STAFF PAPER

Site-specific Versus Whole-field Fertility and Lime Management in Michigan Soybeans and Corn

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ABSTRACT

Prior research into variable-rate application (VRA) of fertilizer nutrients has found profitability to be lacking in single nutrient applications to U.S. cereal crops. This study examines the yield and cost effects of VRA phosphorus, potassium and lime application on Michigan corn and soybean farm fields in 1998-2001. After four years, we found no yield gain from site-specific management, but statistically significant added costs, resulting in no gain in profitability. Contrary to results elsewhere, there was no evidence of enhanced spatial yield stability due to site-specific fertility management. Likewise, there was no evidence of decreased variability of phosphorus, potassium or lime after VRA treatment. Site-specific response functions and yield goals might also enhance the likelihood of profitable VRA in the future.

Keywords: Precision agriculture, variable rate application, phosphorus, potassium, lime, profitability, variable cost, yield, corn, soybean

39 pages

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INTRODUCTION

Variable rate application (VRA) of phosphorus (P) and potassium (K) fertilizers on cereal crops in the United States has been marked by uneven profitability. In a review of nine university studies Swinton and Lowenberg-DeBoer (1998) found that after imposing standard minimum information and application cost assumptions, VRA's added benefits failed to cover the added costs in half the reported experiments in corn-soybean systems and all experiments in wheat and barley systems. They cited several possible reasons for the unprofitability of VRA in these crops. Since VRA increases fixed information and application costs for a given field, in order to be profitable it must provide compensating input savings or yield gains. Most early VRA experiments applied a single nutrient, meaning that the entire information cost of soil testing and mapping had to be paid back from the variable-rate management of a single input. If the information investment were spread among multiple inputs, then there would exist multiple opportunities for input cost savings and multiple biological avenues to achieve yield gains. Given that lime VRA has shown stand-alone profitability in Midwestern corn (Bongiovanni and Lowenberg-DeBoer, 2000), the inclusion of lime might be especially helpful to improving net returns from this new technology. Apart from profitability, VRA fertilization with P and K has also shown modest potential for reducing spatial yield variability in Indiana corn (Lowenberg-DeBoer and Aghib, 1999).

In order to explore the potential for profitability and enhanced yield stability from VRA of multiple fertility inputs, we conducted this on-farm research into corn and soybean production under Michigan growing conditions. The general objective was to compare variable rate application of P, K and lime with whole field application. Comparative analysis of site-specific management (SSM) and conventional whole-field fertility management (WFM) was undertaken on working farms with randomized treatments in farmer-managed fields. This report updates and completes preliminary findings reported in 2000 (Swinton et al., 2000).

MATERIALS AND METHODS

In the early spring of 1998, two cooperating farmers in eastern Michigan each donated the use of two 16.2 ha fields. At each site, one field was planted to corn and one to soybeans in 1998. In 1999, the 1998 corn fields were planted to soybeans and the 1998 soybean fields were planted to corn. Historical details for the four fields are found in Table 1.

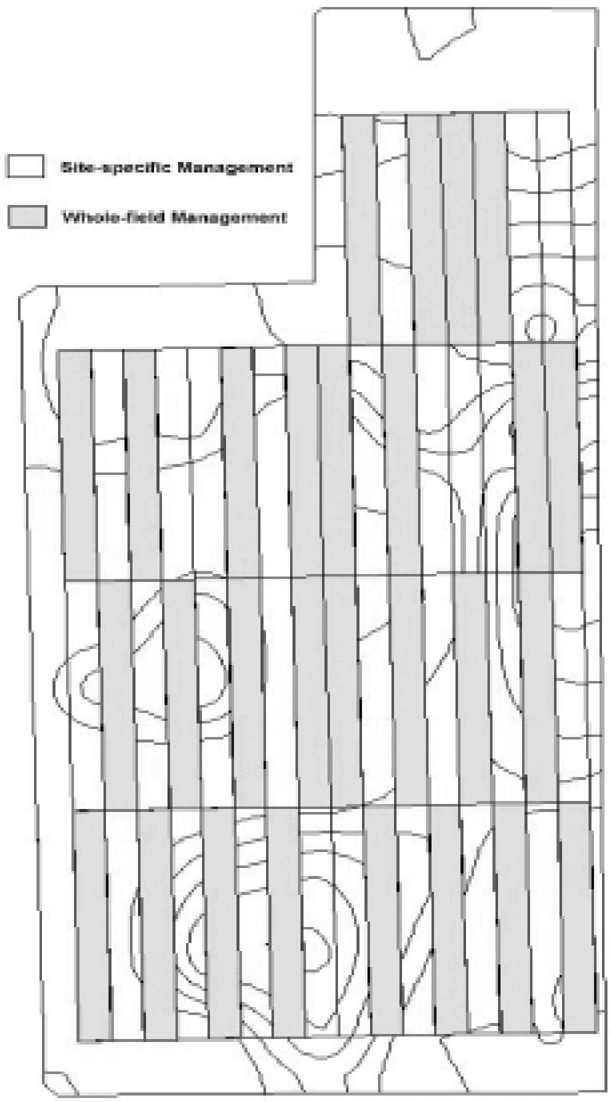
Table 1: Historical information on four farm fields for SSM experiments, Michigan, 1998-99.

Characteristic	**L(J)**	**C(J)**	**M(H)**	**K(H)**
Crop History				
1996	Dry beans	Soybeans	Corn	Wheat
1997	Sugar beets	Corn	Soybean	Corn
Crop Planted				
1998	Soybeans	Corn	Corn	Soybean
1999	Corn	Soybean	Soybean	Corn
2000	Soybeans	Corn	Corn	Soybeans
2001	Corn	Soybean	Soybean	Corn
Predominant Soil Texture	Loam	Loam	Sandy clay	Clay
Weeds	Giant foxtail and quack grass	Velvet leaves, lamb quarters, cocklebur, foxtail, queen annes lace and common rag weed		
Herbicide	Command, Frontier and Sencor with late application of Pinnacle	Dual herbicide at planting with late application of post emergence Clarity with Resource		
Pest	White mold	White mold		
Tillage	Fall chisel plow for both crops; for soybeans, two passes with soil finisher in the spring		Spring chisel plow for soybeans; fall chisel plow for corn	
Harvesting	John Deere with Greenstar™		Case Int'l with Ag Leader™	
Livestock History	None	No live-stock past 15 yrs	None	None
Year Purchased/ in Production	1970	1970	1983	1981
Drainage tile	15.2 m (50 ft) spacing	Random tiled	None	None

Experimental Design

A generalized, randomized block design (GRBD, Hinkelmann and Kempthorne, 1994, p. 279) was used in the experiment. Each field was divided into four or more blocks, with each block having four strips. Each strip was further subdivided to two sub-strips. These sub-strips were randomly assigned treatments of whole field management (WFM) or site-specific management (SSM). Each sub-strip was designed to be18.2 m wide and 152-243 m long (see Figure 1 for an example of the plot layout and classification).

Figure 1: Plot map of L(J) field.


Site-specific Management
Whole-field Management

The fields were initially soil sampled on a 61 m grid. The fields were resampled in the spring of 1999, 2000, 2001 and 2002 at the centroid of each sub-strip. Based on the 1998 soil sample results and the yield goal of the crop to be planted in 1998, interpolated maps were generated for P, K and lime requirements for each field. Yield goals were established for each field based on previous field production history. Michigan State University fertilization recommendations were followed for corn and soybeans to compute fertility needs at the sample points. Recognizing the plot layout and the designation of the sub-strips as either WFM or SSM, surface maps were created using the gridding algorithms in SSToolbox™. For the sub-strips designated WFM, the recommended application was determined by the average of the soil sample results for the whole field. For the sub-strips designated SSM, the recommended application was variable based on the surface map for the area of that sub-strip.

As farmer-managed experiments, these trials were developed to apply the experimental design within the habitual management framework of the cooperating farms. In the discussion that follows, the two fields on the J farm are referred to as the C(J) and L(J) fields, and the ones on the H farm are referred to as the K(H) and M(H) fields.

Fertility treatments for each of the four fields

The C(J) field was planted to corn in 1998 and 2000 and to soybeans in 1999 and 2001. P source for the corn crops was banded 10-34-0 liquid starter fertilizer applied at 112 l ha^{-1} (1998) and 140 l ha^{-1} (2000) for both SSM and WFM strips. Two yr of expected K uptake was applied prior to each corn crop as KCl (0-0-60). Additional P was applied in May of 2000 to the SSM plots wherever the corn starter did not meet the full P requirement of the corn-soybean rotation. P was also applied to soybeans in 2001 as 10-52-0. Agricultural lime was variable-rate applied April 15, 1999. The spreader path maps indicated that three plots were skipped; additional pelletized lime was applied to these plots in the fall of 1999.

The L(J) field was planted to soybeans in 1998 and 2000 and to corn in 1999 and 2001. P was spot-applied to the SSM plots wherever the corn starter did not meet the full P requirement of the corn-soybean rotation in the spring of 1998 as 10-52-0, adjusted for the anticipated corn starter fertilizer applied in the spring of 1999. A 2-yr recommendation of K was applied in the fall of 1999 and spring of 2001 as KCl (0-0-60). Starter fertilizer was banded in 1999 and 2001 as 140 l ha^{-1} 10-34-0. Agricultural lime was variable-rate applied April 14, 1999. The spreader path maps indicated that some plots were skipped; additional pelletized lime was applied to these plots in the fall of 1999.

The M(H) field was managed as a pair of fields. M1(H) and M2(H) were planted to corn in 1998 and 2000 and to soybeans in 1999. The M2(H) field was planted to soybeans in 2001 whereas the M1(H) field was not planted in 2001. P source for the corn crops was banded with the corn planter as 10-34-0 at 112 l ha^{-1} (1998) and 84 l ha^{-1} (2000). KCl was variable-rate applied based only on a 1-yr corn recommendation to prevent leaching in the sandy soils in this field. Prior to each soybean crop, dry fertilizer was applied (5-26-30 in 1999 and 9-23-30 in

2001) based on the P recommendation for the 2-yr rotation minus P applied as corn starter. No lime was applied to this field since it already tested adequate to high in pH. Yield variability was high in 2000 due to an early December snow that fell after half the field was harvested and delayed harvest on the other half for a month.

The K(H) field was planted to soybeans in 1998 and 2000 and to corn in 1999 and 2001. P was applied in the form of 0-26-26 fertilizer in 1998, based on a 3-yr projected P need, adjusted for starter fertilizer (10-34-0 at 84 l ha^{-1}) applied in the spring of 1999. Two yrs of K was applied in spring 1999 as 0-0-60, adjusted for the potash applied in 1998, with a minimum rate set at 112 kg ha^{-1}. In 2000 and 2001 0-0-60 was applied in the spring based on the K recommendation for that year's crop. Pelletized lime was variable-rate applied in the fall of 1998.

For the C(J) and L(J) fields, the VRA inputs were custom applied using an airflow applicator for fertilizers and a spinner spreader for lime. For the M(H) and K(H) fields, the inputs were custom-applied using a spinner spreader. There was no attempt to check spreader calibration, but both companies calibrate their equipment regularly. As-applied maps were not available.

Side-dressed nitrogen for corn was applied at a uniform rate as anhydrous ammonia. Other management decisions were taken by the cooperating farmers in consultation with the independent crop consultant associated with the project.

Combine yield monitor data was taken for each of the fields. Using the plot overlay for each field, yield data were "cut-out" representing each plot so that combine passes included for any plot did not overlap with another plot; the first and last 7.6 m of each plot was not included. This was increased to 15.2 m for both the H farm fields in 1998 and for the M(H) field in 1999 because of problems with differential correction of the global positioning system (GPS) signals.

Statistical Models

A fundamental design problem for experiments in crop SSM is the confounding of treatment and block effects when one treatment varies with site characteristics (Gotway Crawford et al, 1997). The confounding problem can be aggravated in on-farm research when other unintended factors may vary as well (e.g., multiple combines on the same field at harvest, changes in herbicide treatment when one product runs out before the entire field is treated, etc.). In order to control for these factors insofar as possible, the GRB design was analyzed using a mixed multiple regression model that included variables for treatment effects as well as for non-treatment factors suspected of being correlated with the outcome variables of interest.

All the statistical analyses were based on the same general linear model. The general model was designed to capture not only the conventional treatment, block, and interaction effects common to two-way analysis of variance, but also to capture other potentially related non-treatment effects such as sub-block strip differences, directional orientation effects, and other covariates based on unintended management differences across the field. The general statistical model takes the form:

$$Y = \beta_0 + \beta_1 TRT + \beta_2 BLK + \beta_3 STRIP + \beta_4 OR + \beta_5 TRT * BLK + \beta_6 BLK * OR + \beta_7 COV1 + \beta_8 COV2 + \varepsilon$$

where ***Y*** is the dependent variable. Four dependent variables were analyzed: plot average dry yield, plot standard deviation of dry yield, costs that vary between treatments, and gross margin over costs that vary.

As for explanatory variables, *TRT* is the treatment (main) effect, which takes the value 1 for SSM and 0 for WFM. *BLK* stands for block. An experimental block consists of 2 rows of 4 individual plots making a total of 8 plots. A block contains random arrangement of four plots, each containing two sub-plots where the SSM and WFM treatments were randomly assigned. *BLK* is a vector of integer identifiers (a, a+1, a+2,…, a+k) representing the blocks in each field. For example, BLK_K for the K(H) field would be BLK_K = [1,2,3,4] since there are 32 sub-plots and therefore 16 plots comprising four rectangles. *STRIP* is the variable representing strips within the rectangle. As a vector like [1 2 3 4], STRIP simply tells whether a plot within a given block falls within the first, second, third or fourth strip. *OR* refers to plot orientation and indicates whether the plot is in the northern or southern half of the rectangle. ***TRT*BLK*** is the treatment X block interaction. ***BLK*OR*** is the block X orientation interaction. ***COV1*** and *COV2* are two covariates that have different meanings for different fields and years. For the M(H) field in 1998-99 and the K(H) field in 1998, two combines were used. As a result, for those fields ***COV1*** is the proportion of yield points in the sub-plot harvested by combine 1. For the L(J) field in 1998, ***COV1*** is the proportion of yield points where operators flagged weed problems, and *COV2* marks K values, some of which were very low. For the C(J) field, the entries of

COV2 in 1998 mark P values, some of which were very low; *COV1* values in 1999 mark the east side of the field where a different postemergence herbicide caused crop injury. Finally the β_i's are the coefficients to be estimated and ε is a random disturbance term assumed to be distributed normal$(0,\sigma^2)$.

The covariates were included in the model in case they influence the relevant dependent variable (and hence might avoid spurious inferences about the treatment effect). When specific covariates were found not to be significant, they were dropped from the analysis.

The general null hypothesis tested states that SSM is no better than WFM. Because higher yields and gross margins are preferred, whereas higher costs and yield variability are not, the four types of null hypothesis take slightly different forms:

1. H_0: Yield (SSM) $\leq$ Yield (WFM)
2. H_0: Costs (SSM) $\geq$ Costs (WFM)
3. H_0: Gross margin (SSM) $\leq$ Gross margin (WFM)
4. H_0: Standard deviation of yield (SSM) $\geq$ Standard dev. of yield (WFM)
5. H_0: Standard deviation of soil test values (SSM) $\geq$ Standard dev. of soil test values for P, K and pH (WFM)

Note that all hypothesis tests are comparisons of main-effect means from the general model above. The main effect variable for Model 4 is the plot-level standard deviation of yield, so the comparison applies to the mean of the plot-level yield standard deviations. The main effect variable for Model 5 is the field-level standard deviation of soil test values for P, K and pH. Percentage changes in these standard deviations (and also means) were compared based on soil test values in 1999 and 2002. The 1998 baselines values were not used because they were not sampled at plot centroids and so introduced a risk of spatial measurement error that was absent in subsequent years.

The first four models were estimated in SAS™ 7.1 using the MIXED procedure. Results reported include estimates of the main effect means (β_1) and standard deviations for SSM and the difference of means (SSM-WFM) and associated coefficient standard error. The other coefficients for models 1-4 were estimated as well, but are not reported here. One-sided p-values from t-tests of the null hypotheses were calculated from SAS output as [Pr>|t|]/2 where the mean had the expected sign and (1 –[Pr>|t|]/2) where the mean had a sign opposite the expected one.

Profitability and Cost Calculations

Profitability was measured by calculating the value of crop production minus the costs of the fertility treatments. The technical name for this measure of profitability is the "gross margin over costs that vary" (CIMMYT, 1988). Costs that vary are the ones that differ between treatments. Fertilizer and lime costs were included, because these vary between the SSM and WFM treatments (Table 2). Application costs too were included at a flat rate for WFM plots ($7.41 ha^{-1} = $3 ac^{-1}), versus a rate for SSM plots that reflects both the higher per-acre fee for variable-rate spreading ($14.82 ha^{-1} covered) and the proportion of acres covered by the spreader path (since under SSM, not all plots require spreading). SSM plots received a special annual charge for the additional soil sampling costs associated with georeferencing and preparation of nutrient maps.

Certain costs need to be spread across several years. This is true of both the supplemental SSM soil sampling and mapping costs, as well as the costs of lime and its spreading. Because these costs are paid only once per soil sampling or liming cycle, they are converted to an annual basis by using an annuity formula (Swinton and Lowenberg-DeBoer, 1998). This calculation is similar to what a bank does when it calculates an annual fixed mortgage payment; it is the uniform annual payment whose present discounted value at the end of the cycle equals that of the amount paid up front. The 10% discount rate (like an interest rate) used here reflects the rate of return that funds invested in SSM might have earned if instead they had been invested elsewhere on the farm. The GPS soil sampling and map-making cost figures used here were the 1999 rate premiums above conventional whole-field average sampling as charged by Agri-Business Consultants, Inc. This premium of \$8.65 ha^{-1} was annualized over a 4-yr sampling cycle for an annual charge of \$2.72 ha^{-1}. Similarly, the costs of lime and its application were annualized over five yr for the M(H) and K(H) fields (\$0.26 per dollar per yr) and over seven yr for the L(J) and C(J) fields (\$0.21 per dollar per yr) for those areas where it was applied (Table 2).

Although prices vary from year to year, the profitability analyses presented are each based on a single set of prices. The reasoning for this was to avoid confounding the yield and input use effects with varying annual prices. Results presented are based on 1998 prices for fertilizer, lime and crops (Table 2).

Table 2: Price, cost and SSM treatment data, Michigan, 1998-2001.

	Unit	**1998**	**1999**	**2000**	**2001**
Crop Product Prices (after harvest cost)*					
Soybean	$ kg^{-1}	0.184	0.147	0.162	0.147
Corn	$ kg^{-1}	0.063	0.055	0.067	0.067
Fertilizer prices					
0-0-60	$ MT^{-1}	154	138	146	149
10-52-0	$ MT^{-1}	265	209	n.a.	270
6-26-26	$ MT^{-1}	221	193	n.a.	218
Lime	$ MT^{-1}	n.a.	18	n.a.	n.a.
Application prices					
WFM	$ ha^{-1}	7.41	7.41	7.41	7.41
SSM	$ ha^{-1} spread	8.42	8.42	8.42	8.42
Lime	$ ha^{-1} spread	n.a.	3.00	n.a.	n.a.
Annualized Information costs					
ABC GPS sampling(1)	$ ha^{-1}	2.72	2.72	2.72	2.72
Field Crop Rotation and fertilizers (apart from 10-34-0 starter on corn)					
M1(H)** & M2(H)		Corn (0-0-60)	Soy (5-26-30)	Corn (0-0-60)	Soy (9-23-30)
K(H)		Soy (6-26-26)	Corn (0-0-60)	Soy (0-0-60)	Corn (0-0-60)
L(J)		Soy (10-52-0)	Corn (0-0-60)	Soy (no fert.)	Corn (0-0-60)
C(J)		Corn (0-0-60)	Soy (no fert.)	Corn (0-0-60)	Soy (10-52-0)
Proportion of SSM plots Covered by VR Applicator					
M1(H)		1.00	1.00	0.83	(not farmed)
M2(H)		0.26	0.53	0.26	0.53
K(H)		0.50	1.00	0.41	1.00
L(J)		0.81	0.29	0.00	0.29
C(J)		0.98	0.86	0.98	0.42
Proportion of SSM plots Limed in 1999					
M1(H)			0.00		
M2(H)			0.00		
K(H)			0.25		
L(J)			0.75		
C(J)			0.86		

* Raw crop prices are Nov-Dec bid/auction averages at Lapeer, Michigan, as reported by DTN. Prior to conversion to SI units, farm-gate prices were rounded to nearest $0.10 after subtracting $0.20/bu for harvest and trucking.

Crop prices were rounded to the nearest ten cents from the mean of weekly auction prices at Lapeer, Michigan, for the months of November-December of each year (as reported on DTN). Prices from 1998 are close to averages for the 1998-2001 period. Gross margins over costs that vary were calculated by multiplying crop dry yield by crop price and subtracting the costs that vary between treatments.

**M1(H) was not farmed in 2001.

RESULTS AND DISCUSSION

The first set of analyses was conducted to choose the best models from which to report results. In all but three cases, F-tests (not shown) revealed that the covariates had no significant effect on the regression models. Hence, the results of the simpler model without covariates are reported for these cases. The cases where covariates did matter were all in 1998: Cov2 (K level) in L(J), Cov2 (P level) in C(J), and Cov1 (second combine harvester) in K(H) (this last applied to the standard deviation model only). For these cases, the model with the relevant covariate included formed the basis for the mean treatment effects reported below. Results of hypothesis tests on the four final models chosen are presented as follows: mean yields, costs that vary, gross margin and yield stability. They apply to 19 site-years of data, 1998-2001 for three whole fields and the two distinctly managed halves of the M(H) field, except for the M1(H) field half, which was not farmed in 2001. The p-values reported are for one-sided t-tests of the null hypotheses stated above.

No measurable yield gain from SSM treatment

Mean yields did not differ between the SSM and WFM treatments in any of the four years (Table 3). In the M2(H) half field in 1998, corn yields under SSM were significantly lower (at the 5% probability level of error). Mean yields were also calculated on a per-block basis by simple effect tests, but results were similar to the overall analysis and so are not reported.

Table 3: Mean differences of crop yield, SSM-WFM, Michigan, 1998-2001.

Year and Field	Crop	Mean SSM yield (std.dev.)	Mean difference (SSM-WFM) (std. error)	Degrees of freedom (t-test)	Pr > t (one-sided)
1998		kg ha^{-1}	kg ha^{-1}		
L(J)	Soybean	3,200	50	10	0.32
		(80)	(110)		
M1(H)	Corn	9,900	-140	3	0.77
		(130)	(170)		
M2(H)	Corn	9,400	-240	4	0.93
		(90)	(90)		
C(J)	Corn	7,200	110	10	0.16
		(70)	(100)		
K(H)	Soybean	3,300	90	8	0.06
		(40)	(50)		
1999					
L(J)	Corn	10,700	50	10	0.35
		(100)	(140)		
M1(H)	Soybean	2,900	0	4	0.59
		(10)	(20)		
M2(H)	Soybean	3,000	-30	4	0.71
		(40)	(50)		
C(J)	Soybean	3,400	-70	10	0.93
		(30)	(40)		
K(H)	Corn	9,800	100	8	0.21
		(80)	(120)		
2000					
L(J)	Soybean	2,900	-20	10	0.91
		(10)	(20)		
M1(H)	Corn	7,800	-40	4	0.54
		(310)	(440)		
M2(H)	Corn	9,200	-40	4	0.53
		(380)	(540)		
C(J)	Corn	11,900	-180	10	0.83
		(130)	(180)		
K(H)	Soybean	3,800	80	8	0.63
		(160)	(230)		
2001					
L(J)	Corn	6,600	10	10	0.49
		(230)	(330)		
M1(H)	Not planted	n.a.	n.a.	4	n.a.
		n.a.	n.a.		
M2(H)	Soybean	1,500	0	4	0.50
		(30)	(40)		
C(J)	Soybean	2,600	20	10	0.35
		(40)	(60		
K(H)	Corn	6,200	230	8	0.11
		(120)	(170)		

NB: Coefficients can be converted to bu ac^{-1} equivalents by dividing by 62.71 for corn and 67.19 for soybean.

Higher costs with the SSM treatment

Costs that vary between treatments were significantly higher for SSM in every case (Table 4). Fertilizer and lime cost savings from SSM did not offset the higher information and application costs of SSM. In most fields, the average amount of material applied was greater in the SSM plots than in the WFM plots.

Table 4: Mean difference of costs that vary at 1998 prices, SSM-WFM, Michigan, 1998-2001.

Year and Field	Crop	Mean SSM costs that vary (std. deviation)	Mean difference SSM-WFM (std . error)	Pr < t (one-sided)
1998		$ ha^{-1}	$ ha^{-1}	
L(J)	Soybean	48.60	32.60	<0.0001
		(2.20)	(3.10)	
M1(H)	Corn	44.90	29.70	<0.0001
		(1.00)	(1.40)	
M2(H)	Corn	23.10	23.10	0.0003
		(1.60)	(2.20)	
C(J)	Corn	67.10	13.50	<0.0001
		(0.80)	(1.10)	
K(H)	Soybean	37.00	37.00	<0.0001
		(1.40)	(1.90)	
1999				
L(J)	Corn	14.00	14.00	<0.0001
		(0.50)	(0.80)	
M1(H)	Soybean	64.30	19.90	0.0005
		(1.60)	(2.30)	
M2(H)	Soybean	33.20	33.20	0.0003
		(2.40)	(3.40)	
C(J)	Soybean	14.00	14.00	<0.0001
		(0.30)	(0.50)	
K(H)	Corn	39.90	15.20	<0.0001
		(0.30)	(0.40)	
2000				
L(J)	Soybean	8.70	8.70	<0.0001
		(0.50)	(0.70)	
M1(H)	Corn	32.30	15.40	<0.0001
		(0.30)	(0.40)	
M2(H)	Corn	11.70	11.70	<0.0001
		(0.20)	(0.30)	
C(J)	Corn	78.00	24.40	<0.0001
		(0.70)	(1.00)	
K(H)	Soybean	19.10	18.10	<0.0001
		(1.00)	(1.40)	
2001				
L(J)	Corn	14.00	14.00	<0.0001
		(0.50)	(0.80)	
M1(H)	Not	n.a.	n.a.	n.a.
	planted	n.a.	n.a.	
M2(H)	Soybean	33.20	33.20	0.0003
		(2.40)	(3.40)	
C(J)	Soybean	25.90	25.90	<0.0001
		(0.40)	(0.60)	
K(H)	Corn	40.00	15.30	<0.0001
		(0.30)	(0.40)	

NB: Degrees of freedom same as Table 3. Coefficients can be converted to U.S. $ per acre by dividing by 2.47.

Profitability was the same or lower with the SSM treatment

The profitability of the SSM treatment, as measured by gross margins over costs that vary, never exceeded that of the WFM treatment (Table 5). The mean calculated gross margins with SSM were lower in every case, but the losses associated with SSM were not statistically significant at the 5% level in 10 of the 19 site-years. The SSM treatments caused statistically significant losses in at least two of the five fields in every year. The C(J) and M2(H) fields each showed significant losses in three of the four years.

Table 5: Mean difference of gross margin over costs that vary at 1998 prices, SSM-WFM, Michigan, 1998-2001.

Year and Field	**Crop**	**Mean SSM gross margin (std. dev.)**	**Mean difference SSM-WFM (std. error)**	**Pr > t (one-sided)**
1998		$ ha^{-1}	$ ha^{-1}	
L(J)	Soybean	530.10	-22.50	0.84
		(15.80)	(22.40)	
M1(H)	Corn	495.90	-119.10	0.89
		(58.20)	(82.30)	
M2(H)	Corn	567.00	-38.40	0.996
		(5.50)	(7.80)	
C(J)	Corn	385.40	-6.50	0.81
		(5.10)	(7.20)	
K(H)	Soybean	576.80	-20.40	0.95
		(7.60)	(10.70)	
1999				
L(J)	Corn	659.20	-10.60	0.88
		(6.00)	(8.40)	
M1(H)	Soybean	470.10	-20.70	0.99
		(3.40)	(4.70)	
M2(H)	Soybean	514.20	-39.00	0.99
		(6.50)	(9.20)	
C(J)	Soybean	610.80	-26.40	0.997
		(5.40)	(7.60)	
K(H)	Corn	580.10	-8.90	0.87
		(5.10)	(7.30)	
2000				
L(J)	Soybean	521.30	-12.80	0.99
		(2.00)	(2.90)	
M1(H)	Corn	457.10	-18.10	0.73
		(19.60)	(27.70)	
M2(H)	Corn	570.00	-14.20	0.65
		(24.10)	(34.00)	
C(J)	Corn	673.30	-35.90	0.99
		(8.30)	(11.70)	
K(H)	Soybean	680.80	-3.70	0.53
		(29.40)	(41.50)	
2001				
L(J)	Corn	398.90	-13.20	0.73
		(14.40)	(20.40)	
M1(H)	Not planted	n.a.	n.a.	n.a.
		n.a.	n.a.	
M2(H)	Soybean	233.80	-33.30	0.99
		(5.90)	(8.30)	
C(J)	Soybean	450.40	-21.40	0.96
		(7.90)	(11.20)	
K(H)	Corn	348.80	-0.90	0.53
		(7.70)	(10.90)	

NB: Degrees of freedom same as Table 3. Coefficients can be converted to U.S. $ per acre by dividing by 2.47.

Yield stability was no different with the SSM treatment

The plot-level standard deviations of yield were no different between treatments in either crop in any of the four years (Table 6). The sole exception was in 1999 in one soybean field (M2(H)) where yields were more highly variable under SSM than WFM. In general, there was no evidence of SSM reducing yield variability within a year.

Table 6: Mean difference of sub-plot standard deviations of dry yield, SSM-WFM, Michigan, 1998-2001.

Year and Field	Crop	Mean of SSM standard deviations (std. error)	Mean difference of standard deviations (std. error)	Pr < t (one-sided)
1998		kg ha^{-1}	kg ha^{-1}	
L(J)	Soybean	670	10	0.61
		(30)	(50)	
M1(H)	Corn	1,570	10	0.55
		(50)	(60)	
M2(H)	Corn	1,460	-160	0.08
		(70)	(90)	
C(J)	Corn	810	-40	0.22
		(30)	(40)	
K(H)	Soybean	330	-40	0.17
		(20)	(30)	
1999				
L(J)	Corn	790	-10	0.45
		(40)	(50)	
M1(H)	Soybean	400	10	0.72
		(10)	(20)	
M2(H)	Soybean	370	40	0.99
		(10)	(10)	
C(J)	Soybean	270	-50	0.12
		(30)	(40)	
K(H)	Corn	580	-130	0.06
		(50)	(70)	
2000				
L(J)	Soybean	240	-20	0.23
		(10)	(10)	
M1(H)	Corn	1,140	-350	0.32
		(220)	(310)	
M2(H)	Corn	1,230	140	0.50
		(140)	(200)	
C(J)	Corn	780	30	0.55
		(30)	(50)	
K(H)	Soybean	850	30	0.57
		(40)	(50)	
2001				
L(J)	Corn	1,520	100	0.33
		(70)	(100)	
M1(H)	Not	n.a.	n.a.	n.a.
	planted	n.a.	n.a.	
M2(H)	Soybean	410	20	0.60
		(30)	(40)	
C(J)	Soybean	420	-20	0.46
		(20)	(30)	
K(H)	Corn	1,300	180	0.20
		(90)	(130)	

NB: Degrees of freedom same as Table 3. Coefficients can be converted to bu ac^{-1} equivalents by dividing by 62.71 for corn and 67.19 for soybean.

Modest differences in soil fertility trends between SSM and WFM treatments

Soil test P levels declined in all fields except C(J) over the 4-year study period (Table 7). The L(J) and C(J) sites began at relatively higher levels (roughly 40 ppm) and thus a downward trend was expected for both treatments. Soil P values in the other three fields began the study at lower levels (roughly 25-30 ppm) where the Tri-State system calls for "maintenance" applications. Nonetheless, they appear to have fallen as rapidly as the higher testing fields.

Variability in P levels did not decline significantly across all fields in paired-sample t-tests of changes over time. However, variability was reduced more in SSM plots than in WFM plots in the C(J) and M1(H) fields, as evidenced by a greater drop in standard deviation of P values at plot centroids from 1999 to 2002 (Table 7). In the M2(H) field, P variability in SSM plots appeared to have *increased* while the standard deviation of WFM plots declined slightly. However, when further points were sampled in addition to plot centroids, this difference was reversed (both treatments still increased, but SSM plot variability increased by a smaller increment). Changes in P variability in the other two fields are more difficult to assess, since the first VRA P fertilizer was applied in 1998, prior to sampling the plot centroids. Thus the best baseline statistic for P variability in these fields comes from the initial 1998 soil sample taken on 0.41 ha acre grids (i.e. not at plot centroids). Using this statistic as a criterion, P variability appears to have dropped more in SSM plots of both fields than in WFM plots, especially in the year following the VRA application.

At the beginning of the study, several areas of the M1&2(H) sites, and to a lesser extent K(H) and C(J) tested below the Tri-State "critical value" for P of 15 ppm (the value below which this approach assumes lack of a nutrient will limit yields). Since the SSM approach should have applied more fertilizer to these areas, one would expect P values to rise significantly in these plots. Indeed, by 2002 the number of sub-critical plot centroids under WFM had increased to 11, compared to only four under SSM. Plant tissue analyses revealed a relationship between lower P-testing plots and lower plant tissue P levels (Swinton et al., 2002b, Figures Annex p. 13). However, those plots with soil test values below the "critical" P value still tested sufficient in tissue P content.

Mean K values on the L(J) and K(H) and M2(H) fields began at relatively high levels (roughly 150-175 ppm), and both treatments on all these sites declined significantly over the 4-year study. The C(J) and M1(H) fields began at lower levels (roughly 100 ppm) and increased slightly over this period.

Since VRA K was applied 2-3 times on each field during the four-year study (compared with 1-2 times for P), one might expect variability of this nutrient to be reduced even more markedly by SSM. In fact, the trend was much less consistent than that of P values (Table 8). K variability increased overall on K(H), but the increase was smaller under SSM plots than under WFM. On M2(H), variability decreased under SSM and increased under WFM. On M1(H) K variability appears to have increased under SSM and remained constant under WFM, while on the remaining fields no similar trends were observed between treatments.

Table 7: Changes in mean and standard deviation of P test values (ppm), 5 Michigan fields, 1998-2002.

	L(J)		M1(H)		M2(H)		C(J)		K(H)	
	SSM	WFM	SSM	WFM	SSM	WFM	SSM	WFM	SSM	WFM
Mean										
1998	152	152	92	106	102	114	162	156	122	106
1999	***145***	147	85	85	102	104	168	174	***101***	79
2000	121	121	***82***	85	***95***	79	***137***	149	82	70
2001	128	131	83	91	89	80	161	172	82	67
2002	131	130			***93***	74	158	162	76	63
Change since '98*	-14%	-14%	-10%	-15%	-9%	-36%	-2%	4%	-38%	-40%
Change since '99	-10%	-11%	-2%	7%	-8%	-29%	-6%	-7%	-25%	-20%
Standard Deviation										
1998	69	74	31	55	36	48	67	54	44	32
1999	***53***	67	53	21	27	21	58	62	***25***	28
2000	49	60	***31***	19	***29***	16	***45***	54	25	23
2001	47	57	36	18	33	13	51	65	27	21
2002	54	62			***30***	16	49	63	25	24
Change since '98*	-22%	-15%	16%	-67%	-16%	-66%	-27%	17%	-43%	-24%
Change since '99	2%	-7%	-33%	-15%	11%	-24%	-16%	2%	1%	-13%

*1998 soil test values are interpolated to plot centroids from a grid sample. Soil tests from 1999 to 2002 were taken at plot centroids.
NB: Bold italic indicates first year following VRA P application in SSM treatment.

Table 8: Changes in mean and standard deviation of K test values (ppm), 5 Michigan fields, 1998-2002.

	L(J)		M1(H)		M2(H)		C(J)		K(H)	
	SSM	WFM	SSM	WFM	SSM	WFM	SSM	WFM	SSM	WFM
Means										
1998	674	714	418	476	672	700	404	384	620	616
1999	530	531	***519***	427	565	636	***444***	466	434	379
2000	***448***	439	575	508	***534***	562	468	489	***474***	426
2001	404	409	***587***	515	586	602	***421***	450	***452***	391
2002	***409***	405			***573***	527	430	435	***506***	460
Change since '98*	-39%	-43%	40%	8%	-15%	-25%	6%	13%	-18%	-25%
Change since '99	-23%	-24%	13%	20%	2%	-17%	-3%	-7%	17%	22%
Standard Deviation										
1998	158	173	108	105	247	175	92	91	162	126
1999	98	105	***102***	83	155	289	***78***	74	92	66
2000	***84***	96	113	95	***100***	237	82	74	***95***	86
2001	69	66	***124***	105	122	193	***67***	67	***90***	80
2002	***74***	81			***148***	184	70	74	***98***	89
Change since '98*	-53%	-53%	15%	0%	-40%	5%	-24%	-19%	-39%	-30%
Change since '99	-24%	-23%	22%	26%	-4%	-36%	-10%	1%	6%	35%

*1998 soil test values are interpolated to plot centroids from a grid sample. Soil tests from 1999 to 2002 were taken at plot centroids.
NB: Bold italic indicates first year following VRA K application in SSM treatment.

At the project outset, areas of C(J) and M1(H) tested below the Tri-State "critical" level for K (87 ppm for these soils). By 2002, additional sub-critical areas had developed in the L(J) field which had tested high initially, and only received small K applications over the 4 years. In contrast to the P pattern, with K, the SSM and WFM plots were equally likely to have dropped to below critical levels. Tissue analyses also identified some plots with below-sufficient K levels. However, there was no apparent relationship between these tissue results and soil test K values. Since soil K values were measured at plot centroids, and plant tissue analyses were taken from the center 150-200 ft of plots, this lack of correlation may be partly due to within-plot variability in K values.

Trends in pH change were also mixed (Table 9). Three fields received VRA lime during the project. Prior to liming, roughly one fourth of the SSM and WFM plots at the C(J) and L(J) sites tested below a pH of 6.3. Lime recommendations were based on 1998 soil samples taken independently of plot location, and the effectiveness of SSM lime management in correcting pH appears to reflect a difference in accuracy of pH mapping in these two fields. Of the 10 SSM plots needing lime on C(J) all but one were identified by the 1998 soil test, and received lime. By 2002, all but one of these plots had increased to pH 6.3 or higher, while 12 WFM plots in the same field remained below 6.3. In contrast, of the 8 low-pH SSM plots on L(J), only 3 were identified by the initial soil test and received VRA lime. By 2002, six SSM plots remained below 6.3 on this field, as did six WFM plots.

Soil pH trends on L(H) are more difficult to assess since plot centroids were not sampled prior to lime application. According to the 1998 soil test, low pH was only a problem in one area of the field (a hilltop in the SE). This area was limed and soil pH appeared to increase on both SSM and WFM plots from this area. Pelletized lime was applied with a spinner-spreader on this field, and apparently the material was thrown beyond the intended plots. One additional low-pH area of this field was missed by the 1998 soil test, and by 2002 one SSM and one WFM plot remained below-optimum for pH.

To test for accuracy of spreader application of fertilizer and lime, in 2002 additional points were sampled in 43 areas where adjacent plots received very high and very low (or zero) rates of fertilizer and/or lime. Samples were taken from the centers of the high-rate plots and the zero-rate plots as well as 4.5m away from the center of the zero-rate plots. In the C(J) field these data suggested lime was applied with reasonable accuracy. Nine plots which were to receive no lime remained at an average of pH 5.7 in plot centers and 5.9 at the sides, while adjacent plots, which received roughly 5.9 Mg/ha lime had increased to an average pH of 6.5.

Table 9: Changes in mean and standard deviation of pH test values, 5 Michigan fields, 1998-2002.

	L(J)		M1(H)		M2(H)		C(J)		K(H)	
	SSM	WFM	SSM	WFM	SSM	WFM	SSM	WFM	SSM	WFM
Means										
1998	6.44	6.72	7.44	7.44	7.37	7.36	6.32	6.68	7.06	6.74
1999	6.41	6.49	6.36	6.66	6.81	6.90	6.30	6.05	***6.62***	6.79
2000	***6.28***	6.42	6.23	6.55	6.81	6.98	***6.66***	6.11	6.92	6.90
2001	6.41	6.46	6.36	6.50	6.65	6.85	6.69	6.18	6.86	6.86
2002	6.57	6.63			6.80	6.78	6.71	6.15	6.94	7.02
Change since '98*	2%	-1%	-14%	-13%	-8%	-8%	6%	-8%	-2%	4%
Change since '99	2%	2%	0%	-2%	0%	-2%	7%	2%	5%	3%
Standard Deviation										
1998	0.26	0.49	0.71	0.49	0.47	0.4	0.42	0.57	0.53	0.13
1999	0.38	0.40	0.67	0.70	0.53	0.37	0.50	0.39	***0.63***	0.52
2000	***0.46***	0.47	0.55	0.75	0.42	0.37	***0.40***	0.38	0.53	0.35
2001	0.39	0.39	0.70	0.74	0.24	0.29	0.36	0.36	0.44	0.34
2002	0.43	0.37			0.38	0.32	0.31	0.37	0.50	0.42
Change since '98*	67%	-25%	-1%	52%	-20%	-21%	-27%	-35%	-5%	219%
Change since '99	14%	-9%	5%	6%	-28%	-16%	-39%	-5%	-20%	-21%

*1998 soil test values are interpolated to plot centroids from a grid sample. Soil tests from 1999 to 2002 were taken at plot centroids.
NB: Bold italic indicates first year following VRA lime application in SSM treatment.

On the M2(H) site, seven plots received no K fertilizer while adjacent plots received 194 kg ha^{-1} K. By 2002, the centers of these plots differed by 21 ppm, while points 4.5m to the side differed by only 14 ppm, suggesting that some fertilizer was spread outside of the intended plot areas. On L(J), M2(H) and K(H) P application rates in adjacent plots differed by 46, 55, and 30 kg ha^{-1} respectively but there were no consistent differences between soil test values by 2002. This lack of any clear trend could be evidence of misapplication. However, with the relatively low VRA P fertilizer rates, differences in pre-existing P levels and crop removal may well have outweighed the impact of VRA fertilizer application, and made the latter difficult to measure.

DISCUSSION OF RESULTS

After four yr of site-specific P, K and lime management, we have documented modest reductions in soil nutrient variability in some fields, but no clear or consistent yield, cost-saving, profitability, or yield stability benefits. The lack of clear profitability response from site-specific application of P and K nutrients to corn and soybean is consistent with several Midwest previous university studies (Anderson and Bullock, 1998; Swinton and Lowenberg-DeBoer, 1998; Mallarino, 2002; Rehm, 2002). On the other hand, research in Indiana has documented benefits from SSM of lime (Bongiovanni and Lowenberg-deBoer, 2000), as well as weak evidence that SSM of P can reduce spatial yield variability (Lowenberg-DeBoer and Aghib, 1999). Neither of these results could be replicated in the current research. Several factors may have contributed to this lack of response in the current study:

1. *Fields that are well managed to begin with have less room to show benefits*

The benefits of SSM may be less on fields that have been well managed than ones with ordinary management. All of the fields in this study had received appropriate prior fertility management, albeit on a whole-field basis. At the outset of the study, P levels on the L(J) field, and most of C(J) and K(H), and K levels on all but the C(J) and M1(H) fields tested above the "critical levels" beyond which Michigan, Ohio and Indiana's Tri-State recommendations (Vitosh et al., 1995) do not predict a yield response to added fertilizer. Under these conditions there were relatively few opportunities for VRA management to improve yields of low-testing areas

2. *Tri-State recommended "critical levels" for P and K may be inappropriate for SSM*

Tri-State "critical levels," designed with whole-field management in mind, may not be appropriate to more intensive sampling and management. Whole-field critical levels must be "padded" somewhat since they assume that areas within a field test well below the field average, and will respond to fertilizer even if the rest of the field does not. In a more intensive, site-specific management approach, these lower-testing areas can potentially be identified and managed separately, so site specific "critical levels" could be significantly lower than in a whole-field approach. Tissue testing conducted during this study supports this idea since even plots with soil test values below Tri-State's critical range for P did not show evidence of nutrient stress in plant samples. Tissue testing for K showed no clear link to soil tests.

3. Spatially inaccurate soil tests

Lack of accuracy in soil testing limited the ability of SSM to manage the variability in soil fertility present in theses sites. Interpolated recommendations based on the 1998 grid soil test appear to have failed to estimate values at plot centroids in several cases. This problem was most evident in the liming of the L(J) field. In a parallel study (Miller et al., 2002), sampling method accuracy was measured independently. Results indicate that sampling and interpolation used widely in the industry do not do an adequate job, particularly with soil K and pH. The fact that in this study, SSM appears to have done a poorer job of managing soil pH and K levels than P levels, provides further support for this idea.

4. VRT equipment problems and operator error

VRT equipment problems and operator error reduced treatment accuracy in some situations. The 18 m plot width allowed some room for error; however, subsequent fertility testing suggests that the accuracy of some applications may have been less than desired. The clearest evidence of this problem occurred on K(H) where WFM plots which were not intended for liming increased significantly in pH. Spreader passes for later applications were either flagged or made with a swathing bar to improve accuracy. However, these practices did not address the problems of spinner-spreaders throwing material beyond the intended application areas.

5. Late lime application reduced potential effect

Lime was applied in fall 1998 and spring 1999, too late to affect the 1998 yields and probably too late to have much effect on 1999 yields. SSM liming appeared to have no effect on yields in 2000 or 2001, even on the C(J) site, where VRA applications corrected most pH problems. This contrasts with the Indiana findings of Bongiovanni and Lowenberg-deBoer (2000).

6. Effective SSM may require site-specific yield goals

The yield goals on which SSM fertilizer recommendations were based were kept uniform throughout each field. Georeferenced, historical yield data were not available at the outset of this study. This information would have undoubtedly improved the accuracy of SSM treatments.

Recent research elsewhere suggests that one possible reason for the lack of profitable response to site-specific management is that the fertilizer recommendations should be based not only on site-specific soil nutrient levels, but also on site-specific yield response relationships (Swinton et al., 2002b; Bongiovanni and Lowenberg-deBoer, 2001; Swinton and Lowenberg-DeBoer, 1998). The latter were not available for these fields.

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