1-3 shows the percentage of potential returns (the difference in return between recommendations based on the models with 1 and 96 partitions and strip effects) captured as the number of partitions used to obtain an optimal recommendation is increased. Separating the two fields to estimate yield response captures about 25 percent of the potential value overall, nearly 40 percent for Morgan, but only 8 percent for Hanska. Regardless, customizing the recommendation to the field captures less than 50 percent of the best estimate of the potential return. Varying nitrogen application within the fields is responsible for more than 50 percent of the potential increase in returns.

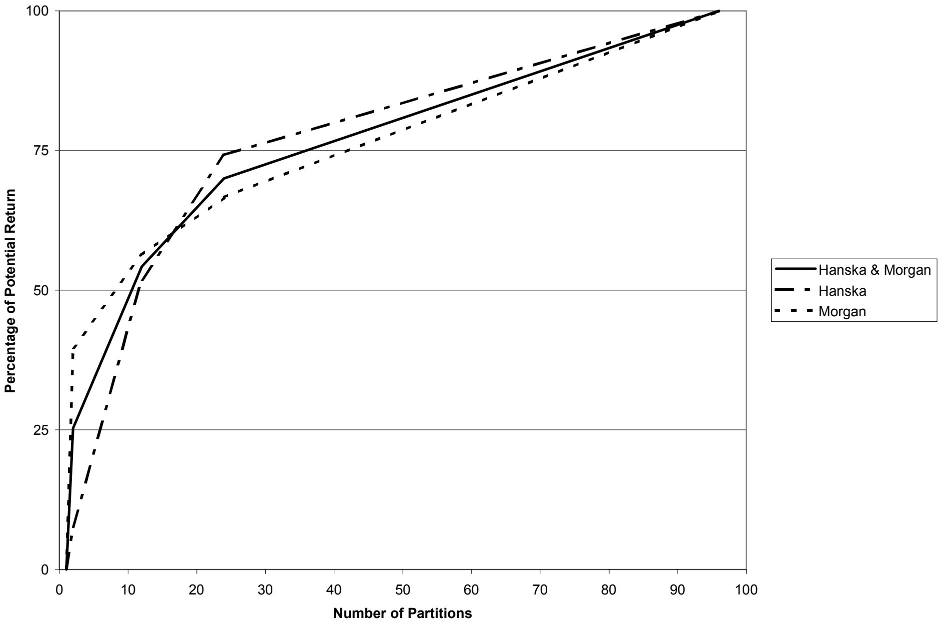

Fig. 9.1-3: Percentage of potential returns captured by the number of field partitions.

Accounting for strip effects increases the estimate of potential returns by 3.16 $/ha overall, 1.87 $/ha in Hanska and 4.48 $/ha in Morgan, which ranges from 8 to 15 percent of the potential increase in returns.

Comparing average nitrogen application rates indicates that University recommendations are lower than what is optimal for both Hanska and Morgan. Even though these recommendations range from 16 to 28 percent lower than the best estimate of the average optimal rate, there are still portions of each field that would receive more than the optimal nitrogen rate.

9.1.5 Discussion and Conclusions

Hanska and Morgan exhibited significant within field variability in corn response to nitrogen in 1995. Had this variability been optimally managed we estimate that returns would be more than 45 $/ha higher than if farmers followed university recommendations. Managing within field variation optimally instead of following the university recommendation would also have increased the amount of nitrogen applied. Whether or not an increase in nitrogen would have result in negative environmental effects depends on how much of the additional nitrogen the crop utilized. Even with a lower average application rate, the university recommendation would have resulted in higher nitrogen applications in some parts of the fields. Therefore, it is not clear that the university recommendation would have had less of an environmental impact.

Estimating the potential value of precision agriculture to farmers and the environment is just one piece of an important puzzle. How farmers and the environment can realize this value is another. Variability in crop response to management can be attributed to variations in soil, landscape, climate, and many other factors. Further research is needed to identify which factors are most important and cost effective for taking advantage of this variability. Detailed plot experiments like the one analyzed here, are an important source of information, but high costs are limiting. Farmers however produce mountains of data every year. Learning how to harvest and process this data effectively may be the key to understanding the full potential of precision agriculture.

The strategy proposed in this paper can be applied to this type of observational data from farm fields as well as experimental data used herein. The strategy could also be improved by using more than just information on yields and nitrogen application rates. For example, soil test, topographical, and remotely sensed information can be incorporated into the model. The model can then be used to determine which pieces of ancillary information are most important.

9.1.6 References

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