Variable-rate Phosphorus Fertilization: On-farm Research Methods and Evaluation for Corn and Soybean

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ABSTRACT

This study adapted precision agriculture technologies to commonly used field-scale strip trials and compared fixed and variable phosphorus (P) fertilization for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Differential global positioning receivers, yield monitors, and grid soil sampling were used. Variable-rate fertilization reduced considerably the total amount of P fertilizer applied in two of four fields and increased yields in one field. Statistical analysis that accounted for spatial correlation of yield improved the evaluation of treatment effects. The results showed that a combination of traditional on-farm strip trials, precision farming technologies, and statistical methods that account for spatial correlation of yields can be used to obtain more thorough comparisons of management practices.

INTRODUCTION

Applied agricultural experimentation involves the comparison of current or new products, technologies, or management practices. Field tests usually are repeated in several locations over two or more years using various experimental designs. New products or management practices are recommended after statistical analyses confirm the advantages over existing practices. Obviously, the recommendations are extrapolated to large geographical areas and not all the environmental conditions are explored during the testing period. Precision agriculture technologies allow for georeferencing of measurements such as soil tests, crop yields, scouting counts, and other agronomic observations. After several cropping seasons these layers of information can be used to generate extensive databases, which will allow the farmers to fine-tune general recommendations to their particular conditions. To achieve this objective, there is the need for comparing alternative management practices on producers' fields.

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On-farm research on the basis of strip plots is an accepted methodology for complementing traditional small-plot research, for generating local recommendations, and for demonstrating management practices (Rzewnicki et al., 1988; Shapiro et al., 1989). Treatments are applied to narrow and long strips (usually of the length of the fields), and the grain is harvested with common combines and weighed using large capacity balances. Precision agriculture technologies can be successfully adapted to these types of field trials (Oyarzabal et al., 1996; Mallarino & Wittry, 1997).

Intensive soil sampling and variable-rate fertilization can improve the efficacy of fertilization compared with the conventional practice of collecting soil samples from large areas and using single-rate fertilizer applications. Although variable-rate fertilization can be used on the basis of the traditional sampling of areas identified on the basis of soil types, landscape, or previous management many people believe that it should be based on intensive grid sampling. Once the distribution of soil nutrients over a field is estimated, the use of variable-rate technology allows for the application of fertilizers as needed. The impact of this practice on soil fertility management and farm profitability depends on several factors. Some important ones are the nutrient levels in relation to crop needs, nutrient variability, the fertilizer recommendations used, expected crop response, and additional costs. Even if economic benefits are not obtained in all situations intensive soil sampling and variable-rate fertilization are likely to reduce the amount of nutrients applied, which could be environmentally beneficial.

In this article we report the methodology used and results of four on-farm experiments conducted in cooperation with farmers and a farmer's cooperative. The objectives were to evaluate corn and soybean response to fixed or variable P fertilization rates and to adapt precision agriculture technologies to strip-trial methods commonly used by farmers, cooperatives, and agribusiness.

METHODOLOGY

Four field strip-trials were established on four farmers' fields. Two trials were conducted in 1996 (Corn 1 and Soybean 1) and two in 1997 (Corn 2 and Soybean 2). All fields had uniform P fertilization in the past. The P treatments were a nonfertilized control, a fixed P rate, and a variable rate in which rates varied depending on soil-test P measurements made before planting. Soil samples were collected following a systematic grid-point sampling scheme in which grid lines were spaced 133 m apart in both directions. This sampling method is commonly used by farmers and cooperatives that use variable-rate fertilization in Iowa. The sampling area at each point was approximately 30 m^2 in size. Composite soil samples (6 to 10 cores from a 15-cm depth) were collected from each sampling area. The soil samples were analyzed for P by the Bray-P1 method (the most commonly used in Iowa) and other nutrients. The few soil samples with pH 7.0 or above were analyzed by the Olsen-P method and the Bray-P1 data were adjusted as needed.

An area of approximately 20 ha of each field was selected for the experiments. The width of each experimental area was divided into blocks

measuring 55 m in width. The blocks corresponded to replications of the experimental designs, and there were four in the two corn trials, four in the Soybean 1 trial, and five in the Soybean 2 trial. Each block was further subdivided into three strips to fit three treatments for each block. The measurements were made with a measuring tape or wheel and georeferences were recorded with a hand-held global positioning receiver equipped with differential correction (DGPS). The strips were the experimental units that received the different treatments. The length of the strips varied from 670 to 800 m among fields (without considering approximately 40 m of border on each end) but were uniform within each field. The P fertilizer was granulated diammonium phosphate in the Corn 1 and Soybean 1 trials and monoammonium phosphate in the others. It was applied after soil sampling and before planting using a bulk fertilizer spreader truck equipped with a DGPS receiver and a controller. Additional N fertilizer was applied for the corn at rates that varied between 120 and 150 kg N/ha among fields. The fixed P rate used was uniform within a field but varied between 46 and 52 kg P/ha among fields, and was selected by the farmers based on expected two-year P removal in corn and soybean grain. The amount of P applied and the number of rates of the variable-rate treatment varied among fields and replications within fields and was determined by soil-test P measurements made before planting. No P was applied when soil-test P was very high (31 mg P/kg or higher) and the rate varied from 35 to 58 kg P/ha for other soil-test classes.

Grain yields at all fields were measured and recorded using combines equipped with yield monitors and real-time DGPS receivers. The yield monitors used were impact flow-rate sensors (Ag Leader 2000, Ag Leader Technology, Ames, IA) and the differential corrections were obtained through the U.S. Coast Guard AM signal. The monitors recorded yields every second. The spatial accuracy was checked by georeferencing several positions in the field with a hand-held DGPS receiver. The yield data were unaffected by field borders because the experimental areas were located at least 40 m from any border. While harvesting, each combine trip (a 4.5-m swath in cornfields and a 7.5-m swath in soybean fields) was identified with a unique number that was recorded with the georeferenced yield data. The raw yield data recorded by the yield monitors were carefully analyzed for common errors when using yield monitors (wrongly georeferenced data because of loss of differential correction, effects of waterways or grass strips, and others) by using spreadsheets and ArcView. The few combine trips that included a mixture of two treatments were not used in the analyses. The data were exported for analysis with the SAS statistical package (SAS Institute, 1996).

The yield responses were analyzed by four procedures. Three procedures analyzed treatment effects on yield assuming a randomized complete block design (RCBD) with or without considering the spatial correlation of yield and the fourth procedure assessed treatment effects for parts of the field with different soil-test P. In one procedure, yields were analyzed by a conventional RCBD and the yield data input were yield means for the strips (i.e., the experimental units). In two procedures, the spatial correlation of yields was accounted for in the analysis of variance. With this objective, nearest neighbor analysis was used in one procedure (NNA) and a modeled semivariogram in the other (SEM). Adjusting for the spatial correlation could reduce the experimental error and could make the analysis more sensitive in discerning treatment differences. Previous studies (Hinz, 1987; Bhatti et. al., 1991; Hinz and Lagus, 1991; Marx, 1993; and Stroup, 1994) have shown the advantages of using NNA or the "mixed" procedure of SAS (SAS, 1996) to adjust spatially correlated data in different ways. In this study, NNA was used by calculating the residuals of subtracting each yield observation from the mean value of its neighbors and including the residuals as a covariate in the analysis of variance. Several types of covariates were calculated by using different numbers of neighbors but only results of using four neighbors (one from each N, S, E, and W direction) are shown because it was the most effective in reducing standard errors of treatment means. For the SEM procedure, initial estimates of the sill, nugget, and range parameters of a spherical isotropic semivariance model were calculated on a data set of residuals after a conventional analysis of variance. In a second step, these estimates were included in appropriate statements of the mixed procedure of SAS to estimate treatment effects on yields. The yield input data for these two analyses were means for small areas of a width defined by each combine trip (4.5 m in corn and 7.5 m in soybean) and 17 m (in 1996) or 33 m (in 1997) in the direction along the crop rows. The individual yield data recorded every second by the yield monitors were not directly considered because of their known lack of accuracy over short distances.

The fourth procedure assessed treatment effects for different parts of the experimental areas with different soil-test P values following a procedure described by Oyarzabal et al. (1996). This procedure provides support for mapping techniques that could show treatment differences over a field (such as absolute or relative yield increases due to fertilization). The method was used for other nutrients as well but is demonstrated in this article only for soil-test P. The yield input data were means for areas defined by the width of each strip (18 m) and the separation distance of the soil sampling grid lines (133 m) in the direction along crop rows (0.24 ha). The soil-test input data were the soil-test P values from areas defined by the width of each replication (55 m) and the separation distance of the sampling grid lines in the direction along crop rows (0.73 ha). Each yield value was classified according to the soil-test P interpretation class of the area. The Iowa State University soil-test P interpretation classes very low, low, optimum, and high include values of 0 to 8, 9 to 15, 16 to 20, 21 to 30 mg/kg, respectively (values greater than 30 mg/kg are classified as very high). In this study, there were very few values in the very low or very high classes so they were included in the low or high class, respectively. The analysis of variance included estimates of "soil-test P group" and interaction "treatments by soil-test P group" effects. The soil-test P groups were considered as repeated measures within the experimental units. A significant interaction "soil-test group by P fertilization" suggests that treatment effects differed for areas of the field with different soil-test P levels.

RESULTS AND DISCUSSION

The results of the soil sampling showed large nutrient variability in all fields. Table 1 shows descriptive statistics for selected soil-test values. The soil-test P interpretation classes within the Corn 1 and Corn 2 trials encompassed the five classes used by Iowa State University. No soil-test was very low in the Soybean 1 field and no soil-test was very high in the Soybean 2 field. The soil test classes varied from low to high in most strips (not shown). According to Iowa State University P fertilizer recommendations for corn and soybean, large to moderate yield responses to P should be expected in the very low and low classes, small or no responses should be expected in the optimum class, and no responses should be expected within the high or very high classes.

Table 1. Descriptive statistics for selected soil tests for four strip trials.

Trial	Soil test	Mean	Minimum	Maximum	SD
Corn 1	P (mg/kg)	18	8	34	8
	K (mg/kg)	205	165	296	37
	pH	6.7	5.8	7.8	0.7
	Org. matter (%)	3.5	2.8	4.4	0.5
Corn 2	P (mg/kg)	15	6	35	8
	K (mg/kg)	142	100	206	27
	pH	6.2	5.7	7.5	0.5
	Org. matter (%)	3.5	2	4.9	0.7
Soybean 1	P (mg/kg)	22	13	96	18
	K (mg/kg)	187	132	347	43
	pH	6.3	5.8	8	0.6
	Org. matter (%)	3.2	2.3	3.9	0.4
Soybean 2	P (mg/kg)	16	8	24	5
	K (mg/kg)	177	141	229	24
	pH	5.9	5.7	6.2	0.1
	Org. matter (%)	2.7	2.1	3.5	0.4

Table 2 shows the observed (unadjusted) and estimated (adjusted for spatial correlation) mean yields for the treatments applied in the four trials and the corresponding statistics. Comparisons of the treatment means obtained by adjusting for spatial correlation show little difference with the observed means. Although there were some differences between procedures, the ranking of the treatments usually was similar for the three procedures. In agronomic terms, there was a moderate response to fertilization in the Corn 2 trial and there were no major fertilization effects in other trials. At the responsive Corn 2 trial, the yield for the variable-rate treatment was higher than for the fixed-rate treatment.

A potential advantage of adjusting for spatial correlation is to improve the statistical test of treatment effects. Data in the table show that adjusting for spatial correlation always reduced standard errors and increased the levels of significance of treatment effects. This adjustment resulted in a different interpretation of the results in some trials but not in others. The statistics for all procedures showed that fertilization did not affect yields in the Corn 1 trial at commonly used probability levels. At the other trials, the statistical interpretation of the results differed for the three procedures. At the Corn 2 trial, all procedures detected a positive effect of fertilization but only the NNA procedure confirmed an obvious higher yield for the variable-rate treatment. At the Soybean 1 trial, only the SEM procedure detected a very small advantage for the fixed-rate treatment. At the Soybean 2 trial, the two procedures that adjusted for spatial correlation confirmed the higher yields for the fertilized treatments but only the NNA procedure confirmed a small advantage for the fixed-rate treatment.

Table 2. Effect of P fertilization on corn and soybean grain yields as evaluated by three methods of analysis for four strip trials.

Crop	Treatment and statistics‡	Method of analysis† RCBD	NNA	SEM
		--- kg/ha and level of significance ---		
Corn 1	Control	11238	11251	11080
	Fixed	11104	11102	11018
	Variable	11204	11193	11061
	SE	135.3	61.9	36.3
	Main effect	0.62	0.13	0.24
	F vs. V	0.49	0.20	0.22
Corn 2	Control	9039	9045	9130
	Fixed	9182	9186	9251
	Variable	9321	9311	9306
	SE	86.9	13.6	40.9
	Main effect	0.05	0.01	0.01
	F vs. V	0.16	0.01	0.17
Soybean 1	Control	4017	4024	4046
	Fixed	4118	4116	4073
	Variable	4080	4075	4037
	SE	70.1	36.1	15.6
	Main effect	0.40	0.11	0.05
	F vs. V	0.61	0.31	0.02
Soybean 2	Control	2744	2742	2682
	Fixed	2803	2805	2767
	Variable	2755	2754	2740
	SE	36.9	7.4	21.1
	Main effect	0.29	0.01	0.01
	F vs. V	0.23	0.01	0.18

† SE = average standard error of the difference between two means, F vs. V = comparison of the fixed and variable fertilization treatments.

‡ RCBD = observed means and statistics for the randomized complete block design, NNA = analysis combined with nearest neighbor analysis, and SEM = SAS proc mixed analysis including a spherical semivariance model.

The differences in adjusted means and standard errors between the NNA and SEM procedures were small and inconsistent among trials. Although differences cannot be explained with complete certainty, they likely were related to differences in the structure of the spatial correlation of yields, the way in which the spatial correlation is accounted for by the NNA and SEM procedures, and the assumptions involved in each procedure. Observation of isotropic sample semivariograms for these fields showed evident spatial structures, good fits of the spherical models, and suggested no obvious explanation for the differences with the NNA procedure. The fact that using more than four neighbors did not improve the NNA analysis suggests that a covariate calculated from few residuals may have accounted for localized variability better than procedures that considered greater number of observations. The results also suggest that the NNA procedure was more effective than the SEM procedure when treatment differences were large (i.e., at the Corn 2 and Soybean 2 trials). No attempt is made here to draw general conclusions and the methods are being compared for other trials with different treatment structure and/or physical field layout.

Results of the procedure that assessed treatment effects for areas of the field with different soil-test P suggest that within-field variation in soil-test P influenced the effect of P fertilization only in the Corn 2 trial. This is suggested by the data shown in Table 3. At the Corn 2 trial, there was a significant (at the 0.06 level of significance) interaction between the treatments and the soil-test classes, and responses were greater when soil-test P was within the low interpretation class. The significance of the interaction probably was not higher because of a small responsive trend observed at the high soil-test interpretation class. At the other three trials, the interactions between the treatments and the soil-test classes were not significant and the ranking of the means among the soil-test classes was similar.

The lack of significant crop response to P fertilization for areas with low soil-test P in the Corn 1, Soybean 1, and Soybean 2 trials, although not expected, is not rare in field experimentation and could be explained by several reasons. One likely reason is that no soil sampling cell tested very low in the Soybean 1 trial and only one cell tested very low and borderline with the low class (8 mg/kg) in the Corn 1 and Soybean 2 trials. Another likely reason is that crop yields are affected not only by soil-test P and other growth factors could have had greater influence in yields and may have masked any effect of P fertilization. Also, soil tests are not perfect estimates of nutrient availability. Usually there is high sampling error and a sample may not represent an area appropriately. This could have been the case in these studies because soil samples attempted to represent areas 1.78 ha in size and only 6 to 10 cores were collected from each sampling area. The results for these studies suggest that the cell size used was too large for an effective variable-rate fertilization. This has also been suggested by other soil sampling and/or fertilization studies (Wollenhaupt et al., 1994; Franzen and Peck, 1995; Mallarino and Wittry, 1997). Moreover, even with a perfect sampling, analyses of soil samples collected before planting and from the top 15-cm of soil can only predict the P availability over the entire growing season and errors should not be surprising. A failure of the yield monitors to measure yields appropriately over crop row distances of 133 m is possible but unlikely.

Table 3. Mean grain yield as affected by fertilization for areas of four fields having different soil-test P values.

		Soil-test P class						
		Low		Optimum		High		
Trial	Treatment	Yield	SP†	Yield	SP	Yield	SP	Statistics‡
		kg/ha	mg/kg	kg/ha	mg/kg	kg/ha	mg/kg	
Corn 1	Control	11342		10994		11128		
	Fixed	11124	12	10784	16	11188	28	0.93
	Variable	11279		10905		11207		
Corn 2	Control	8957		9378		8919		
	Fixed	9155	10	9370	17	9118	26	0.06
	Variable	9333		9341		9280		
Soybean 1	Control	4060		4004		4006		
	Fixed	4138	14	4131	18	4101	41	0.44
	Variable	4065		4086		4089		
Soybean 2	Control	2817		2635		2765		
	Fixed	2855	10	2660	17	2892	23	0.76
	Variable	2794		2699		2762		

† Mean soil-test P for areas encompassed by the three treatments for samples collected before the fields were fertilized and planted.
‡ Level of significance of the interaction between treatments and soil-test classes.

An interesting aspect to consider, other than yields, when comparing fixed or variable fertilization rates is the total amount of fertilizer applied over a field by each method. In this study, the average amount of P fertilizer used with the variable-rate treatment compared with the fixed-rate treatment were 2 kg P/ha more at the Corn 1 trial, 2 kg P/ha less at the Soybean 1 trial, 8 kg P/ha less at the Corn 2 trial, and 11 kg P/ha less at the Soybean 2 trial. Of course, these differences cannot be extrapolated to other fields because differences depend on the rates used and on the level and distribution of soil test values within a field. Consideration of differences in the amount of fertilizer applied, crop yields, and costs (equipment, soil sampling, etc.) determine the economic benefit of variable-rate fertilization. A complete economic analysis is beyond the scope of this article because of the variety of assumptions and scenarios that should be involved and because data were collected only from four fields. It is fairly obvious, however, that variable-rate fertilization did not offset additional costs in the Corn 1 and Soybean 1 trials and increased the benefits from fertilization in the other two trials. The advantages and disadvantages of fertilization methods largely depend on the conditions at each field and growing season. Although the economic benefit of variable-rate fertilization will vary greatly among fields, it will likely result in more efficient and environmentally sound distribution of fertilizers when it is based on reliable estimates of nutrient availability and when soil nutrients within a field vary from deficient to above-optimum levels.

CONCLUSIONS

The yield response to P fertilization and to the method of application varied among fields. Variable-rate P fertilization reduced considerably the total amount of P fertilizer applied in two of four fields and increased yields in one field. The benefits of variable-rate fertilization will vary greatly among fields but will likely result in more efficient and environmentally sound distribution of fertilizers when it is based on reliable estimates of nutrient availability and when soil nutrients within a field vary from deficient to above-optimum levels. Statistical analysis that accounted for spatial correlation of yield improved the evaluation of treatment effects. The results showed that a combination of traditional on-farm strip trials, precision farming technologies, and statistical methods that account for spatial correlation of yields can be used to obtain more thorough comparisons of management practices.

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