**Impact of variable-rate and starter fertilizer application methods on the crop response to phosphorus**

by

Manuel Bermudez

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Program of Study Committee:
Antonio P. Mallarino: Major Professor
Alfred M. Blackmer
Lee C. Burras
Thomas S. Colvin
Dale E. Farnham

Iowa State University

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Graduate College
Iowa State University

This is to certify that the doctoral dissertation of

Manuel Bermudez

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program

**To:**

**Cecilia**

**Maria Paula and Ruben**

**Maria Felicitas and Peta**

**Maria Cristina and Manuel Ramon**

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# CHAPTER 1.

# GENERAL INTRODUCTION

## INTRODUCTION

Corn and soybean are the primary crops grown in Iowa. Surveys indicate that approximately 80% of the crop production area is managed with conservation tillage (chisel-plow and disk or field cultivator). Soil erosion associated with conventional tillage and the lack of crop rotation can also degrade the soils significantly. Many farmers need to change farming practices in order to improve the sustainability of crop production. Particular advantages of no-tillage over conventional tillage are the increase of residue cover, the reduction of soil erosion, and the increase of crop water use efficiency. No-till systems became popular because they have the potential to minimize or alleviate these problems. However, a disadvantage of no-tillage for spring planted crops in the north central region of the United States is that it creates cooler and wetter soil conditions at planting time. These conditions can reduce early growth, early nutrient uptake, and grain yield. Starter fertilization is a common fertilizer practice used in some areas of the U.S. to improve nutrient uptake and early crop growth even in soils high in available nutrients. However, several questions have arisen about the use of this placement method mainly relating to its cost-effectiveness for predominant production conditions of no-till or conventionally tilled Iowa fields. From an environmental perspective the use of starter fertilization can help reduce the amount of P and K fertilizer added to fields, especially in soils with high fertility levels.

Crop production removes P and other essential nutrients from the soil that need to be replaced by fertilizer application in order to maintain higher yields. Surveys indicate that approximately 70% of the Iowa fields test above optimum P and K levels needed for corn and soybean production. Moreover, surveys at a watershed level have shown that in certain areas 30 to

40% of the fields test at least twice the optimum level needed for crop production. The original fertility level, the removal of nutrients, and the replacement of these nutrients often is not uniform over an entire field. Many farmers, agricultural scientists, and extension specialists are concerned about potential environmental degradation associated with P fertilization practices commonly used in conventional agriculture. For example, excess P in surface runoff can enter neighboring lakes or streams and degrade water quality.

Spatial variability of P in soils with long histories of cropping and fertilization has been recognized for a very long time. Soil variability arises through complex interactions between natural and management factors. Natural variability is caused by variation in topography, climate, native vegetation, parent material, and other factors. Management practices such as tillage, fertilization, manure application, and others can affect variability patterns of soil chemical and physical properties. Studies of the spatial variability of soil-test P have shown large within-field variability even in fields with apparent uniform soil properties. Recognition of the spatial variability of nutrients led to the development of variable-rate fertilizer application equipment and methods. The variable-rate equipment include controllers that vary specific material flow rates in response to information provided by a computer. Traditionally fields have been managed as homogeneous units and have been fertilized with a single rate of fertilizer. The usual practice of applying a uniform rate of fertilizer to an entire field may be inefficient because this practice it may over fertilize some areas and under fertilize others, decrease efficiency in use of fertilizer resources, and increase potential for contamination of surface and ground water. Use of variable-rate technology allows for changing fertilizer rates on-the-go over a field to apply the amount of fertilizer needed where it is needed.

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. Precision farming technologies such as yield monitors, differential global positioning systems, and geographical information systems, allow producers to generate yield maps capable of identifying and estimating the yield variability over the landscape. The new technologies can be used to study treatment effects on yield and relationships between yield variability and soil characteristics over the landscape with much less cost than in the past.

The overall objective of this research was to assess the impact of P fertilization methods on crop and soil-test P responses. Two distinct studies were conducted to achieve this general objective based on a strip-trial methodology. Specific objectives of one study were (1) to evaluate yield, early growth, and early nutrient uptake of corn as affected by liquid starter fertilization (mainly N and P mixtures) and reduced spring tillage in no-till fields, and (2) to assess these crop yield responses for field areas with different soil-test values and soil series. Specific objectives of the other study were (1) to evaluate the yield responses of corn and soybean to P fertilizer using uniform-rate and variable-rate application methods, and (2) to assess the effect of these application methods on grain yield variability.

## DISSERTATION ORGANIZATION

This dissertation is presented as two papers suitable for publication in scientific journals of the American Society of Agronomy. The title of the first paper is "Corn response to starter fertilizer and reduced tillage in fields with no-till management". The title of the second paper is "Yield response to uniform and variable-rate phosphorus fertilization for corn and soybean". Each paper is divided in sections that included abstract, introduction, materials and methods, results and discussion, conclusions, reference list, and tables. The papers are preceded by a general introduction and are followed by a general conclusion.

# CHAPTER 2.

# CORN RESPONSE TO STARTER FERTILIZER AND REDUCED TILLAGE IN FIELDS WITH NO-TILL MANAGEMENT

A paper to be submitted to Agronomy Journal

Manuel Bermudez and Antonio P. Mallarino

## ABSTRACT

Early season corn (*Zea mays* L.) growth often is slower in no-tilled soils than in tilled soils. The objective of this study was to evaluate the impact of reduced spring tillage and starter fertilization on early growth, nutrient uptake, and grain yield of no-till corn. Seven replicated strip trials were conducted using yield monitors, intensive soil sampling, differential global positioning systems (DGPS), and geographical information systems (GIS). Treatments were no-starter and liquid starter with or without spring tillage. Starter rates varied across fields from 3.9-27.2 kg N ha$^{-1}$, 5.2-24.2 kg P ha$^{-1}$, and 0-6.5 kg K ha$^{-1}$. They were applied to the seed furrow in five fields and beside and below the seeds in two fields. Tillage treatment was done with a strip-till unit that tilled a zone of 18-cm wide and 15-cm deep in two fields and a field cultivator that mixed soil and residue to a 10-15 cm depth in other fields. Measurements were grain yield, early plant growth (V5-V6) and N-P plant uptake. Tillage increased grain yield in five fields (210 to 500 kg ha$^{-1}$). The starter increased yield in three fields (170 to 522 kg ha$^{-1}$) and reduced yield with the no-till treatment in one field (-97 kg ha$^{-1}$). Soil-test P, K, pH, and organic matter content did not clearly explain the yield response variation across fields. Tillage and starter fertilization usually increased early growth and nutrient uptake markedly. Across all fields, tillage increased yield by 2.5%, early growth by 27% , P uptake

by 20% and N uptake by 21%. Across all fields, starter increased yield by 1.3%, early growth by 29%, P uptake by 30%, and N uptake by 30%. Starter had no consistent effect on within-field yield variability and its spatial structure. Early growth and nutrient uptake responses were poorly related with grain yield response. Starter fertilization did not substitute for tillage effects on yield.

Abbreviations: ANOVA, analysis of variance; GPS, global positioning systems; GIS, geographical information systems; ISU, Iowa State University; NNA, nearest-neighbor analysis; RCBD, randomized complete block design; SD, standard deviation; STK, soil-test K; and STP, soil-test P.

## INTRODUCTION

Adoption of no-tillage in the Corn Belt increased rapidly during the early 1990s. This trend has slowed mainly because of observed yield reductions in corn. Iowa research has shown lower yields for no-till corn compared with corn managed with chisel-disk tillage (Mallarino et al., 1998a). Particular advantages of no-tillage over conventional tillage are reduction of soil erosion and an increase of crop water use efficiency (Jones et al., 1969; Blevins et al., 1971). However, increased residue results in cooler and wetter soils in spring and creates conditions that can reduce early nutrient uptake and growth for spring-seeded crops such as corn (Al-Darby and Lowery, 1987; Imholte and Carter, 1987; Swan et al., 1987; Kaspar et al., 1990; Gordon et al., 1995). Fortin (1993) found that residue removal along rows of no-till corn increased corn early height, and produced development rates similar to those for conventional tillage.

Starter fertilization (usually as N-P-K mixture) is a common practice used in some areas of the U.S. to improve nutrient uptake and early crop growth, even in soils high in available nutrients. Granulated or liquid starter mixtures are applied in bands beside and below the seeds or in the seed furrow. Although potential benefits to starter fertilization are well documented (Touchton et al., 1988; Mengel et al., 1992), there is uncertainty concerning the probability and degree of yield response. The response to starter fertilizer is more likely with reduced tillage. For example, Mengel et al. (1992) found that starter fertilization increased corn yield in only one site under conventional tillage but in eight sites under no-till management in Indiana. Wolkowski (2000) reported yield responses to starter fertilizer in soils testing high in P and K when corn was managed with no-till, but not with conventional tillage. Vyn and Janovicek (2001) showed that yield increases to starter applied K were greater with continuous no-till systems than with conventional systems. Vetsch and Randall (2002) reported corn yield increases to N-P-K starter mixture across different tillage systems despite high soil P and K.

The response to starter fertilizer usually is attributed to the P in the mixture (Randall and Hoeft, 1988), which is consistent with known high P requirements for early plant growth and development. In some situations, however, responses to N also occur (Ritchie et al., 1995). Scharf (1999) found larger responses to N-P starter fertilizers compared with N-only starter in sites where STP was low but no differences when STP was above optimum. Rehm et al. (1988) reported that the magnitudes of increased growth and yield due to starter fertilization increase when the starter is applied to soils with low STP, but also found significant responses to P-K starter fertilization in high STP soil during a cool and wet spring season. Bordoli and Mallarino (1998) found significant no-till corn yield increases to granulated P fertilization in low testing soils in Iowa, but no differences among P fertilizer placement methods that included broadcast, deep band (15 cm depth), and planter-bands (5 cm beside and below the seeds). Planter-band and broadcast K, resulted in significantly lower yield increases compared with deep-band K placement in soils that tested optimum or higher in K.

Precision farming technologies such as yield monitors, differential global positioning systems (DGPS), and geographical information systems (GIS) are useful to describe yield variability over the landscape. Major factors producing yield variability are variation in soil tests. soil physical properties. and topography. These factors also may influence the response to fertilization. Bermudez and Mallarino (2002) used precision agriculture technologies in conjunction with a strip trial methodology (Shapiro et al., 1989) to study the within-field variation in no-till corn response to starter fertilization. They showed that large yield responses to starter fertilization are more likely when STP is below optimum and (or) when preplant or sidedress N rate is deficient. They also reported large early growth responses in most areas within fields independently of STP. Wittry and Mallarino (2002) used similar techniques to study the within-field variation in corn and soybean response to P fertilization. They reported that responses to P were greater in field areas testing low in P. They also found that responses were more frequent for some soil series than for others.

Methods such as those used by Bermudez and Mallarino (2002) can be used to study the within-field variation of the yield response to starter fertilization of crops managed with tillage or no-till. The main objective of this study was to evaluate yield, early growth, and nutrient uptake of corn as affected by liquid starter fertilization and spring reduced tillage in no-till fields. A second objective was to assess the variation in growth, nutrient uptake, and yield responses for field areas with different soil tests levels and soil series using precision agriculture technologies.

## MATERIALS AND METHODS

Seven strip-trials were conducted during 1998 and 1999 to evaluate corn yield, early growth, and nutrient uptake responses to starter fertilizer and reduced spring tillage. Trials were established on Iowa farmers' fields that had 8 to 14 years of no-till management. Table 1 gives field locations and predominant soil series for the fields. Soils were among typical agricultural soil series of Iowa and neighboring states. Management practices were those used by each farmer and, thus, corn hybrids, seeding rates, planting dates, herbicide management, and planting equipment varied among fields (Table 2). At Fields 2, 3, 5,and 7, the farmers broadcasted P and K rates uniformly in November of the previous year, at rates that varied across fields from 35 to 70 kg P ha$^{-1}$ and 90 to 120 kg K ha$^{-1}$. Field 4 had received no P and K since November 1996. Field 1 received broadcast P and K fertilization in spring three weeks before planting the corn for this study. At Fields 1, 2, 3, 4, and 6, the farmer applied N fertilizer (28% urea-ammonium nitrate solution in Fields 3, 4, and 6, and anhydrous ammonia in other fields) uniformly when corn was 15 to 25 cm tall at rates of 100 to 145 kg N ha$^{-1}$. At Fields 5 and 7, anhydrous ammonia was injected into the soil in November of the previous year at a rate of 170 kg N ha$^{-1}$.

A replicated strip-trial methodology was used for all trials. Approximately 12 to 20 ha at each field located at least 40 m from field borders were selected for the experiments. The width of each experimental area was divided across future corn rows into blocks that ranged from 60 to 90 m in width. These blocks corresponded to replicates of a split plot experimental design. There were three replicates in Field 4 and four in the other fields. Each block was subdivided into two strips to fit two tillage treatments, and were further subdivided to fit two starter fertilization treatments. The width of each starter strip was uniform within each field and ranged from 12 to 24 m across fields to accommodate one or two passes of the corn planter. A 16-row planter set for a 76-cm row spacing was used for Fields 1, 2, 4, 5, and 7. An eight-row planter set for a 96-cm row spacing was used for Fields 3 and 6. The strip length was uniform within each field but varied from 270 to 600 m among fields. Measurements were made with a measuring tape or wheel, and georeferences were recorded with a hand-held DGPS receiver. The tillage treatments were no-till and reduced spring tillage. In Fields 3 and 6, the tillage treatment was applied one month before planting with a strip-till unit that tilled a zone approximately 18-cm wide and 15-cm deep on 96-cm spacings. Corn was planted directly into the tilled zone. In all other fields, the tillage was done with a field-cultivator that mixed soil and residue to a 10-15 cm depth. The tillage was done two weeks before planting in Fields 1, 4, and 7, and immediately before planting in Fields 2 and 5. The starter treatments were no starter and liquid starter. The starter fertilizer mixtures (all commercial products) and rates varied across fields (Table 2). In Fields 1, 2, 3, 5 and 6 the starter was applied into the seed furrow. In Fields 4 and 7 the starter was applied 5 cm beside and below the seeds.

Soil samples were collected immediately before planting following a systematic grid-point sampling scheme (Wollenhaupt et al., 1994). The spacing between grid lines across the corn rows coincided with the width of the replications (60- to 90 m) and was 24 to 36 m in the direction along crop rows. Composite samples (10 to 12 cores, 15-cm depth) were collected from an area approximately 80 $m^2$ in size located at the center of each cell. Soil samples were analyzed for P by the Bray-$P_1$ method, K by the ammonium acetate method, organic matter content by the Walkey-Black method, and pH (1:1 soil-water) following standard soil testing procedures recommended for the North Central Region (Brown, 1998). Iowa State University (ISU) soil test interpretation classes for corn grain production (Voss et al., 1999) were used to classify soil test P and K ranges in this report. Boundary values of five STP classes are <8 mg $kg^{-1}$ for Very Low, 9 to 15 mg $kg^{-1}$ for Low, 16 to 20 mg $kg^{-1}$ for Optimum, 21 to 30 mg $kg^{-1}$ for High, and >31 mg $kg^{-1}$ for Very High. Boundary values of five soil-test K (STK) classes are <60 mg $kg^{-1}$ for Very Low, 61 to 90 mg $kg^{-1}$ for Low, 91 to 130 mg $kg^{-1}$ for Optimum, 131 to 170 mg $kg^{-1}$ for High, and >170 mg $kg^{-1}$ for Very High.

The above-ground portion of corn plants was sampled when corn height to the center of the whorl averaged 15 to 25 cm across treatments and field areas which corresponded to V5 to V6 growth stage. Ten plants were cut at ground level from the center of each treatment strip and soil sampling cell along the crop rows. Plant samples were dried in a forced-air oven at 60 °C, weighed, and ground to pass a 2-mm screen. Total N and P in the tissue were extracted by digesting samples with $H_2SO_4$ and $H_2O_2$ (Digesdahl Analysis System, Hach Inc., Boulder, CO). Nitrogen in extracts for Fields 1, 2, 3, and 4 were determined by the Kjeldahl procedure (Bremner, 1960) and for Fields 5, 6, and 7 by a colorimetric procedure (Hach, 1985). Phosphorus in extracts was measured by a colorimetric method (Murphy and Riley, 1962). Plant N and P were expressed as concentrations in dry matter and as uptake on a per-plant basis.

Grain yields were measured 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, 2202 S. Riverside Dr., Ames, IA), Green Star (John Deere Inc., John Deere Place, Moline, IL), or Micro-Trak (Micro-Trak Systems, Inc., 111 East Leray Ave., Eagle Lake, MN). Differential corrections were obtained through the U.S. Coast Guard AM signal. The spatial accuracy was checked by georeferencing several positions in the field with a hand-held DGPS receiver. Yield data were unaffected by field borders because at least 40 m from any border (buffer strip) were harvested but not used. While harvesting, each combine trip (a 4.5-m swath) was identified with a unique number that was recorded with the georeferenced yield data. Only yield averages for each treatment strip could be recovered from the electronic card of the yield monitor used in Field 1. The raw yield data points recorded by the yield monitors used in other fields were analyzed for common errors such as incorrect geographic coordinates due to total or partial loss of good differential correction and effects of waterways or grass strips. The affected data were corrected (incorrect coordinates) or deleted. The data were imported into spreadsheets and then exported to ArcView (Environmental Systems Research Inst. Inc., 380 New York St., Redlands, CA) for GIS management and later to the SAS statistical package (SAS Institute, 2000) for statistical analyses. The maps in Figs. 1 and 2 are ArcView layouts that show an example (for Field 3) of the strip trial methodology used and the type of maps generated using ArcView GIS. Figure 1 shows treatments, soil survey series, and various soil test values. Figure 2 shows yield points, means of grain yield and early growth by strip, and grain yield differences by strip and replication.

Treatment effects on yield for each field were analyzed by two procedures. Procedure 1 analyzed treatment effects for the entire experimental area. Data from Field 1 (for which only strip means were recovered) were analyzed using a randomized complete-block split-plot design (RCBD). Data from Fields 2 to 7 (for which all field monitor points were recovered) were analyzed using a randomized complete-block split-plot design (RCBD) with nearest neighbor analysis (NNA). The NNA was used to calculate values of a covariate which is included into the RCBD following a procedure used before (Hinz, 1987; Hinz and Lagus, 1991, Mallarino et al., 1998b). One covariate value is calculated to correspond to each number input for the RCBD analysis. Yield input data were means of all yield monitor points recorded at 1-s intervals for small areas delineated by the width of the combine head (4.5 m) and the length of the soil sampling cell (which varied from 24 to 36 m across fields) along the crop rows. The individual data recorded by the yield monitors were not directly considered because of the known lack of accuracy of yield monitors over distances shorter than 30 to 40 m (Lark et al., 1997; Colvin and Arslan, 2000). The first step in the calculation was to obtain yield residuals by removing treatment and block effects with a conventional ANOVA. Afterwards, covariate values were calculated by subtracting each yield residual from the mean value of its four residual neighbors (one from each N, S, E, and W direction).

Procedure 2 assessed treatment effects separately for parts of each field having contrasting soil test values or soil series following a procedure first described by Oyarzabal et al. (1996) and used later by Mallarino et al. (2001) and Bermudez and Mallarino (2002). This analysis could not be conducted for Field 1 because only strip yield means were recovered from the electronic yield monitor card. Five statistical analyses considered separately STP, STK, pH, organic matter, and soil series. Arcview GIS was used to produce the input data from different areas of each field. Yield data were means for areas defined by the width of each strip (12 to 24 m) and the separation distance along crop rows of the soil sampling grid lines (24 to 36 m). The soil-test data corresponded to the initial soil samples and represented values for areas defined by the width of each replicate and the separation distance of the sampling grid lines in the direction along crop rows. Soil-test values were classified into the five ISU interpretation classes for STP and STK, into four classes for pH (pH <5.5, 5.5-6.2, 6.3-7.0, and >7.0), and into three classes for organic matter (<30, 30-40, and >40 g $kg^{-1}$). For analysis of responses for different soil series, each yield value was matched by the corresponding soil series from digitized, scale 1:12000 soil survey maps (Iowa Coop. Soil Survey, available online at http://icss.agron.iastate.edu). The analysis was performed for the two predominant soil series of each field because areas for other soil series were too small. The *F* test from a one-way ANOVA was used to estimate the consistency of starter effects for each interpretation class of each soil test and for each soil series. The numerator mean square represented variation introduced by the treatments (tillage and starter) and the denominator means square represented variation within groups (cells with a similar classification). Values were not used for these analyses when there were less than three yield cells for any soil-test class or soil series within a field. Treatment effects on corn early growth (dry weights at V5 to V6 developmental stages) and N and P uptake were analyzed in the same manner as described for the yield data. In these instances, the input data were derived from one sampling point from each small cell defined by the width of each treatment strip and the separation distance of grid sampling lines along crop rows.

Simple correlation and regression analyses were performed with SAS (SAS Institute, 2000) to study relationships between soil-test values and responses of relative yield, plant early growth, and plant nutrient uptake to starter fertilization across tillage and tillage effect across starter fertilization for areas defined by each strip and soil sampling cell. Relative yield increases were used to minimize differences in absolute yields between fields and areas within a field. The relative increases for starter fertilization were calculated from treatment means (without starter and with starter across tillage for the area defined by a soil sampling cell) by subtracting the yield without starter from the yield with starter, dividing by the yield without starter, and multiplying by 100. The same procedure was used to calculate relative increases for tillage by subtracting the yield in no-till from the yield with tillage, dividing by the yield in no-till, and multiplying by 100.

Geostatistical analysis (S-Plus version 6.0 and Spatial Statistics Supplement: Insightful Corp.; 2001, Seattle, WA 98109) was used to quantify the effect of starter fertilizer and tillage on the spatial structure of the variability of yield, early dry weight, N and P uptake. General geostatistical methods and terminology are described by Marx and Thompson (1987), and more comprehensive discussions can be found in Journel and Huijbregts (1978). One unidirectional semivariogram (along the strips) was calculated for each set of strips corresponding to each treatment. Semivariance values were calculated for a minimum lag distance of 15 m for yield and 45 m for dry weight, N and P uptake; and a maximum lag distance of 60% the strip length (120 to 320 m depending on the field). There were at least 15 pairs of points for each lag distance. Linear, linear-plateau, spherical, and exponential models (Waugh et al., 1973) were fitted to the semivariance values by weighted least squares regression to estimate sample semivariogram parameters. The spherical model was the best-fitting model in most instances and is the only one presented. This model estimates nugget, sill, and range parameters. Briefly, the nugget semivariance is not related to spatial dependence and represents random variation and the residual influence of all variabilities with ranges smaller than the distance of observation. The range represents the distance at which samples become independent or are no longer correlated with each other. As the distance between sample points increases, semivariance increases curvilinear towards a maximum value that is called the sill.

## RESULTS AND DISCUSSION

Soil-test P values within each field ranged from Low to Very High, and STK ranged from Optimum to Very High (Table 3). Thus, the soils had adequate K according to the current ISU interpretations for corn. The pH data indicated that most fields had acidic areas, but only Field 4 had a mean pH value for which lime is recommended according to ISU interpretations (pH <6.0 or <6.3, depending on the soil series; Voss et al., 1999). However, most fields had acidic areas where soil pH could influence nutrient availability for crops. Across fields, organic matter ranged from 35 to 50 g $kg^{-1}$, and values within fields varied according to different soil series and landscape positions. In these landscapes, higher organic matter values usually are associated with higher late-spring soil moisture.

## Field Average Responses

Tillage influenced ($P \leq 0.05$) grain yield in five fields and the starter fertilizer increased yield in four fields (Table 4). A lack of tillage by starter interaction at any site ($P \leq 0.05$) indicated that the starter effect was proportionally similar for both tillage treatments. The yield response across fields due to tillage ranged from 251 to 498 kg $ha^{-1}$. The response to the strip tillage in Field 3 was comparatively similar to tillage done with a field cultivator, but in Field 6 strip tillage slightly reduced yield when compared with no-till. This result agrees with the finding of Vetsch and Randall (2002) who reported that in some years corn yield in no-till could be greater than with strip tillage. Across all fields, the tillage increased yield by 2.5 %. The yield increase from starter fertilization in Fields 2, 4, and 7 ranged from 93 to 522 kg $ha^{-1}$. A statistically significant lower yield for the starter treatment at Field 5 cannot be explained. The starter fertilizer applied in the furrow at this site did not decrease ($P \leq 0.05$) plant population (not shown) or early growth. Across all fields, the starter increased yield by 1.3 %.

Both tillage and starter fertilization increased ($P \leq 0.05$) early growth markedly in most fields (Table 5), and there was no significant tillage by starter interaction. Tillage increased early growth in Fields 2, 3, 5, 6, and 7. Other studies (Vetsch and Randall, 2002) have shown that early corn growth in conventional tillage is greater than with no-till. The largest early growth response to tillage was found in Field 1 (51%) and in Field 5 (49 %). The methods used in this study do not allow for explanations of tillage effects because important factors such as residue cover and soil temperature were not measured. The starter fertilization increased early plant growth in all fields. The largest response was observed in Fields 3 and 6 (1.0 and 1.2 g plant$^{-1}$) where mean STP was Low, but the response was also large in Field 1 (0.8 g plant$^{-1}$) where STP was Very High. Smaller differences were found at other fields (0.2 to 0.6 g plant$^{-1}$) where mean STP ranged from High to Very High. Other studies found that early growth response to starter fertilization often does not have a direct relationship to soil test values or weather conditions (Mengel et al., 1992; Randall and Hoeft, 1988).

The treatments seldom influenced early plant N, P, or K concentrations and results are not shown. Tillage decreased ($P \leq 0.05$) P concentration in Field 3 and increased it in Field 5, decreased N concentration in Fields 5 and 7, and never influenced K concentrations. Starter fertilization decreased early plant P concentration in Fields 3 and 7, and never influenced N or K concentration. These results are not surprising because effects of starter N and P on N or P concentrations often are diluted by relatively larger effects on plant growth (Mallarino et al., 1999). A lack of K concentration response was reasonable because mean STK was above optimum in all fields, and K was a component of the starter mixture only in three fields (Fields 1, 2, and 7).

Results for P and N uptake of small plants are shown in Tables 6 and 7. Tillage significantly increased P uptake in Fields 1, 5, and 7. The tillage effect could be explained by more favorable conditions for early shoot and root growth such as higher soil temperature, improved soil tilth or soil aeration. This agrees with other studies that improved soil tilth could increase P availability and consequently early P uptake when compared with untilled soils (Mackay et al., 1987). Starter fertilization increased P uptake in all fields. Relative responses were higher in Field 3 (5.4 mg plant$^{-1}$) and Field 6 (4.2 mg plant$^{-1}$) where mean STP was in the Low interpretation class. These responses coincided with larger early growth responses observed for these two fields compared with other fields. Starter fertilization and spring tillage increased ($P < 0.05$) mean P uptake across all fields by 30% and 20%, respectively. Tillage increased N uptake in most fields (except Fields 2 and 4). Starter fertilization increased N uptake in most fields (except in Field 2). Responses were larger in Fields 3 (48 mg plant$^{-1}$) and 6 (41 mg plant$^{-1}$), which coincide with larger responses in early growth and P uptake compare with other fields. Means across all fields showed that tillage and starter fertilization increased ($P < 0.05$) N uptake by 30% and 21%, respectively.

The yield responses to starter in Fields 4 and 7 cannot be easily explained by deficient P or K because mean STP and STK were in the High or Very High classes in both fields. The starter was applied 5 cm beside and below the seeds in these two fields, and the N rates applied were the highest (16.3 and 27.2 kg N ha$^{-1}$) among all fields. Although other factors may have determined the response to starter in these fields, we suggest that the starter N was responsible for the response. Previous research has shown that responses to N-P-K starter usually are due to P, but often also are explained by the N in the starter when preplant or sidedressed N rates are not high enough, and seldom are explained by K (Randall and Hoeft, 1988; Scharf, 1999). The starter increased early N uptake significantly at both sites. In Field 4, a uniform N rate (145 kg N ha$^{-1}$) was applied when corn was 15-25 cm tall. In Field 7, a uniform N rate (157 kg N ha$^{-1}$) was applied 5 months before planting. Perhaps these N rates were insufficient or were not effective.

Over all fields, tillage increased yield by 2.5%, early growth by 27% , P uptake by 20%, and N uptake by 21%. Starter increased yield by 1.3%, early growth by 29%, P uptake by 30%, and N uptake by 30%. These results suggest that starter fertilization and spring tillage increases early growth and N-P uptake of corn more frequently and to a larger extent than grain yield, and that large early growth responses are not necessarily reflected in grain yield responses.

Grain moisture at harvest time was recorded with the yield monitor, but because starter fertilization and tillage did not influence grain moisture significantly ($P \leq 0.05$) in any field, data are not shown. An analysis across all fields indicated that tillage reduced ($P \leq 0.05$) grain moisture by 3 g $kg^{-1}$ and starter fertilizer reduced grain moisture by 5 g $kg^{-1}$. Other studies (Vetsch and Randall, 2000; Wolkowski, 2000) showed starter fertilization often produced drier grain.

The starter fertilizer did not consistently influence yield variability estimated by standard deviations (SD) calculated for each treatment (Table 8). With no-till, the starter decreased yield variability in Field 6, increased it in Field 5, and did not affect it in other fields. With tillage, the starter reduced variability in Fields 2, 4, and 6; increased it in Fields 5 and 7; and did not affect it in Field 3. Starter fertilization increased early growth variability ($P \leq 0.05$) in four fields (Fields 3, 5, 6, and 7), P uptake in five fields (Fields 3, 4, 5, 6, and 7) and N uptake in four fields (Fields 3, 5, 6, and 7) and did not affect the variability of any plant measurement in any other fields. Because of the numerous SD involved (four treatments and three plant measurements) data are presented only for early growth (Table 9). Semivariogram parameters show that the structure of the spatial variability of yield differed greatly among fields (Table 8). There was a small nugget semivariance in most fields. The sill, was not consistently affected by starter fertilization. It tended to be larger for the tilled and no-till treatments in Fields 3, 5, and 7 and smaller in the other fields. Modeled semivariograms showed that the spatial structure of early growth, and P and N uptake was not consistently affected by the starter fertilizer or the tillage (only parameters for early growth are shown in Table 9).

## Treatment effects for Field Areas with Contrasting Soil Test and Soil Series

Study of yield responses for areas with different soil-test values showed that only the within-field variation in STP influenced the effect of starter fertilization and only in Fields 2 and 3 (Table

10). Early growth response to starter fertilizer analyses for areas with different STP interpretation classes showed no consistent differences (Table 11) and indicate that starter fertilization often increased early growth in field areas testing low or high in P. The results of this study and previous work (Welch et al., 1966; Randall and Hoeft, 1988; Rehm et al., 1988) suggest that increased P availability near the seeds always tended to increase early growth independently of the STP level or that early growth was responding to a nutrient other than P in the starter. Tillage increased early growth in most areas with different STP interpretation classes. Phosphorus uptake (not shown) often responded positively to starter fertilization (which confirmed results of whole-field analyses shown in Table 6) but when responses occurred, they were observed for all STP interpretation classes within a field (which agrees with the same responses obtained with early growth). Tillage did not affect P uptake consistently. It increased it in the Very High class of Field 1, 2, and 7, but also did for Field 5 in the Low class.

Analysis of variance of regression analysis of grain yield, plant DW, PU, and NU responses for field areas having different STK, pH, and organic matter within each field showed few statistically supported or consistent ($P \leq 0.05$) differences. Because of this general result, data are not shown. The finding that crop responses to starter and tillage were not related to STK in most fields, is reasonable because mean STK was borderline between the Optimum and High class or higher in all fields, and K was a component of the starter only in Fields 1, 2, and 7. Differences in crop response for areas of the fields with contrasting pH were infrequent, inconsistent, small, and difficult to explain with the methods used in this study. Yield responses to starter fertilization with different organic matter values differed ($P \leq 0.05$) only in Fields 4 and 5 and relative responses were larger in the lowest organic matter (<30 g $kg^{-1}$) class. Yield responses to tillage also were larger ($P \leq 0.05$) in the lower organic matter classes of Fields 3 and 4.

Analyses of yield response to starter fertilizer for field areas with contrasting soil series showed no differences between soils for any field except for Field 4 (Table 12). In this field there was a response to starter ($P \leq 0.05$) in areas with Dickinson series and no response in areas with Klinger series. The Dickinson series is an excessively well-drained soil found in upland positions with moderate slopes (Iowa Coop. Soil Survey, available online at http://icss.agron.iastate.edu). The mean STP for areas of the Dickinson series was in the High class and for the Klinger series in the Very High class. We expected starter fertilizer responses in field areas with low-laying, wet, and poorly drained soils which are conditions that may promote low nutrient availability in spring.

Yield responses to tillage were more pronounced than starter fertilizer for field areas with contrasting soil series and responses differed ($P \leq 0.05$) in three fields. In Fields 5 and 7 there was a response in areas with Sawmill, Kenyon, and Dinsdale soil series and no response in areas with Klinger series. The Dinsdale and Kenyon series are well-drained, loam or silty clay loam soils of upland and moderately sloping topographic positions; the Sawmill series are poorly to moderately well-drained, fine-silty soils found in valleys; and the Klinger series are somewhat poorly drained, silty loam or silty clay loam soils found in upland positions with small slope. In Field 3 (located western Iowa), there was response in areas with Marshall series and no analysis was performed for the second predominant soil series (Colo) because the area was flooded and poor yield data were recovered. The Marshall series series is a well-drained, silty clay loam soil found in ridges or slopes of upland positions, and the Colo include poorly drained, silty clay found in valleys often subject to flooding. We expected tillage responses in field areas with high amount of surface residue and fine textured soils that may promote poor aeration and cooler soil temperatures.

Analyses of early growth responses to starter fertilizer for field areas with different soil series showed differences ($P \leq 0.05$) between soils only for Fields 2 and 6 (Table 13). Responses for early N and P uptake were similar to early growth responses (not shown). In Field 2, there was a response in the Donnan series, which is a fine-loamy and moderately well-drained soil, and no response in the Kenyon series. In Field 6 responses were observed in the Marshall soil but not in the Colo series. These results are difficult to explain with the method used. Mean STP, organic matter, particle size, and drainage pattern were similar for both soil series in Field 2. Variations in the soil series for Field 6 were more pronounced, and the responses found in the Marshall soil are reasonable because it had significantly lower mean STP.

Early growth responses to tillage were more pronounced than starter fertilizer for field areas with contrasting soil series and responses differed ($P \leq 0.05$) in four fields. In Fields 1, 2, and 7 there was a response in areas with Maxfield, Donnan, and Dinsdale soil series and no response in areas with Muscatine, Kenyon, and Klinger. The Donnan and Dinsdale series are well-drained to moderately well-drained soils, loam or silty clay loam soils of upland and moderately to strongly sloping topographic positions; the Maxfield series consist of deep, nearly level, poorly drained soils. In Field 6, there was response in areas with Marshall and not for the Colo series. We expected tillage responses in field areas low-laying, wet, and fine textured soils that can promote cooler soils.

Correlation and regression analyses showed poor relationships between STP or organic matter with relative grain yield or plant responses within and across fields (Table 14). Soil test P and the relative yield increase due to starter fertilization were correlated in Fields 2, 4, 5, and 6. In these fields, the response to starter fertilization decreased linearly from areas with low STP to areas with higher STP. The correlations between organic matter and relative yield increase were negative for Fields 2, 4, and 5 and positive in Field 7. Trends of significant relationship involving yield were linear in most instances.

No clear conclusions were possible from study of relationships between response of the plant measurements and STP or organic matter and results are not shown. There were few instances in which linear trends were statistically significant ($P \leq 0.05$), and were either negative (as expected) or positive (an unexpected and difficult to explain result). However, N uptake often increased with increase soil organic matter.

## CONCLUSIONS

Grain yield, early plant growth, and early nutrient uptake often were greater with tillage than with no-tillage. Frequent and large early growth and nutrient uptake responses to tillage were not reflected in large grain yield responses. Across all sites, tillage increased yield by 2.5%, early growth by 27% , P uptake by 20% and N uptake by 21%. Spring tillage produced higher and more consistent yield responses than starter fertilization. Yield responses to starter fertilization were less frequent and smaller than for tillage, and did not substitute for tillage effects on yield. Early growth and nutrient uptake responses to starter were large, and occurred in most fields and in most areas within fields. Across all sites, starter increased yield by 1.3%, early growth by 29%, P uptake by 30% and N uptake by 30%. These responses sometimes were larger when STP was low but were also observed when STP was high. Yield responses in some areas with high STP could partly be attributed to either the P or N in the starter. Tillage and starter fertilization increased early growth markedly in all fields, although starter fertilization produced a higher increase than tillage.

Standard deviations indicated inconsistent differences in yield variability between starter and no starter treatment, while spring tillage tended to increase yield variability. Dry weight and nutrient uptake variability were higher for the starter fertilizer application and tillage effect. Modeled semivariograms showed that the spatial structure of the variability of all plant measurements was not consistently affected by the tillage or starter treatment.

Overall, the results indicated that frequent and large responses of early corn growth and nutrient uptake to starter fertilization resulted in small and poorly predictable yield responses. The yield response to tillage was smaller than for early growth and nutrient uptake but was more consistent across fields than responses to starter fertilization.

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Table 1. Field locations and predominant soils series for seven strip trials.

| Field | County | Year | Dominant soil series | | | | | Second dominant soil series | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Series | Classification | Area | STP | OM | Series | Classification | Area | STP | OM |
| | | | | | % | mg kg$^{-1}$ | g kg$^{-1}$ | | | % | mg kg$^{-1}$ | g kg$^{-1}$ |
| 1 | Benton | 1998 | Maxfield | T. Endoaquolls | 78 | 48 | 48 | Muscatine | A. Hapludolls | 20 | 45 | 45 |
| 2 | Grundy | 1998 | Donnan | A. Hapludalfs | 42 | 21 | 33 | Kenyon | T. Hapludolls | 32 | 19 | 31 |
| 3 | Carroll | 1998 | Marshall | T. Hapludolls | 90 | 14 | 38 | Colo | C. Endoaquolls | 10 | 18 | 40 |
| 4 | Linn | 1998 | Klinger | A. Hapludolls | 82 | 38 | 35 | Dickinson | T. Hapludolls | 11 | 30 | 31 |
| 5 | Grundy | 1999 | Sawmill | C. Endoaquolls | 42 | 18 | 56 | Kenyon | T. Hapludolls | 37 | 19 | 45 |
| 6 | Carroll | 1999 | Marshall | T. Hapludolls | 88 | 15 | 39 | Colo | C. Endoaquolls | 12 | 25 | 52 |
| 7 | Linn | 1999 | Dinsdale | T. Argiudolls | 50 | 43 | 41 | Klinger | A. Hapludolls | 34 | 50 | 51 |

† A= Aquic, C= Cumulic, T= Typic.

Table 2. Corn hybrids, planting dates, seeding rates, starter mixtures, and rates used for seven strip trials.

| Field | Hybrid † | Planting date | Seeding rate | Starter fertilizer | | Nutrient rate | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Mixture ‡ | Rate | N | P | K |
| | | | Seeds $ha^{-1}$ | | ------------------ kg $ha^{-1}$ ------------------ | | | |
| 1 | DK586 | 29 Apr | 71600 | 6-8-6-0 | 65 | 3.9 | 5.2 | 1.6 |
| 2 | A601 | 11 May | 76100 | 7-8-5-0 | 65 | 4.5 | 5.2 | 1.3 |
| 3 | DK580RR | 25 Apr | 62500 | 10-15-0-0 | 86 | 8.6 | 12.8 | 0 |
| 4 | GHH2390 | 14 May | 76100 | 10-15-0-0 | 163 | 16.3 | 24.2 | 0 |
| 5 | P34R07 | 29 Apr | 76600 | 10-15-0-0 | 91 | 9.1 | 13.5 | 0 |
| 6 | DK580RR | 20 Apr | 62500 | 10-15-0-0 | 74 | 7.4 | 11.0 | 0 |
| 7 | GHH2529 | 9 May | 76600 | 16-10-3-1 | 170 | 27.2 | 12.1 | 4.1 |

† DK = Dekalb, A = Asgrow, GHH = Golden Harvest, P = Pioneer.
‡ Analysis of the commercial starter fertilizer used (N-P-K-S).

Table 3. Descriptive statistics for soil-test P, K, pH, and organic matter†.

| Field | Mean | Median | Min | Max | SD |
|---|---|---|---|---|---|
| | Soil-test P | | | | |
| | mg kg$^{-1}$ | | | | |
| 1 | 48 | 45 | 21 | 99 | 16 |
| 2 | 23 | 21 | 10 | 96 | 10 |
| 3 | 15 | 14 | 10 | 23 | 4 |
| 4 | 37 | 35 | 14 | 79 | 13 |
| 5 | 17 | 14 | 7 | 51 | 8 |
| 6 | 16 | 14 | 7 | 38 | 7 |
| 7 | 48 | 45 | 18 | 102 | 14 |
| | Soil-test K | | | | |
| | mg kg$^{-1}$ | | | | |
| 1 | 158 | 146 | 95 | 258 | 34 |
| 2 | 143 | 141 | 76 | 215 | 24 |
| 3 | 189 | 185 | 131 | 247 | 25 |
| 4 | 137 | 128 | 89 | 226 | 32 |
| 5 | 146 | 144 | 104 | 227 | 26 |
| 6 | 203 | 203 | 167 | 265 | 22 |
| 7 | 189 | 185 | 107 | 320 | 37 |
| | pH | | | | |
| 1 | 6.2 | 6.3 | 5.5 | 6.9 | 0.4 |
| 2 | 6.3 | 6.3 | 5.7 | 7.0 | 0.3 |
| 3 | 6.3 | 6.2 | 6.0 | 6.8 | 0.2 |
| 4 | 5.5 | 5.6 | 5.0 | 6.0 | 0.3 |
| 5 | 6.2 | 6.1 | 5.4 | 7.1 | 0.4 |
| 6 | 6.2 | 6.2 | 5.6 | 6.8 | 0.3 |
| 7 | 6.0 | 6.0 | 5.2 | 6.7 | 0.3 |
| | Organic matter | | | | |
| | g kg$^{-1}$ | | | | |
| 1 | 47 | 46 | 36 | 61 | 6 |
| 2 | 35 | 36 | 10 | 50 | 7 |
| 3 | 38 | 40 | 25 | 44 | 5 |
| 4 | 35 | 35 | 20 | 44 | 5 |
| 5 | 50 | 48 | 37 | 70 | 8 |
| 6 | 40 | 40 | 28 | 61 | 6 |
| 7 | 43 | 46 | 10 | 74 | 12 |

†Min= minimum, Max= maximum, SD= standard deviation.

Table 4. Corn grain yield response to tillage and starter fertilization for seven strip trials.

| Field | Tillage effect across starter † | | | Starter effect across tillage † | | |
|---|---|---|---|---|---|---|
| | T | NT | Statistics ‡ | S | NS | Statistics ‡ |
| | ------- kg $ha^{-1}$ ------- | | $P > F$ | ------- kg $ha^{-1}$ ------- | | $P > F$ |
| 1 | 9386 | 9150 | 0.09 | 9305 | 9230 | 0.74 |
| 2 | 9932 | 9673 | 0.01 | 9890 | 9715 | 0.01 |
| 3 | 9760 | 9463 | 0.01 | 9670 | 9553 | 0.16 |
| 4 | 10559 | 10299 | 0.15 | 10690 | 10168 | 0.01 |
| 5 | 12043 | 11545 | 0.01 | 11746 | 11843 | 0.02 |
| 6 | 11309 | 11339 | 0.93 | 11352 | 11296 | 0.46 |
| 7 | 11121 | 10870 | 0.02 | 11042 | 10949 | 0.03 |
| Mean | 10591 | 10328 | 0.01 | 10518 | 10401 | 0.06 |

† T = Tillage, NT = No-Till, S = Starter, NS = No Starter.

‡ There were no significant interactions between tillage effect and starter.

Table 5. Early plant dry weight (V5 to V6) response to tillage and starter fertilization for seven strip trials.

| Field | Tillage effect across starter † | | | Starter effect across tillage † | | |
|---|---|---|---|---|---|---|
| | T | NT | Statistics ‡ | S | NS | Statistics ‡ |
| | ------- g plant$^{-1}$ ------- | | $P > F$ | ------- g plant$^{-1}$ ------- | | $P > F$ |
| 1 | 3.24 | 2.14 | 0.07 | 3.09 | 2.30 | 0.01 |
| 2 | 2.44 | 1.94 | 0.04 | 2.31 | 2.07 | 0.03 |
| 3 | 3.06 | 2.76 | 0.03 | 3.52 | 2.30 | 0.01 |
| 4 | 2.98 | 2.69 | 0.47 | 3.07 | 2.60 | 0.02 |
| 5 | 5.95 | 4.00 | 0.01 | 5.42 | 4.54 | 0.01 |
| 6 | 2.92 | 2.33 | 0.03 | 3.15 | 2.10 | 0.01 |
| 7 | 7.96 | 6.93 | 0.02 | 8.02 | 6.88 | 0.01 |
| Mean | 4.12 | 3.28 | 0.01 | 4.12 | 3.28 | 0.01 |

† T = Tillage, NT = No-Till, S = Starter, NS = No Starter.

‡ There were no significant interactions between tillage effect and starter.

Table 6. Early P uptake response to tillage and starter fertilization for seven strip trials.

| Field | Tillage effect across starter † | | | Starter effect across tillage † | | |
|---|---|---|---|---|---|---|
| | T | NT | Statistics ‡ | S | NS | Statistics ‡ |
| | ----- mg P plant$^{-1}$ ----- | | $P > F$ | ----- mg P plant$^{-1}$ ----- | | $P > F$ |
| 1 | 12.84 | 8.75 | 0.01 | 12.13 | 9.46 | 0.01 |
| 2 | 7.95 | 6.64 | 0.12 | 7.67 | 6.92 | 0.03 |
| 3 | 14.52 | 13.80 | 0.13 | 16.86 | 11.46 | 0.01 |
| 4 | 9.35 | 8.49 | 0.51 | 10.14 | 7.70 | 0.05 |
| 5 | 17.55 | 14.29 | 0.03 | 17.45 | 14.39 | 0.01 |
| 6 | 12.55 | 10.19 | 0.08 | 13.44 | 9.30 | 0.01 |
| 7 | 30.04 | 26.96 | 0.01 | 32.05 | 24.96 | 0.01 |
| Mean | 15.19 | 12.88 | 0.01 | 15.89 | 12.19 | 0.01 |

† T = Tillage, NT = No-Till, S = Starter, NS = No Starter.

‡ There were no significant interactions between tillage effect and starter.

Table 7. Early N uptake response to tillage and starter fertilization for seven strip trials.

| Field | Tillage effect across starter † | | | Starter effect across tillage † | | |
|---|---|---|---|---|---|---|
| | T | NT | Statistics ‡ | S | NS | Statistics ‡ |
| | ----- mg N plant$^{-1}$ ----- | | $P > F$ | ----- mg N plant$^{-1}$ ----- | | $P > F$ |
| 1 | 123.73 | 86.92 | 0.01 | 119.08 | 91.57 | 0.01 |
| 2 | 85.52 | 71.30 | 0.11 | 82.30 | 74.51 | 0.07 |
| 3 | 116.15 | 102.88 | 0.03 | 133.54 | 85.49 | 0.01 |
| 4 | 97.38 | 89.72 | 0.62 | 104.02 | 83.08 | 0.01 |
| 5 | 174.24 | 135.97 | 0.01 | 167.91 | 142.30 | 0.01 |
| 6 | 111.76 | 90.30 | 0.04 | 121.29 | 80.77 | 0.01 |
| 7 | 293.41 | 263.21 | 0.02 | 300.44 | 256.18 | 0.01 |
| Mean | 144.93 | 121.10 | 0.01 | 148.52 | 117.51 | 0.01 |

† T = Tillage, NT = No-Till, S = Starter, NS = No Starter.

‡ There were no significant interactions between tillage effect and starter.

Table 8. Effect of tillage and starter fertilization on corn grain yield variability and spatial structure.

| Field | Treatment§ | Yield variation† SD | $P>F$ | Semivariogram parameters (spherical model)‡ Nugget | Sill | Range |
|---|---|---|---|---|---|---|
| | | ---- kg ha$^{-1}$ ---- | | $C_0$ (x10$^3$) | $C_0 + C$ (x10$^3$) | m |
| 2 | TS | 533 | 0.04 | 12 | 226 | 82 |
| | TNS | 608 | | 24 | 453 | 96 |
| | NTS | 689 | 0.34 | 19 | 352 | 95 |
| | NTNS | 667 | | 24 | 462 | 120 |
| 3 | TS | 2326 | 0.21 | 293 | 5559 | 127 |
| | TNS | 2120 | | 212 | 4029 | 90 |
| | NTS | 2033 | 0.24 | 211 | 4004 | 133 |
| | NTNS | 1877 | | 148 | 2815 | 70 |
| 4 | TS | 1151 | 0.06 | 44 | 836 | 186 |
| | TNS | 1431 | | 51 | 969 | 200 |
| | NTS | 680 | 0.47 | 11 | 201 | 65 |
| | NTNS | 688 | | 19 | 356 | 103 |
| 5 | TS | 703 | 0.01 | 16 | 309 | 62 |
| | TNS | 570 | | 9 | 173 | 67 |
| | NTS | 543 | 0.05 | 17 | 326 | 50 |
| | NTNS | 465 | | 12 | 237 | 66 |
| 6 | TS | 458 | 0.02 | 14 | 259 | 40 |
| | TNS | 573 | | 20 | 376 | 38 |
| | NTS | 542 | 0.06 | 17 | 331 | 52 |
| | NTNS | 647 | | 25 | 475 | 67 |
| 7 | TS | 729 | 0.06 | 16 | 313 | 57 |
| | TNS | 631 | | 13 | 252 | 52 |
| | NTS | 626 | 0.40 | 13 | 244 | 67 |
| | NTNS | 612 | | 10 | 184 | 51 |

† SD = Standard deviation. The number of observations (n) and variances for $F$ tests correspond to means of yield monitor points recorded at 1-s intervals for areas delineated by the width of the combine and 15 m length. The n values ranged from 54 to 168.

‡ The maximum lag distance ranged from 160 to 320 m.

§ TS = Tillage with starter, TNS = Tillage without starter, NTS = No till with starter, NTNS = No till without starter.

Table 9. Effect of tillage and starter fertilization on early dry weight variability and spatial structure

| Field | Treatment[§] | Dry weight variation[†] SD | Dry weight variation[†] $P>F$ | Semivariogram parameters (spherical model)[‡] Nugget | Sill | Range |
|---|---|---|---|---|---|---|
| | | ---- g $pl^{-1}$ ---- | | $C_0$ | $C_0 + C$ | m |
| 1 | TS | 0.67 | 0.27 | 0.05 | 0.29 | 54 |
| | TNS | 0.59 | | 0.03 | 0.33 | 70 |
| | NTS | 0.44 | 0.20 | 0.10 | 0.15 | 54 |
| | NTNS | 0.37 | | 3.57 | 3.68 | 65 |
| 2 | TS | 0.43 | 0.31 | 0.01 | 0.17 | 97 |
| | TNS | 0.46 | | 0.03 | 0.19 | 73 |
| | NTS | 0.42 | 0.36 | 0.13 | 0.13 | 73 |
| | NTNS | 0.44 | | 0.03 | 0.18 | 73 |
| 3 | TS | 0.65 | 0.01 | 0.36 | 0.36 | 76 |
| | TNS | 0.45 | | 0.01 | 0.20 | 80 |
| | NTS | 0.55 | 0.33 | 0.09 | 0.31 | 61 |
| | NTNS | 0.59 | | 0.34 | 0.34 | 76 |
| 4 | TS | 1.15 | 0.15 | 0.19 | 0.54 | 127 |
| | TNS | 0.90 | | 0.02 | 0.60 | 220 |
| | NTS | 0.57 | 0.44 | 0.00 | 0.33 | 74 |
| | NTNS | 0.59 | | 0.31 | 0.31 | 73 |
| 5 | TS | 1.87 | 0.18 | 1.48 | 3.10 | 68 |
| | TNS | 1.65 | | 2.54 | 3.19 | 68 |
| | NTS | 0.88 | 0.05 | 0.85 | 0.85 | 86 |
| | NTNS | 0.70 | | 0.15 | 0.61 | 69 |
| 6 | TS | 1.19 | 0.05 | 0.00 | 1.51 | 104 |
| | TNS | 0.92 | | 0.40 | 1.03 | 98 |
| | NTS | 0.96 | 0.01 | 0.03 | 0.72 | 114 |
| | NTNS | 0.46 | | 0.14 | 0.24 | 98 |
| 7 | TS | 1.51 | 0.02 | 0.94 | 2.01 | 187 |
| | TNS | 1.14 | | 0.38 | 1.37 | 188 |
| | NTS | 1.45 | 0.11 | 2.10 | 2.10 | 0 |
| | NTNS | 1.24 | | 1.20 | 1.20 | 0 |

† SD = Standard deviation. The number of observations (n) and variances for $F$ tests correspond to data derived from one sampling point from each small cell defined by a treatment strip and 45 m length. The n values ranged from 18 to 60.

‡ The maximum lag distance ranged from 120 to 260 m.

§ TS = Tillage with starter, TNS = Tillage without starter, NTS = No till with starter, NTNS = No till without starter.

Table 10. Grain yield response to starter fertilization for areas of six fields with different soil-test P values.

| | Soil-test P class | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | | | | Optimum | | | | High | | | | Very High | | | |
| Field | ABS† | REL‡ | *P>F* | A§ | ABS | REL | *P>F* | A | ABS | REL | *P>F* | A | ABS | REL | *P>F* | A |
| | kg ha$^{-1}$ | % | | % | kg ha$^{-1}$ | % | | % | kg ha$^{-1}$ | % | | % | kg ha$^{-1}$ | % | | % |
| 2 | 373 | 4.0 | 0.05 | 13 | 182 | 1.9 | 0.42 | 27 | 165 | 1.7 | 0.42 | 41 | 37 | 0.4 | 0.74 | 19 |
| 3 | 171 | 1.7 | 0.44 | 60 | 71 | 0.8 | 0.37 | 40 | -¶ | - | - | - | - | - | - | - |
| 4 | - | - | - | - | - | - | - | - | 574 | 5.7 | 0.01 | 22 | 495 | 4.9 | 0.10 | 78 |
| 5 | -19 | -0.2 | 0.70# | 50 | -73 | -0.6 | 0.63 | 25 | -191 | -1.6 | 0.30 | 18 | -424 | -3.6 | 0.06 | 7 |
| 6 | 66 | 0.6 | 0.43 | 57 | -131 | -1.2 | 0.44# | 18 | 161 | 1.4 | 0.62 | 25 | - | - | - | - |
| 7 | - | - | - | - | - | - | - | - | - | - | - | - | 96 | 0.9 | 0.47 | 100 |

† ABS= absolute yield response to starter fertilization across tillage. Starter - No starter.

‡ REL= relative yield response to starter fertilization across tillage. (Starter - No starter) / No starter * 100.

§ A= percentage area for each soil-test P class. Percentage area for the mean was calculated based on the total number of cells.

¶ Only two or fewer soil samples tested in that class and were not used for this analysis.

# Significant interaction for tillage effect by starter ($P \leq 0.05$).

Table 11. Early dry weight response to starter fertilization for areas of seven fields with different soil-test P values.

| | Soil-test P class | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | | | | Optimum | | | | High | | | | Very High | | | |
| Field | ABS† | REL‡ | *P>F* | A§ | ABS | REL | *P>F* | A | ABS | REL | *P>F* | A | ABS | REL | *P>F* | A |
| | g pl$^{-1}$ | % | | % | g pl$^{-1}$ | % | | % | g pl$^{-1}$ | % | | % | g pl$^{-1}$ | % | | % |
| 1 | -¶ | - | - | - | - | - | - | - | - | - | - | - | 0.78 | 33.8 | 0.01 | 100 |
| 2 | 0.18 | 9.6 | 0.19 | 13 | 0.05 | 1.9 | 0.85 | 27 | 0.37 | 18.0 | 0.03 | 41 | 0.28 | 12.7 | 0.19 | 19 |
| 3 | 1.23 | 54.8 | 0.01 | 60 | 1.22 | 51.0 | 0.01 | 40 | - | - | - | - | - | - | - | - |
| 4 | - | - | - | - | - | - | - | - | 0.79 | 33.1 | 0.08 | 22 | 0.36 | 13.5 | 0.26 | 78 |
| 5 | 0.86 | 20.0 | 0.01 | 50 | 1.07 | 23.5 | 0.04 | 25 | 0.90 | 20.2 | 0.05 | 18 | 0.40 | 6.4 | 0.98 | 7 |
| 6 | 0.35 | 13.4 | 0.06 | 57 | 0.21 | 8.9 | 0.55 | 18 | 1.27 | 47.4 | 0.03 | 25 | - | - | - | - |
| 7 | - | - | - | - | - | - | - | - | - | - | - | - | 1.14 | 16.6 | 0.01 | 100 |

† ABS= absolute yield response to starter fertilization across tillage. Starter - No starter.

‡ REL= relative yield response to starter fertilization across tillage. (Starter - No starter) / No starter * 100.

§ A= percentage area for each soil-test P class. Percentage area for the mean was calculated based on the total number of cells.

¶ Only two or fewer soil samples tested in that class and were not used for this analysis.

Table 12. Corn yield response to tillage and starter fertilization for the two predominant soils series for six strip trials.

| | Predominant soil series | | Yield Response | | | | | |
|---|---|---|---|---|---|---|---|---|
| Field | Series | Classification † | Tillage | | *P>F* | Starter | | *P>F* |
| | | | kg ha$^{-1}$ | % | | kg ha$^{-1}$ | % | |
| 2 | Donnan | A. Hapludalfs | 283 | 3.0 | 0.18 | 314 | 3.3 | 0.15 |
| | Kenyon | T. Hapludolls | 393 | 4.2 | 0.19 | 63 | 0.7 | 0.48 |
| 3‡ | Marshall | T. Hapludolls | 417 | 4.3 | 0.02 | 222 | 2.2 | 0.19 |
| 4 | Klinger | A. Hapludolls | 276 | 2.7 | 0.32 | 476 | 4.7 | 0.11 |
| | Dickinson | T. Hapludolls | 1016 | 9.4 | 0.18 | 831 | 7.6 | 0.06 |
| 5 | Sawmill | C. Endoaquolls | 505 | 4.4 | 0.01 | -182 | -1.5 | 0.35 |
| | Kenyon | T. Hapludolls | 614 | 5.4 | 0.01 | -41 | -0.3 | 0.73 |
| 6 | Marshall | T. Hapludolls | -38 | -0.3 | 0.46 | 64 | 0.6 | 0.46 |
| | Colo | C. Endoaquolls | 350 | 3.2 | 0.11 | 270 | 2.5 | 0.29 |
| 7 | Dinsdale | T. Argiudolls | 446 | 4.2 | 0.01 | 197 | 1.8 | 0.23 |
| | Klinger | A. Hapludolls | 65 | 0.6 | 0.54 | 8 | 0.1 | 0.75 |

† A= Aquic, C= Cumulic, T= Typic.

‡ Analysis not performed for the second predominant soil series because the area was flooded and poor yield data were recovered.

Table 13. Early dry weight response to tillage and starter fertilization for the two predominant soils series for seven strip trials.

| | Predominant soil series | | Early dry weight response | | | | | |
|---|---|---|---|---|---|---|---|---|
| Field | Series | Classification † | Tillage | | *P>F* | Starter | | *P>F* |
| | | | g $pl^{-1}$ | % | | g $pl^{-1}$ | % | |
| 1 | Maxfield | T. Endoaquolls | 1.19 | 56.2 | 0.01 | 0.79 | 34.2 | 0.01 |
| | Muscatine | A. Hapludolls | 0.45 | 19.7 | 0.20 | 0.95 | 46.3 | 0.01 |
| 2 | Donnan | A. Hapludalfs | 0.55 | 31.5 | 0.01 | 0.33 | 17.9 | 0.01 |
| | Kenyon | T. Hapludolls | 0.40 | 19.8 | 0.16 | 0.23 | 10.8 | 0.15 |
| 3 | Marshall | T. Hapludolls | 0.30 | 10.9 | 0.02 | 1.17 | 51.2 | 0.01 |
| | Colo | C. Endoaquolls | 0.35 | 11.0 | 0.05 | 1.75 | 69.3 | 0.01 |
| 4 | Klinger | A. Hapludolls | 0.22 | 8.2 | 0.50 | 0.41 | 15.9 | 0.25 |
| | Dickinson | T. Hapludolls | 0.75 | 25.6 | 0.21 | 0.26 | 8.2 | 0.45 |
| 5 | Sawmill | C. Endoaquolls | 2.32 | 58.3 | 0.01 | 1.04 | 22.5 | 0.04 |
| | Kenyon | T. Hapludolls | 2.08 | 55.4 | 0.01 | 1.00 | 23.3 | 0.01 |
| 6 | Marshall | T. Hapludolls | 0.61 | 26.9 | 0.01 | 1.06 | 52.6 | 0.01 |
| | Colo | C. Endoaquolls | 0.55 | 16.7 | 0.17 | 0.94 | 30.6 | 0.13 |
| 7 | Dinsdale | T. Argiudolls | 1.40 | 20.6 | 0.01 | 1.20 | 17.4 | 0.01 |
| | Klinger | A. Hapludolls | 0.48 | 6.7 | 0.11 | 0.85 | 12.1 | 0.01 |

† A= Aquic, C= Cumulic, T= Typic.

Table 14. Correlation coefficients of within-field relationships between soil-test P and organic matter with relative plant responses †.

| | | Plant response and correlation coefficient | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Soil test P | | | Organic Matter | | | |
| Field | Effect | Yield | Dry Weight | P Uptake | Yield | Dry Weight | P Uptake | N Uptake |
| 1 | Tillage | na‡ | 0.14 | 0.25 * | na | 0.19 * | 0.29 * | 0.37 * |
| | Starter | na | -0.02 | 0.01 | na | 0.13 | 0.20 * | 0.20 * |
| 2 | Tillage | -0.03 | -0.01 | -0.01 | -0.33 * | 0.18 * | 0.29 * | 0.17 * |
| | Starter | -0.20 * | 0.08 | 0.02 | -0.17 * | -0.06 | -0.11 * | -0.10 * |
| 3 | Tillage | 0.01 | 0.06 | 0.06 | -0.17 * | 0.07 | 0.06 * | 0.06 |
| | Starter | -0.11 | 0.22 * | 0.07 | -0.11 | -0.22 * | -0.08 | -0.26 * |
| 4 | Tillage | 0.40 * | 0.15 | -0.03 | -0.35 * | -0.36 * | -0.25 * | -0.35 * |
| | Starter | -0.30 * | 0.01 | -0.05 | -0.20 * | -0.31 * | -0.29 * | -0.25 * |
| 5 | Tillage | 0.15 * | 0.35 * | 0.21 * | 0.18 * | -0.12 * | -0.12 * | -0.18 * |
| | Starter | -0.23 * | -0.06 | -0.16 * | -0.17 * | 0.04 | 0.07 | 0.06 |
| 6 | Tillage | 0.22 * | 0.14 * | 0.28 * | -0.02 | 0.12 * | 0.15 * | 0.12 * |
| | Starter | -0.12 * | 0.26 * | 0.30 * | 0.06 | 0.23 * | 0.16 * | 0.22 * |
| 7 | Tillage | 0.11 * | 0.13 * | 0.10 * | 0.07 | -0.20 * | -0.09 * | -0.30 * |
| | Starter | 0.01 | 0.04 | -0.08 | 0.09 * | -0.33 * | -0.26 * | -0.27 * |
| Overall | Tillage | 0.03 | -0.11 * | -0.02 | 0.02 | 0.14 * | 0.03 | -0.01 |
| | Starter | -0.02 | -0.05 * | 0.06 * | -0.17 * | -0.06 * | -0.08 * | -0.10 * |

† Relative increase (yield or plant measurement) between starter fertilizer and no starter across tillage or between tillage and no-till across starter.

* Significant at $P < 0.05$.

‡ na = not available (only mean yield was recovered from the electronic card).

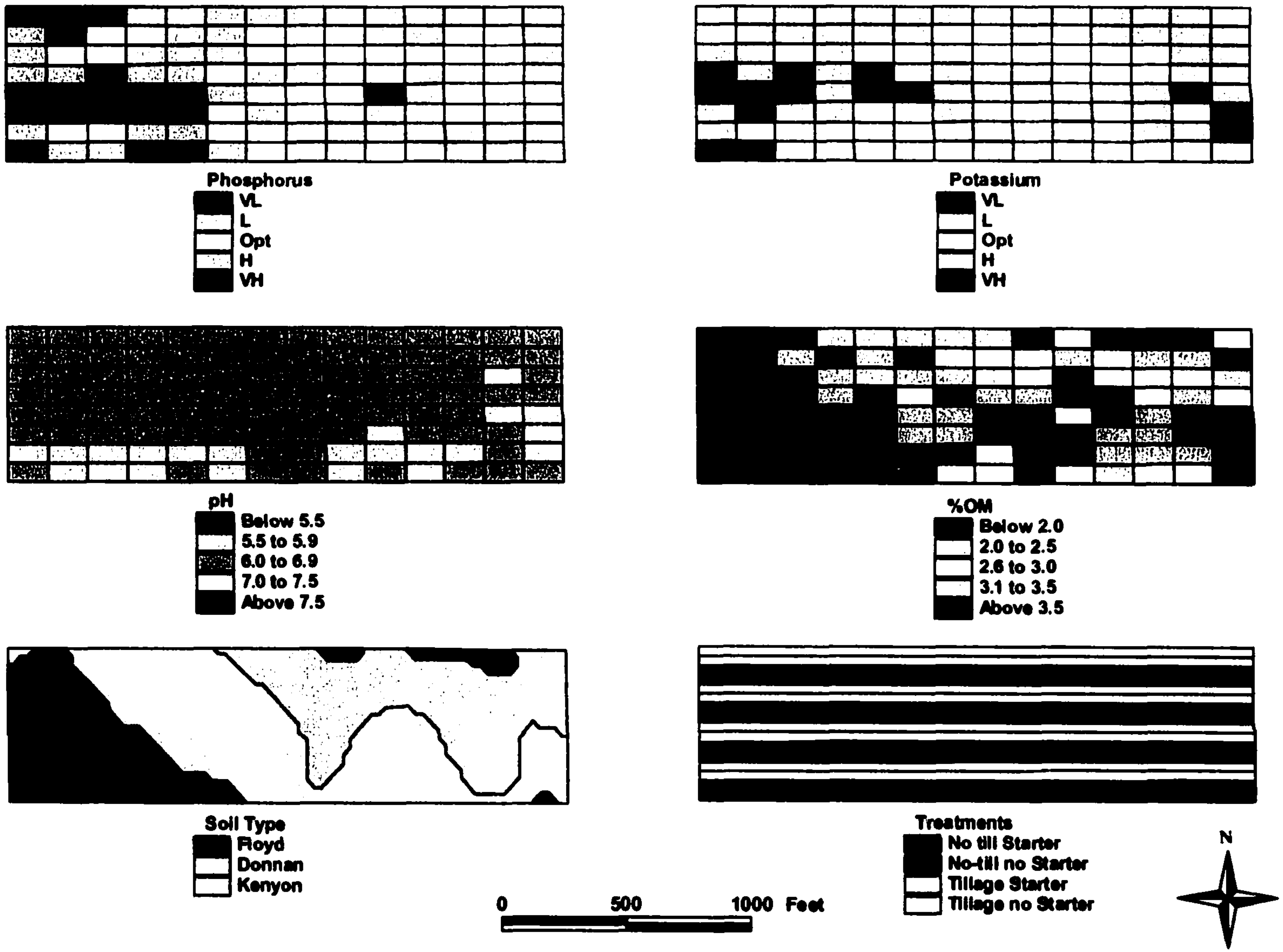


Figure 1. Example (Field 3) of field and GIS methods used. Treatments, soils series, and soil sampling for various soil test.

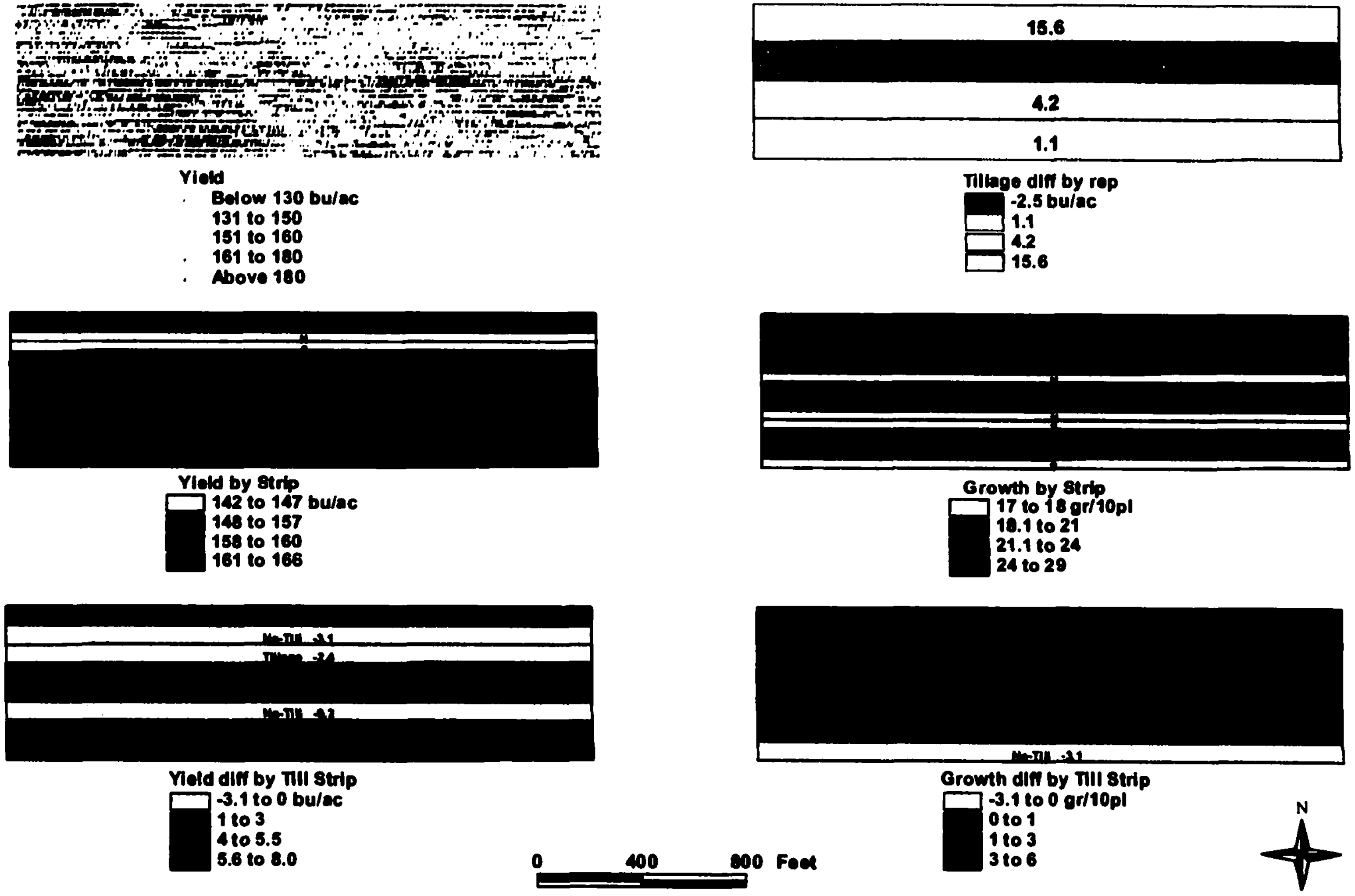


Figure 2. Example (Field 3) of field and GIS methods used. Yield map, yield difference due to spring tillage by replication, mean yield and early growth by strip, and yield and early growth difference by tillage strip.

# CHAPTER 3.

# YIELD RESPONSE TO UNIFORM AND VARIABLE-RATE PHOSPHORUS FERTILIZATION FOR CORN AND SOYBEAN

A paper to be submitted to Agronomy Journal

Manuel Bermudez and Antonio Mallarino

## ABSTRACT

Most agricultural fields have high nutrient variability. Variable-rate (VR) technology facilitates the application of different fertilization rates over a field and may reduce within-field nutrient and yield variability while maintaining or increasing yield. Replicated strip trials (10 to 20 ha) were established in six Iowa fields (20 site-yr) to compare VR and uniform-rate (UR) P fertilization for the corn (*Zea mays* L.)-soybean (*Glycine max* L. Merr.) rotation. Treatments were a check, VR based on soil-test P (STP) from 0.1-0.3 ha grid soil sampling schemes, and UR based on field-average STP. Iowa P recommendations for the 2-year crop rotation were used. Grain was harvested with yield monitors and P was applied with commercial VR spreaders equipped with differential global positioning systems (DGPS). There were whole-field yield responses ($P \leq 0.05$) to P fertilizer in 11 site-years. Mean initial STP was ≤ 16 mg P $kg^{-1}$ (Bray-$P_1$) in all responsive fields. Within-field crop responses to P were higher in low-testing areas. Assessment of yield responses to P for different soil series showed larger responses in areas of Clarion (Typic Hapludoll) soil. However, this soil often had lower STP than other soils. The UR method increased yield more than VR in one field, but the reverse result was observed in another field. The two methods seldom differed for field areas with contrasting STP or soil series. Fertilizer recommendations for

low-testing soils higher than needed to maximize yield may explain the lack of difference between VR and UR. Yield standard deviations (SD) and modeled semivariograms showed that VR tended to reduce yield variability. The VR method reduced the total amount of fertilizer applied in nine fields (35% on average) and increased it in three fields (21%). Current VR fertilization technology is useful to reduce nutrient variability, avoid excess fertilization of high-testing field areas, and to improve nutrient management but will not necessarily produce higher yields.

Abbreviations: ANOVA, analysis of variance; DGPS, differential global positioning systems; UR, uniform rate; GIS, geographical information systems; ISU, Iowa State University; NNA, nearest neighbor analysis; RCBD, randomized complete-block design; SD, standard deviation; STP, soil-test P; VR, variable rate.

## INTRODUCTION

Precision farming technologies such as yield monitors, differential global positioning systems (DGPS), and geographical information systems (GIS), are widely used for monitoring and mapping soil test and spatial yield variability. Agricultural fields usually include several soil map units that may have different nutrient supplying capabilities (Fergurson and Gorby, 1967; Power et al., 1961). Schweitzer (1980) reported that differences in fertility levels between soils sometimes are a major cause of yield variation within a field. Soil properties may influence nutrient availability by affecting the total amount of nutrients in soils or the fraction that is available to crops (Mulla and Schepers, 1997). Spatial variability of soil properties can range from regional scales to a sub-cm scale (Yost et al., 1982; Cahn et al., 1994; Franzen and Peck, 1995). It is the within-field variability that is of concern for soil testing and fertilizer application. Studies of STP spatial variability have shown large within-field variability even in fields with apparent uniform soil properties (Peck and Melsted, 1973; Cahn et al., 1994; Franzen and Peck, 1995; Mallarino and Wittry, 2002). The usual practice of applying a uniform rate of fertilizer to an entire field may be inefficient because it may overfertilize some areas and underfertilize others (Wibawa et al., 1993; Sawyer, 1994), decrease efficiency in use of fertilizer resources, and increase potential for contamination of surface and ground water. Use of VR technology allows for changes in fertilizer rates on-the-go and better control of the amount of the inputs applied to specific field areas.

Several researchers have compared and estimated potential differences in crop yield response or amount of fertilizer applied between VR and UR. Different approaches have been used to assess this comparison. Most studies have estimated the value of VR from trials based on single or multiple fixed nutrient rates applied to strips. In Montana for example, Carr et al. (1991) measured wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) grain yield differences between contrasting soil series and the crop response to single or multiple fixed rates of N-P-K mixtures in five fields. They concluded that grain yields and net returns to fertilization varied greatly among fields and soils, but both yield and net returns were either statistically similar or inconsistent between fertilization methods. Rehm and Lamb (2000) evaluated the soybean response to various uniform P fertilizer rates in two fields in Minnesota. They concluded that P increased yield only in low-testing areas and that VR fertilization could have been more effective than any of the UR methods used.

Other studies have directly compared UR and VR fertilization. Traditional on-farm research methods based on narrow and long strips have been adapted to precision agriculture tools such as DGPS, VR controllers, and yield monitors (Shapiro et al., 1989; Long et al., 1996; Oyarzabal et al., 1997). Wibawa et al. (1993) studied barley and wheat yield responses to uniform and variable N and P fertilizer according to a 15 m sampling grid and with yield goals according to soil type. The VR treatment produced greater yield than UR in two of three fields. However economic analyses showed greater net returns for UR compared with VR when the sampling costs were considered. Mulla et al. (1992) studied wheat yield response to uniform and VR of N-P mixtures according to three management zones that differed in soil-test values and yield potential. They observed no grain yield difference between fertilization methods for any zone, although two of the three zones had less N and P fertilizer applied than the UR. Anderson and Bullock (1998) compared VR and UR of P-K mixtures based on a 1-ha grid soil sampling to yield response of corn and soybeans. They observed no yield response to fertilization in any field, even though there were areas of the fields with low soil-test P and K values. They suggested that larger than needed fertilizer recommendations may explain the lack of response. Research done in Indiana by Lowenberg-DeBoer and Aghib (1999) compared UR of N-P mixtures with VR based on a sampling by soil series and variable rate based on a 1.2-ha grid soil sampling in corn, soybeans and wheat fields. They showed that VR did not increase net returns when the cost of fertilization and soil sampling was included. They also concluded that VR based on sampling by soil series sometimes showed the largest net returns. Yang et al., (2001) compared VR and uniform applications of N-P mixtures for grain sorghum [*Sorghum bicolor* (L.) Moench] in the southern Great Plains and showed that small yield benefits of VR fertilization often are offset or turn negative by increasing the cost of soil sampling and equipment. Wittry and Mallarino (2002) studied the within-field variation in corn and soybean response to uniform and VR P fertilization in six Iowa fields. They compared uniform P fertilization and VR fertilization based on a grid soil sampling scheme of 1.8-ha cells in four fields and a more intensive 0.2-ha cells in two fields. They reported that crop responses for field areas with different STP were greater in field areas testing optimum or less in P. However, they also reported that this was not always the case for all fields and the trend was more clear for the two fields with the most intensive sampling density (0.2-ha cells). They found no yield difference between UR and VR fertilization methods and they explained the lack of response by high-small scale STP variation that could not be measured with the sampling density they used. However, they reported that amount of P fertilizer applied with VR were 12 to 41% less than with FR.

Little research has focused on studying fertilization effects on yield variability over the landscape. Also, no study comparing UR and VR fertilization used methods of data analysis that account for spatial correlation of yield and geostatistics that in addition to the classical statistics describe treatment effect on spatial variability of yield. The objectives of this study were (1) to evaluate the yield responses of corn and soybean to P fertilizer using UR and VR application methods and (2) to assess the effect of VR on grain yield variability. This study follows and improves the study conducted by Wittry and Mallarino (2002) by using different fields, a more intensive soil sampling method, data analysis methods that account for spatial correlation of yield, and by studying UR and VR effects on yield variability.

## MATERIALS AND METHODS

Field P-response strip-trials were conducted on six Iowa farmer's fields located in Boone, Carroll, and Guthrie counties that were managed with a corn-soybean rotation. Soil series represented in the experimental areas were among typical agricultural soil series of Iowa and neighboring states (Table 1). Clarion (Typic Hapludoll), Webster (Typic Endoaquoll), and Canisteo (Typic Endoaquoll) series predominated in Fields 1 to 4, but there also were significant areas of Nicollet (Aquic Hapludoll), Harps (Typic Calciaquoll), and other soils. The surface layer of Canisteo and Harps soils have high pH due to free calcium carbonate. In Fields 5 and 6 the Marshall (Typic Hapludoll) series were the most predominant and differed in slopes. Management practices were those used by each farmer and, thus, corn hybrids, seeding rates, planting dates, and other practices varied among fields. All fields had histories of uniform P fertilization. In Fields 1-4 corn residues were chisel plowed after harvest in October or November (fall), and were field cultivated before planting in April or early May (spring). Fields 5 and 6 were in continuous no-till for 20 years.

A replicated strip-trial methodology was used for all trials. Approximately 6 to 12 ha at each field located at least 40 m away from field borders were selected to fit experiments with three treatments and a randomized complete-block design (RCBD). Treatments were a control without P fertilizer, a UR P application method, and a VR P application method. There were three replication in Fields 1 and 2, and four in Fields 3-6. The strip width was 18.3 m for Fields 1 to 4 and 21.3 m for Fields 5 and 6, and strip length varied from 310 to 505 m among fields but were similar within a field (Fig. 1). All blocks and strips were contiguous in Fields 1-4, but two blocks were separated from the others in Fields 5 and 6 because of contoured terraces. Measurements were made with a measuring tape or wheel, permanent plastic pipes were buried at each trial corner, and corner coordinates were recorded with a hand-held DGPS receiver. Experiments in Fields 1 and 2 were established in 1998 and evaluated 4 yr (soybean - corn - soybean - corn in Field 1 and corn - soybean - corn - soybean in Field 2). Experiments in Fields 3, 4, 5, and 6 were established in 1999 and evaluated 3 yr (corn - soybean - corn in Field 3; soybean - corn - soybean in Field 4 and 5 and corn - soybean - soybean in Field 6). Thus, the study included nine corn crops and 11 soybean crops. A field-crop code includes a field number (1 to 6), suffixes "a" and "b" to indicate the first and second crop of the rotation and suffixes "$a_2$" and "$b_2$" indicate crops of a second rotation cycle. Results for the two crops of the first rotation cycle for Fields 1 and 2 were previously presented and discussed by Wittry and Mallarino (2002). The data of these two fields are included in this study to be analyzed and interpreted with different statistical analyses.

The P treatments were based on STP of soil samples collected prior to treatment application. Composite samples (8-12 cores from a 15-cm depth) were collected using a systematic, grid-point sampling method (Wollenhaupt et al., 1994). The width of the grid coincided with the width of the strip (18.3 m for Fields 1 to 4 and 21.3 m for Fields 5 and 6), and grid lines were spaced 45 m along crop rows (0.08-ha cells) in Fields 1-4 and 30 m (0.07-ha) in Fields 5 and 6. Cores were collected from 100 $m^2$ areas at the center of each cell. Samples from Fields 3-6 were analyzed with the Bray-$P_1$ test, and samples from Fields 1 and 2 were analyzed with the Mehlich-3 P test (Frank et al. 1998) because field histories suggested that soil pH ranged from very acid (pH near 5.0) to alkaline (up to pH 8.0 due to $CaCO_3$). Iowa STP interpretations are similar for the Bray-$P_1$ and Mehlich-3 tests (with a colorimetric P determination). However, the Mehlich-3 test is recommended for all Iowa soils while the Bray-$P_1$ test is recommenced only for soils with pH < 7.4 based on local field calibrations (Mallarino, 1997; Voss et al., 1999). Table 2 shows descriptive statistics for soil organic matter, pH, STP, and the distribution of STP values within the five Iowa State University (ISU) interpretation classes. The classes for both the Bray-$P_1$ and Mehlich-3 P tests are ≤8 mg $kg^{-1}$ for Very Low, 9 to 15 mg $kg^{-1}$ for Low, 16 to 20 mg $kg^{-1}$ for Optimum, 21 to 30 mg $kg^{-1}$ for High, and ≥31 mg $kg^{-1}$ for Very High. Composite soil-samples (12 cores, 15-cm depth) also were collected from the treatment strips for STP analysis in November after harvesting the second crop of the first 2-year rotation cycle and before re-applying fertilizer treatments for the third crop. Samples were collected from 100 $m^2$ areas at the center of the cells defined by the width of each treatment strip and the separation distance of the soil sampling grid lines along crop rows.

Table 3 shows the P rates applied with the UR and VR treatments. The P rates used in most fields were the ISU Soil and Plant Analysis Laboratory recommendations based on STP for a 2-yr corn-soybean rotation applied once before the first crop (either corn or soybean). Treatments were reapplied for the second rotation cycle of all fields based on new STP from the UR and VR strips. The UR was defined on the basis of the mean STP of each experimental area. For the VR treatment, interpolated STP and P application maps were prepared for each field by using an inverse-distance method with a distance-weighing exponent of two (Wollenhaup et al., 1994). The recommendations were 70 kg P $ha^{-1}$ for the Very Low interpretation class, 54 kg P $ha^{-1}$ for the Low class, 34 kg P $ha^{-1}$ for the Optimum class, and no fertilization for the High and Very High classes. The only exceptions involved application for the UR treatment for some fields because a consensus was reached with the cooperating farmers to apply the rate they would apply to the entire field. In Fields 1a and 2a, the 70-kg rate applied was higher than the ISU recommended rate of 54 kg $ha^{-1}$ (because mean STP was in the Low class) but matched the median value (which was in the Very Low class). In Field 5a (mean STP was in the Optimum class) the 54 kg $ha^{-1}$ rate applied was higher than the ISU recommended rate of 34 kg $ha^{-1}$. In Field $4a_2$ and $5a_2$, where the mean STP was in the High class the P rates were 24 kg P $ha^{-1}$.

Granulated di-ammonium phosphate or mono-ammonium phosphate was spread before planting with commercial broadcast VR spreaders (spinners in Field 3 and 4, and air-powered in Fields 1, 2, 5, and 6) equipped with DGPS receivers and controllers. Fertilizer was applied in the fall after harvest and incorporated into the soil by disking except for Fields 5 and 6 that were in no-till. Corrective N rates (at same time of applying P) were used for corn in Fields 5 and 6 to offset the small N rate applied with mono-ammonium phosphate. However, the farmer applied a uniform rate of 120 kg N $ha^{-1}$ as urea-ammonium nitrate across all strips on top of the corrective N. At other fields, a N rate of 150 kg N $ha^{-1}$ as anhydrous ammonia (the highest N rate suggested by ISU for corn after soybean) was uniformly applied for corn across all treatments. Initial soil-test K ranged from Low to High across Fields and a uniform K rate equivalent to the 2-yr expected K removal was applied before the first crop of each rotation cycle in all fields.

Grain yields were measured 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, 2202 S. Riverside Dr., Ames, IA), Green Star (John Deere Inc., John Deere Place, Moline, IL), or Micro-Trak (Micro-Trak Systems, Inc., 111 East Leray Ave., Eagle Lake, MN). Differential corrections were obtained through the U.S. Coast Guard AM signal. The spatial accuracy was checked by georeferencing several positions in the field with a hand-held DGPS receiver. Yield data were unaffected by field borders because at least 40 m from any border were harvested but not used. While harvesting, each combine trip (a 4.5-m swath) was identified with a unique number that was recorded with the georeferenced yield data. Grain moisture was determined by a sensor located in the combine auger, and yield was corrected to 155 g $kg^{-1}$ $H_2O$ for corn and 130 g $kg^{-1}$ $H_2O$ for soybean. The raw yield data recorded by the yield monitors were analyzed for common errors such as incorrect geographic coordinates due to total or partial loss of good differential correction and effects of waterways or grass strips. The affected data were corrected (incorrect coordinates) or deleted. The data were imported into spreadsheets and then exported to ArcView (Environmental Systems Research Inst. Inc., 380 New York St., Redlands, CA) for GIS management and later to the SAS statistical package (SAS Institute, 2000) for statistical analyses.

Treatment effects on yield response for Fields 1-4 (where all strips were contiguous) were analyzed using SAS (SAS Institute, 2000) by an analysis of variance (ANOVA) procedure for a randomized complete-block design (RCBD) that accounted for spatial correlation of yield with nearest neighbor analysis (NNA). The basis for this procedure and potential applications were described before (Hinz, 1987; Bhatti et al., 1991; Hinz and Lagus, 1991; Stroup et al., 1994). More recently, the procedure was adapted to a strip-trial methodology by Mallarino et al. (2001) and Bermudez and Mallarino (2002). Because details of the method were provided before, only a brief explanation is provided here. Yield input data were means of yield monitor points recorded at 1-s intervals for areas delineated by the width of the combine header and 15 to 31 m (depending on the field) along the crop rows (8 to 12 points). Individual yield monitor records were not directly used because of known insufficient accuracy at shorter distances (Lark et al., 1997; Colvin and Arslan, 2000). The first step in the calculation was to obtain yield residuals by removing treatment and block effects with a conventional RCBD ANOVA. Afterwards, covariate values for a conventional RCBD covariance analysis were calculated by subtracting each yield residual from the mean value of its four neighbors. The treatment sums of squares was partitioned into a comparison of the control vs. the mean of the two application methods and a comparison of the two application methods. This analysis could not be applied to Fields 5 and 6 because treatment strips were following field contours and two blocks were not contiguous to other blocks. In these two fields, a conventional RCBD ANOVA was performed where the data input were yield means for the strips (i.e., the experimental units receiving the treatments).

The relationship between treatment effects and STP values was analyzed by two procedures. Procedure 1 analyzed treatment effects on yield for field areas with different STP interpretation classes or with different soil series by a procedure developed by Oyarzabal et al. (1997) and later used by Mallarino et al. (2001) and Bermudez and Mallarino (2002). Yield input data for the yield - STP analyses were means for areas defined by the width of each treatment strip (18.3 or 20.5 m depending on the field) and the separation distance of the soil sampling grid lines (45 m in Fields 1-4, and 30 m in Fields 5 and 6). The STP input were the initial values. Three yield means (one for each treatment) corresponded to one initial STP value. To assess the consistency of treatment effects for field areas testing within different STP classes for each crop and field, we used a RCBD ANOVA for each STP class in which sources of variation were replications (blocks) and P treatments. Similar data management and ANOVA were used to test treatment effects for different soil series. Yield data for each soil series were determined by overlaying (using ArcView GIS) yield maps (with treatment and replication attributes) and digitized soil-survey maps (scale 1:12,000). Values were not used for these analyses when there were less than three yield cells for any soil-test P class or soil series. The STP classes and soil series used in analyses for each field were represented at least once in two replications of the design, which assured at least two true replications for the statistical analyses.

In the second procedure, simple correlation regression analysis was used (SAS Inst., 2000) to study the relationship between yield response (absolute and relative yield increases) and STP across the field with and without interpolating the variables. Relative responses were used to minimize potential effects of differences in absolute yield across or within fields. Relative responses were calculated for each STP value by subtracting data for the control from the mean of the fertilized treatment, dividing the result by the data from the control, and multiplying by 100. The procedure without interpolation was based on yield means and STP areas measuring 820 $m^2$ for Field 1-4 and 560 $m^2$ for Field 5 and 6 which corresponded to the area delineated by the soil sampling grid lines. In the procedure with interpolation, the data pairs were calculated by interpolating and surfacing yield-monitor data points and STP values using a methodology described by Mallarino et al. (2000). Briefly, before interpolating the yield data, the data set (with yield points corresponding to all observations) was split into two data sets. One data set contained data for the nonfertilized treatment and the other contained data for the two fertilized treatments. Data in both data sets were interpolated using a weighted inverse-distance method and were surfaced to a 5-$m^2$ grid size. In a second step, the yield data set containing the nonfertilized treatment was subtracted from the data set containing the fertilized treatments using GIS spatial analysis methods, which resulted in a map with treatment differences. In a third step, the yield differences data were regressed on the soil-test P data.

The yield variation was assessed with SD and geostatistics (semivariograms). Geostatistical analyses were used to quantify the effect of uniform and variable rate of P fertilizer on the spatial structure of the variability of corn and soybean yield. One unidirectional semivariogram (along the strips) was calculated for each set of strips corresponding to each treatment using S-Plus version 6.0 and Spatial Statistics Supplement (Insightful Corp.; 2001, Seattle, WA 98109). General geostatistical methods and terminology are described by Marx and Thompson (1987), and more comprehensive discussions can be found in Journel and Huijbregts (1978). Semivariance values were calculated for a minimum lag distance of 15 m and a maximum lag distance of 60% the strip length (120 to 320 m depending on the field). There were at least 15 pairs of points for each lag distance. Linear, linear-plateau, spherical, and exponential models were fitted to the semivariance values by weighted least squares regression to estimate sample semivariogram parameters. The spherical model was the best-fitting model in most instances and is the only one presented. This model estimates nugget, sill, and range parameters. The nugget semivariance is not related to spatial dependence and represents random variation and the residual influence of all variabilities with ranges smaller than the distance of observation. The range represents the distance at which samples become independent or are no longer correlated with each other. As the distance between sample points increases, semivariance increases curvilinearly towards a maximum value that is called the sill.

## RESULTS AND DISCUSSION

Analysis of samples collected before treatment application (Table 2) showed that STP encompassed at least four ISU interpretation classes in all fields. According to ISU fertilizer recommendations for corn and soybean, a large to moderate yield response to P should be expected when STP is Very Low or Low. The proportion of the experimental areas testing Very Low or Low ranged from 10 % in Field 5 to 75% in Field 1. Thus, all fields except Field 5 contained large areas where a yield response to P fertilizer would be expected.

### Field Average Responses

Phosphorus fertilization increased ($P \leq 0.05$) yield of all crops in Fields 1 and 2, the two corn crops in Field 3, and the last soybean crop in Field 6 (Table 4). Yield responses to P were observed only in fields that tested on average Optimum or lower in STP (Table 2). Although in Field 2 the average STP was in the Optimum class, values ranged from Low to High. In the unresponsive Fields

4 and 5, small areas of the fields tested below Optimum (25% in Field 4 and 10% in Field 5), which may explain the general lack of response. A lack of significant response in Field 6a (mean STP was in the Low class and borderline with Very Low class) could be explained by two reasons. One possible reason is that this field was managed with no-till and broadcast P was applied in spring two months before planting the crop. Although previous research in Iowa (Bordoli and Mallarino 1998) showed that broadcast P fertilizer applied in the fall to no-till fields is as efficient as banded or incorporated P, it is possible that a spring application to the surface is less efficient. In those situations a higher probability of response will be expected for the second crop after fertilizer application. A small soybean yield response to P was observed in the second (significant at $P \leq 0.1$) and third year. A second reason for the lack of statistically significant response the first year in Field 6a is that the small (0.11 Mg ha$^{-1}$) yield increase could not be detected by the conventional ANOVA. Other work (Bermudez and Mallarino, 2002) showed that small yield differences often become statistically significant when using spatial analysis in conjunction with ANOVA.

The method of fertilizer application affected ($P \leq 0.05$) grain yield only in two site-years (Fields 2b and 5a$_2$). The VR method produced higher soybean yield than the UR method in Field 5a$_2$ but less in Field 2b. The average amount of P fertilizer applied varied markedly between the two application methods (Table 3). In Fields 1, 1$_2$, 2, 2$_2$, 3$_2$, 4, 4$_2$, 5, and 6$_2$ which tested Optimum or less on average, the VR method applied less P than the UR corresponding to field-average STP values. When the total amount of fertilizer applied with the UR or VR methods is expressed as the average amount applied per hectare, the VR method applied 3 to 29 kg P ha$^{-1}$ less depending on the soil test distribution of each field. Special attention should be considered when interpreting rates for Fields 1, 2, 4a$_2$, and 5a$_2$. In Fields 1 and 2, mean STP would have determined a lower rate for the UR (54 kg P ha$^{-1}$ instead of 70 kg P ha$^{-1}$). This decision should have not affected the response of the first crop of the rotation to UR because both rates are higher than needed to maximize yields but, although unlikely, the lower rate could have resulted in a smaller response of the second crop to UR in field areas testing Very Low. In Fields $4a_2$ and $5a_2$, no P fertilizer would have been necessary with the UR method if the field mean STP value and current ISU interpretations had been used to decide the rate. This assumption is confirmed by a lack of response to either UR or VR fertilization in these fields.

There are two likely reasons for the infrequent, small, and inconsistent differences between fertilization methods. One possible reason is that the 2-year fertilizer recommendations for the corn-soybean rotation were applied once. Thus, the rates applied with both methods should have been sufficient to maximize yield of the first crop. Another possible reason is the use of fertilizer recommendations that have an implicit build up component for soil test classes below Optimum (Voss et al., 1999).

## Responses in Field Areas with Different Soil-Test P or Soil Series

Analysis of corn and soybean yield response for field areas having different initial STP levels showed that within-field variation in STP influenced the crop response to P fertilization and that the yield response to P was larger when STP was below Optimum (Table 5 and 6). Corn responses to P ($P \leq 0.05$) were observed in the Very Low or Low testing class of fields in which a field-average response was observed, but also in Field 4b where no field-average was observed. The application methods differed only in the Very Low class of Fields $2a_2$ and $3a_2$. The VR method increased yield more than the UR in Field $2a_2$ but less in Field $3a_2$. The result for Field $2a_2$ can be explained by the amount of P applied because there were large areas testing Very Low and Low and the amount of P applied with VR for these classes was higher than with UR. The larger response with UR compared with VR in Field $3a_2$ cannot be explained. Analysis of responses for field areas with different STP for soybeans (Table 6) showed significant responses ($P \leq 0.05$) for areas testing Very Low or Low of Fields $1a_2$, $2b_2$, $4a_2$, and $6a_2$. However, responses were not observed in all Low areas. and moreover there was a significant response in the Optimum class of Field 1a. An analysis for whole-field had suggested soybean response to P in Field 2b. The method of fertilizer application differed in Low areas of Field $5a_2$ and Optimum areas of Field 1a. In Field $5a_2$ the VR increased yield more than the UR and the difference could be explained by a higher rate of P applied with VR in the Low areas (24 kg P $ha^{-1}$ with UR and 54 kg P $ha^{-1}$ with VR). In Field 1a the VR increased yield more than the UR in areas that tested Optimum but not in low-testing areas. This difference is difficult to explain because less P was applied with VR than with UR for areas testing Optimum of this field.

Tables 7 (corn) and 8 (soybean) show the results of correlation and regression analyses of absolute and relative yield response on initial STP by procedures based on cell averages or interpolation. The relationship between yield and STP was linear in most fields and, as expected, yield increases expressed in either absolute or relative terms usually were smaller as STP increased. An unexpected result was observed for Field $6a_2$. In this field there was a significant and positive correlation between STP and soybean yield. The result is difficult to explain because the field contained large areas with STP in the Very Low and Low classes and the whole field analysis detected a significant yield response to P. Across fields, use of relative responses slightly improved the correlations probably because it reduced variation due to different yield levels in different parts of the field. The correlations were stronger for the method without interpolation, although the statistical significance was higher probably because of a higher number of observations. Observations of the equations for both procedures show that the slopes of the relationships differed greatly between methods. The interpolation method described a steeper decrease in yield response as STP increased in few fields (Fields $1a_2$, $1b_2$, $2b_2$, and $4a_2$) and a slower decrease in the rest of the fields. It is noteworthy that the the interpolation method may result in slightly different correlations and statistical significance depending on the interpolating method used and the output grid size used.

Because of imposed replication requirements, analysis of yield response to P for field areas with different soil series included the three most dominant series for Fields 3 and 4, two dominant series for Field 1 and 2, and only one series in Fields 5 and 6. Data for a second dominant soil series in Field 5 and 6 could not be statistically analyzed because of lack of true replication and only yield means are presented. Corn grain yield response to P for different soil series (Table 9) and soybean yield (Table 10) showed that responses differed among soils. The Clarion soil was more responsive to P than the other soils in five site years (Field $1b_2$ and 3a for corn and Field 1a, 2b, and $2b_2$ for soybean). This result agrees with previous research in Iowa (Wittry and Mallarino, 2002) in that Clarion soils tended to be the most responsive soil to P in the Clarion-Nicollet-Webster soil association of Central Iowa. However, in this study not all fields that had Clarion soil responded significantly to P. For example, in Field $1a_2$ the Canisteo soil was more response to P than the Clarion soil; and in Field 2a and $2a_2$ both Webster and Clarion soils responded equally the same. In Fields 1a, 2b, $1b_2$, and $2b_2$, larger responses for the Clarion soil could be explained by lower average initial STP (Table1). In Field 1, STP was Low for Clarion (12 mg P $kg^{-1}$) and Optimum for Webster (16 mg P $kg^{-1}$). In Field 2, STP was Low for Clarion (13 mg P $kg^{-1}$) and borderline between the Optimum and High classes for Webster (19 mg P $kg^{-1}$). However, STP was similar for soil series within Field 3, and usually was in the Optimum class or borderline between the Optimum and Low classes. Moreover, initial mean STP was slightly higher for the Clarion soil (17 mg P $kg^{-1}$) than the Nicollet soil (15 mg P $kg^{-1}$). Although all soils were formed on loam glacial till, the Clarion series occupies higher and steeper landscape positions and is better drained than the Canisteo, Nicollet, or Webster soils. Further speculation about reasons for this different response is risky because the soils differ in many properties and the methods used in this study do not allow for such explanation. Differences between application methods were few, inconsistent and difficult to explain across sites.

The UR method produced slightly higher yield than VR in the Nicollet series of Fields $3a_2$ and in the Clarion series of Field $4a_2$, but lower yield in the Clarion soils of Field 1a.

## Effect of Variable-Rate P Application on Yield Variability

Standard deviation values showed that yield variability differed markedly across fields and crops. Soybean yield often was more variable than corn yield. In corn, fertilizer P application decreased ($P \leq 0.05$) yield variability in Fields 1b, 2a, $2a_2$, 3a, and 6a and increased variability in Field $3a_2$ (Table 11). In soybean, the P application decreased yield variability in Fields 4a, and increased variability in Fields $1a_2$, 2b, 3b, 5a (Table 12). Overall, we expected that use of P fertilizer would reduce corn and soybean yield variability because it would increase yield in low-testing areas and not affect yield in high-testing areas. Comparisons between fertilizer application methods showed that VR tended to reduce yield variability compared with UR. For corn, VR reduced yield variability in Fields 2a, $2a_2$, and 5b. For soybean, VR reduced yield variability in Fields 3b and 6b but increased it in Fields 5a and $5a_2$.

Although knowledge of the SD of yield is useful, a study of the spatial structure of yield variability provides additional useful information. Unidirectional semivariograms showed that the structure of the spatial variability of yield differed greatly among fields and crops (Table 11 and 12). Observation of sample semivariograms parameters such as the sill (which is an estimate of total variability) and nugget (the random variability) indicate that the spatial structure of soybean yield was more variable than for corn yield. In cornfields, P application consistently decreased nugget and sill parameters except for Field $3a_2$ where both were increased. The results in Field $3a_2$ agree with the SD results. In soybean, the sill and nugget parameters were not consistently affected by fertilization. Phosphorus application increased both parameters in Fields $1a_2$, 2b, 5a, and $6a_2$, decreased them in Field 3b, and did not affect them in Field 1a. We expected that P fertilization would reduce both random and spatially structured variability by increasing yield in low-testing areas and not affecting yield in high testing areas.

Modeled semivariograms showed that VR tended to reduce the proportion of spatially structured yield variability in most fields compared with UR. In cornfields, the VR reduced the nugget and sill in Fields 1b, 2a, $2a_2$, 4b, 5b, and 6a and slightly increased it in Fields $1b_2$, 3a, and $3a_2$. The VR reduced the sill and nugget in Fields 1a, $1a_2$, $2b_2$, 3b, $4a_2$, and $6a_2$ and increased in Fields 2b and 5a. Across fields the range of influence varied markedly between fertilization methods and ranged from 40 to 160 for corn fields, and from 30 to 220 m in soybean fields. The range of influence was more consistent in cornfields than in soybean fields, and generally the VR increased the range of influence when compared to UR. The results found with SD also indicated that the VR fertilization method usually reduced yield variability compared with the UR method. This result and the lack of field-average yield differences between fertilization methods may be explained by small opposite responses (not statistically significant) to the fertilizer application methods in field areas testing Very Low or High.

## CONCLUSIONS

Field-average grain yield responses to P fertilizer were statistically significant in most fields that tested Optimum or lower in STP. Field-average yield responses to P fertilizers were similar for VR and UR application methods. Analyses of responses for field areas with different soil-test interpretation classes showed that the grain yield response was higher for areas with STP testing Very Low or Low compared with areas testing Optimum. Yield responses seldom were statistically significant in field areas testing High or Very High. Differences between application methods for the low-testing classes were small, infrequent, and inconsistent. The lack of large or consistent differences between fertilization methods could be explained by very high small-scale soil-test P variability that current variable rate technology cannot manage and a fertilizer management philosophy (common to the Corn Belt region) that recommends higher than needed fertilizer amounts for low-testing soils in order to build-up soil P. Classic SD analyses and semivariograms showed that VR tended to reduce yield variability in most fields compared with the UR method. This result, and the lack of field-average yield differences between fertilization methods, can be explained by small opposite responses (not statistically significant) to the fertilizer application methods in field areas testing Very Low or High.

The lack of yield difference and the small difference in fertilizer savings between fertilization methods shown by these results suggest that the VR method would not offset additional costs over the traditional UR. However, the VR method should become more cost effective over a long period of time because it will improve nutrient management by applying less fertilizer to high-testing areas and reducing yield variability. Also, reducing nutrient application to high-testing areas likely reduces the risk of excess nutrient loss to water resources.

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Table 1. Predominant soil series in the experimental areas and average soil-test P (0-15 cm) of six fields.

| | Dominant soil series | | | | Second dominant soil series | | | |
|---|---|---|---|---|---|---|---|---|
| Field | Series | Classification † | Area | STP‡ | Series | Classification | Area | STP |
| | | | % | mg kg$^{-1}$ | | | % | mg kg$^{-1}$ |
| 1 | Clarion | T. Hapludolls | 44 | 12 | Canisteo | T. Endoaquolls | 26 | 16 |
| 2 | Webster | T. Endoaquolls | 36 | 19 | Clarion | T. Hapludolls | 33 | 13 |
| 3 | Nicollet | A.Hapludolls | 58 | 15 | Clarion | T. Hapludolls | 21 | 17 |
| 4 | Webster | T. Endoaquolls | 31 | 19 | Canisteo | T. Endoaquolls | 27 | 24 |
| 5 | Marshall | T. Hapludolls | 83 | 20 | Exira | T. Hapludolls | 17 | 25 |
| 6 | Marshall | T. Hapludolls | 90 | 9 | Colo | C. Endoaquolls | 10 | 8 |

† A= Aquic, C= Cumulic, T= Typic.

‡ Mean soil-test P calculated from initial samples collected by grid soil sampling.

Table 2. Descriptive statistics for initial soil-test P, pH, and organic matter, and soil-test P distribution according to ISU interpretation classes.

| | Descriptive statistics for soil-test P † | | | | |
|---|---|---|---|---|---|
| Field | Mean | Median | Min. | Max. | SD |
| | mg kg$^{-1}$ | | | | |
| 1 | 11 | 8 | 5 | 29 | 6 |
| 2 | 12 | 8 | 4 | 40 | 9 |
| 3 | 16 | 14 | 6 | 38 | 6 |
| 4 | 20 | 18 | 7 | 62 | 10 |
| 5 | 20 | 20 | 10 | 40 | 6 |
| 6 | 9 | 9 | 5 | 22 | 3 |

| | Field area for five soil-test P classes ‡ | | | | |
|---|---|---|---|---|---|
| Field | VL | L | Opt | H | VH |
| | % | | | | |
| 1 | 8 | 67 | 13 | 12 | 0 |
| 2 | 17 | 50 | 4 | 13 | 16 |
| 3 | 7 | 45 | 30 | 18 | 0 |
| 4 | 4 | 32 | 18 | 36 | 10 |
| 5 | 0 | 10 | 25 | 55 | 10 |
| 6 | 47 | 47 | 3 | 3 | 0 |

| | Descriptive statistic for soil pH | | | | |
|---|---|---|---|---|---|
| Field | Mean | Median | Min. | Max. | SD |
| 1 | 5.9 | 5.5 | 5.1 | 7.5 | 0.7 |
| 2 | 6.7 | 6.4 | 5.4 | 7.9 | 0.9 |
| 3 | 6.1 | 6.0 | 5.4 | 7.9 | 0.5 |
| 4 | 6.2 | 6.1 | 5.5 | 7.9 | 0.4 |
| 5 | 6.2 | 6.2 | 5.6 | 7.0 | 0.3 |
| 6 | 5.6 | 5.6 | 5.0 | 6.3 | 0.3 |

| | Descriptive statistics for organic matter | | | | |
|---|---|---|---|---|---|
| Field | Mean | Median | Min. | Max. | SD |
| | g kg$^{-1}$ | | | | |
| 1 | 45 | 45 | 6 | 100 | 25 |
| 2 | 60 | 61 | 35 | 92 | 16 |
| 3 | 45 | 45 | 31 | 79 | 7 |
| 4 | 49 | 47 | 36 | 70 | 5 |
| 5 | 40 | 40 | 36 | 49 | 3 |
| 6 | 36 | 36 | 25 | 48 | 6 |

†Min= minimum, Max= maximum, SD= standard deviation.
‡VL= very low, L= low, Opt= optimum, H= high, and VH= very high.

Table 3. Target fixed P rates and variable P rates for six fields.

| | | Variable rate for various soil-test P classes † | | | |
|---|---|---|---|---|---|
| Field | Fixed rate | Very low | Low | Optimum | AVG ‡ |
| | kg P $ha^{-1}$ | | | | |
| 1a | 70 | 70 | 54 | 34 | 48 |
| $1a_2$ | 54 | 70 | 54 | 34 | 37 |
| 2a | 70 | 70 | 54 | 34 | 41 |
| $2a_2$ | 34 | 70 | 54 | 34 | 31 |
| 3a | 34 | 70 | 54 | 34 | 40 |
| $3a_2$ | 34 | na § | 54 | 34 | 23 |
| 4a | 34 | 70 | 54 | 34 | 29 |
| $4a_2$ | 24 | na | na | 34 | 5 |
| 5a | 54 | na | 54 | 34 | 28 |
| $5a_2$ | 24 | na | 54 | 34 | 35 |
| 6a | 54 | 70 | 54 | na | 61 |
| $6a_2$ | 34 | 70 | 54 | 34 | 24 |

† Target variable rate for the soil-test P classes Very Low, Low, and Optimum.

‡ AVG = weighted average variable rate applied for the entire field area, including not fertilized high-testing areas.

§ na = not applicable (there were no field areas testing for that particular class).

Table 4. Corn and soybean grain yield response to P applied with two fertilization methods.

| Crop | Field† | Year | Treatment and grain yield | | | Statistics | |
|---|---|---|---|---|---|---|---|
| | | | Check | Variable | Fixed | P effect‡ | F-V§ |
| | | | ------------ Mg ha$^{-1}$ ------------ | | | ------ $P > F$ ------ | |
| Corn | 1b | 1999 | 9.51 | 9.69 | 9.73 | 0.03 | 0.58 |
| | 1b$_2$ | 2001 | 8.17 | 8.76 | 8.85 | 0.02 | 0.67 |
| | 2a | 1998 | 9.98 | 11.12 | 11.04 | 0.01 | 0.16 |
| | 2a$_2$ | 2000 | 7.67 | 8.78 | 8.83 | 0.01 | 0.76 |
| | 3a | 1999 | 7.77 | 8.55 | 8.57 | 0.03 | 0.95 |
| | 3a$_2$ | 2001 | 7.32 | 7.76 | 7.91 | 0.01 | 0.11 |
| | 4b | 2000 | 9.62 | 9.56 | 9.72 | 0.83 | 0.21 |
| | 5b | 2000 | 7.61 | 7.34 | 7.48 | 0.26 | 0.50 |
| | 6a | 1999 | 10.97 | 11.18 | 10.98 | 0.43 | 0.24 |
| Soybean | 1a | 1998 | 3.26 | 3.71 | 3.71 | 0.01 | 0.93 |
| | 1a$_2$ | 2000 | 2.33 | 2.77 | 2.66 | 0.02 | 0.39 |
| | 2b | 1999 | 2.62 | 2.83 | 2.97 | 0.01 | 0.01 |
| | 2b$_2$ | 2001 | 2.32 | 2.62 | 2.81 | 0.01 | 0.09 |
| | 3b | 2000 | 3.04 | 3.06 | 3.18 | 0.21 | 0.09 |
| | 4a | 1999 | 3.66 | 3.72 | 3.70 | 0.23 | 0.72 |
| | 4a$_2$ | 2001 | 2.30 | 2.29 | 2.27 | 0.11 | 0.38 |
| | 5a | 1999 | 3.61 | 3.73 | 3.65 | 0.34 | 0.36 |
| | 5a$_2$ | 2001 | 3.09 | 3.27 | 3.00 | 0.66 | 0.04 |
| | 6b | 2000 | 2.71 | 2.78 | 2.74 | 0.10 | 0.31 |
| | 6a$_2$ | 2001 | 3.09 | 3.28 | 3.29 | 0.01 | 0.88 |

† Suffixes "a" and "b" in the field code identify the first and second crop of the rotation cycle (the P for the 2-yr rotation was always applied once before the first crop). Suffixes "a$_2$" and "b$_2$" indicate that treatments were reapplied for a second rotation cycle.

‡ Mean P effect = probability of the P main effect.

§ F-V = Comparison of the fixed-rate and variable-rate fertilization methods.

Table 5. Corn grain yield response to P for field areas testing within different soil-test P interpretation classes.

| Field | Year | STP class† | Treatment and grain yield | | | Statistics | |
|---|---|---|---|---|---|---|---|
| | | | Check | Variable | Fixed | P effect‡ | F-V§ |
| | | | ------------- Mg ha$^{-1}$ ------------- | | | ------- $P > F$ ------ | |
| 1b | 1999 | L | 9.35 | 9.58 | 9.66 | 0.05 | 0.92 |
| | | Opt | 9.65 | 9.93 | 9.48 | 0.55 | 0.21 |
| | | H | 10.32 | 9.83 | 10.36 | 0.55 | 0.27 |
| $1b_2$ | 2001 | VL | 7.95 | 8.84 | 8.90 | 0.01 | 0.75 |
| | | L | 8.41 | 8.81 | 8.79 | 0.22 | 0.95 |
| 2a | 1998 | L | 10.02 | 11.10 | 10.98 | 0.01 | 0.64 |
| | | H | 11.05 | 11.49 | 11.98 | 0.22 | 0.39 |
| $2a_2$ | 2000 | VL | 7.11 | 8.71 | 8.59 | 0.01 | 0.04 |
| | | L | 7.83 | 8.73 | 8.88 | 0.01 | 0.26 |
| 3a | 1999 | VL | 8.63 | 9.31 | 9.07 | 0.30 | 0.65 |
| | | L | 7.66 | 8.43 | 8.54 | 0.05 | 0.79 |
| | | Opt | 7.86 | 8.79 | 8.57 | 0.02 | 0.46 |
| | | H | 7.18 | 8.11 | 8.45 | 0.20 | 0.71 |
| $3a_2$ | 2001 | VL | 6.93 | 7.43 | 7.95 | 0.02 | 0.04 |
| | | L | 7.33 | 7.87 | 7.96 | 0.01 | 0.36 |
| | | Opt | 7.50 | 7.97 | 7.95 | 0.08 | 0.94 |
| | | H | 7.25 | 7.50 | 7.74 | 0.10 | 0.30 |
| 4b | 2000 | VL | 8.90 | 9.34 | 9.35 | 0.05 | 0.96 |
| | | L | 9.55 | 9.51 | 9.68 | 0.71 | 0.25 |
| | | Opt | 9.79 | 9.77 | 9.88 | 0.84 | 0.53 |
| | | H | 9.60 | 9.50 | 9.64 | 0.80 | 0.31 |
| | | VH | 9.89 | 9.87 | 9.94 | 0.88 | 0.54 |
| 5b | 2000 | Opt | 7.38 | 7.25 | 7.35 | 0.60 | 0.59 |
| | | H | 7.73 | 7.31 | 7.41 | 0.19 | 0.74 |
| | | VH | 7.69 | 7.53 | 7.49 | 0.63 | 0.92 |
| 6a | 1999 | VL | 10.99 | 11.25 | 11.04 | 0.36 | 0.28 |
| | | L | 10.93 | 11.11 | 10.96 | 0.50 | 0.37 |

† STP class = soil-test P classes. VL = very low, L =low, Opt =optimum and H =high.
‡ P effect =probability of the P main effect.
§ F-V = Comparison of the fixed-rate and variable-rate fertilization methods.

Table 6. Soybean grain yield response to P for field areas testing within different soil-test P interpretation classes.

| Field | Year | STP class† | Treatment and grain yield | | | Statistics | |
|---|---|---|---|---|---|---|---|
| | | | Check | Variable | Fixed | P effect‡ | F-V§ |
| | | | ------------- Mg ha$^{-1}$ ------------- | | | ------ $P > F$ ------ | |
| 1a | 1998 | L | 3.23 | 3.55 | 3.68 | 0.05 | 0.54 |
| | | Opt | 3.21 | 4.01 | 3.53 | 0.02 | 0.03 |
| | | H | 3.19 | 3.31 | 3.34 | 0.09 | 0.71 |
| 1a$_2$ | 2000 | VL | 2.14 | 2.74 | 2.77 | 0.01 | 0.82 |
| | | L | 2.45 | 2.75 | 2.64 | 0.19 | 0.54 |
| 2b | 1999 | L | 2.65 | 2.84 | 3.01 | 0.14 | 0.43 |
| | | H | 2.30 | 3.33 | 3.59 | 0.27 | 0.25 |
| 2b$_2$ | 2001 | VL | 2.17 | 2.71 | 2.73 | 0.03 | 0.92 |
| | | L | 1.99 | 2.38 | 2.73 | 0.05 | 0.25 |
| | | VH | 3.24 | 3.11 | 2.91 | 0.20 | 0.30 |
| 3b | 2000 | VL | 2.88 | 3.00 | 3.22 | 0.13 | 0.17 |
| | | L | 3.05 | 3.06 | 3.18 | 0.30 | 0.13 |
| | | Opt | 3.06 | 3.08 | 3.21 | 0.42 | 0.26 |
| | | H | 3.03 | 3.02 | 3.23 | 0.46 | 0.18 |
| 4a | 1999 | L | 3.67 | 3.75 | 3.72 | 0.29 | 0.65 |
| | | Opt | 3.62 | 3.75 | 3.72 | 0.20 | 0.77 |
| | | H | 3.65 | 3.70 | 3.69 | 0.32 | 0.93 |
| | | VH | 3.58 | 3.67 | 3.66 | 0.61 | 0.98 |
| 4a$_2$ | 2001 | L | 2.21 | 2.33 | 2.27 | 0.04 | 0.26 |
| | | Opt | 2.21 | 2.22 | 2.24 | 0.79 | 0.81 |
| | | H | 2.36 | 2.30 | 2.25 | 0.09 | 0.33 |
| 5a | 1999 | Opt | 3.47 | 3.69 | 3.56 | 0.29 | 0.41 |
| | | H | 3.63 | 3.67 | 3.61 | 0.86 | 0.45 |
| | | VH | 3.66 | 3.85 | 3.88 | 0.26 | 0.84 |
| 5a$_2$ | 2001 | L | 3.06 | 3.34 | 3.02 | 0.15 | 0.01 |
| | | Opt | 3.12 | 3.23 | 2.98 | 0.92 | 0.22 |
| | | H | 3.12 | 3.30 | 2.95 | 0.97 | 0.25 |
| | | VH | 3.12 | 3.20 | 3.15 | 0.43 | 0.56 |
| 6b | 2000 | VL | 2.75 | 2.77 | 2.81 | 0.23 | 0.21 |
| | | L | 2.69 | 2.79 | 2.69 | 0.26 | 0.09 |
| 6a$_2$ | 2001 | VL | 3.07 | 3.35 | 3.40 | 0.02 | 0.65 |
| | | L | 3.02 | 3.21 | 3.23 | 0.01 | 0.77 |

† STP class = soil-test P classes. VL = very low, L =low, Opt =optimum and H =high.

‡ P effect =probability of the P main effect.

§ F-V = Comparison of the fixed-rate and variable-rate fertilization methods.

Table 7. Correlation coefficient of relationships between absolute or relative corn yield response (average for two application methods) and initial soil-test P (X) assessed with and without interpolation.

| | | No Interpolation | | | With Interpolation | | |
|---|---|---|---|---|---|---|---|
| Field | Response† | Regression equation | r | $P$>F | Regression equation | r | $P$>F |
| 1b | Absolute | 872 - 52X | -0.48 | 0.01 | 371 - 14X | -0.10 | 0.01 |
| | Relative | 9.6 - 0.6X | -0.49 | 0.01 | 4.1 - 0.2X | -0.12 | 0.01 |
| $1b_2$ | Absolute | 1274 - 60X | -0.53 | 0.01 | 1780 - 107X | -0.35 | 0.01 |
| | Relative | 16.6 - 0.8X | -0.54 | 0.01 | 23.4 - 1.4X | -0.36 | 0.01 |
| 2a | Absolute | 1447 - 26X | -0.57 | 0.01 | 1337 - 17X | -0.25 | 0.01 |
| | Relative | 15.1 - 0.3X | -0.57 | 0.01 | 14.0 - 0.2X | -0.25 | 0.01 |
| $2a_2$ | Absolute | 1673 - 41X | -0.63 | 0.01 | 1090 - 27X | -0.36 | 0.01 |
| | Relative | 23.8 - 0.6X | -0.57 | 0.01 | 15.2 - 0.4X | -0.35 | 0.01 |
| 3a | Absolute | 457 + 21X | 0.10 | 0.25 | 448 + 6X | 0.02 | 0.20 |
| | Relative | 1.7 + 0.7X | 0.19 | 0.03 | 6.3 + 0.1X | 0.03 | 0.10 |
| $3a_2$ | Absolute | 1053 - 36X | -0.42 | 0.01 | 687 - 12X | -0.11 | 0.01 |
| | Relative | 14.5 - 0.5X | -0.42 | 0.01 | 9.6 - 0.2X | -0.11 | 0.01 |
| 4b | Absolute | 90 - 3X | -0.09 | 0.36 | -231 + 9X | 0.08 | 0.01 |
| | Relative | 1.1 - 0.1X | -0.10 | 0.31 | -2.2 - 0.1X | 0.07 | 0.01 |
| 5b | Absolute | -361 + 6X | 0.09 | 0.42 | na‡ | na | na |
| | Relative | -4.4 + 0.1X | 0.09 | 0.42 | na | na | na |
| 6a | Absolute | 76 + 4X | 0.03 | 0.75 | na | na | na |
| | Relative | 0.9 + 0.0X | 0.02 | 0.86 | na | na | na |

† The units are kg $ha^{-1}$ for absolute yield increases and % for relative increases.

‡ na = not available. Interpolation could not be performed in Field 5 and 6 because large separation distance between two replications did not allow for a meaningful analysis.

Table 8. Correlation coefficient of relationships between absolute or relative soybean yield response (average for two application methods) and initial soil-test P (X) assessed with and without interpolation.

| | | No Interpolation | | | With Interpolation | | |
|---|---|---|---|---|---|---|---|
| Field | Response† | Regression equation | r | P>F | Regression equation | r | P>F |
| 1a | Absolute | 811 - 27X | -0.30 | 0.02 | 685 - 22X | -0.22 | 0.01 |
| | Relative | 27.9 - 0.9X | -0.32 | 0.02 | 40.4 - 2.0X | -0.29 | 0.01 |
| $1a_2$ | Absolute | 949 - 55X | -0.45 | 0.01 | 1018 - 64X | -0.46 | 0.01 |
| | Relative | 44.1 - 2.4X | -0.52 | 0.01 | 45.1 - 2.8X | -0.46 | 0.01 |
| 2b | Absolute | 422 - 9X | -0.37 | 0.01 | 322 - 3X | -0.10 | 0.01 |
| | Relative | 15.2 - 0.3X | -0.34 | 0.01 | 12.3 - 0.1X | -0.04 | 0.08 |
| $2b_2$ | Absolute | 580 - 16X | -0.57 | 0.01 | 871 - 33X | -0.45 | 0.01 |
| | Relative | 25.6 - 0.6X | -0.51 | 0.01 | 41.6 - 1.4X | -0.38 | 0.01 |
| 3b | Absolute | 72 + 1X | 0.03 | 0.72 | 9 + 5X | 0.06 | 0.01 |
| | Relative | 2.7 + 0.0X | 0.03 | 0.78 | 2.5 + 0.0X | 0.03 | 0.14 |
| 4a | Absolute | 28 + 2X | 0.10 | 0.27 | 15 + 3X | 0.06 | 0.01 |
| | Relative | 0.8 + 0.1X | 0.10 | 0.25 | 0.4 + 0.1X | 0.07 | 0.01 |
| $4a_2$ | Absolute | 133 - 6.7X | -0.30 | 0.01 | 373 - 15X | -0.27 | 0.01 |
| | Relative | 6.9 - 0.3X | -0.31 | 0.01 | 18.8 - 0.7X | -0.28 | 0.01 |
| 5a | Absolute | 39 + 1X | 0.04 | 0.64 | na‡ | na | na |
| | Relative | 1.8 + 0.0X | 0.01 | 0.95 | na | na | na |
| $5a_2$ | Absolute | 151 - 6X | -0.10 | 0.27 | na | na | na |
| | Relative | 6.4 - 0.3X | -0.13 | 0.17 | na | na | na |
| 6b | Absolute | 105 - 5.5X | -0.13 | 0.17 | na | na | na |
| | Relative | 4.2 -0.2X | -0.12 | 0.18 | na | na | na |
| $6a_2$ | Absolute | -13 +21X | 0.32 | 0.01 | na | na | na |
| | Relative | 0.2 + 6.3X | 0.29 | 0.01 | na | na | na |

† The units are kg $ha^{-1}$ for absolute yield increases and % for relative increases.

‡ na = not available. Interpolation could not be performed in Field 5 and 6 because large separation distance between two replications did not allow for a meaningful analysis.

Table 9. Corn grain yield response to P for field areas with different soil series.

| Field | Year | Soil Series | Treatment and grain yield | | | Statistics | |
|---|---|---|---|---|---|---|---|
| | | | Check | Variable | Fixed | P effect† | F-V‡ |
| | | | ------------- Mg ha$^{-1}$ ------------- | | | ------ $P > F$ ------ | |
| 1b | 1999 | Clarion | 9.48 | 9.72 | 9.76 | 0.14 | 0.79 |
| | | Canisteo | 9.55 | 9.65 | 9.86 | 0.12 | 0.16 |
| 1b$_2$ | 2001 | Clarion | 8.15 | 8.87 | 8.85 | 0.03 | 0.94 |
| | | Canisteo | 8.06 | 8.66 | 8.91 | 0.14 | 0.62 |
| 2a | 1998 | Webster | 10.15 | 11.06 | 11.38 | 0.01 | 0.14 |
| | | Clarion | 9.60 | 11.20 | 10.71 | 0.01 | 0.19 |
| 2a$_2$ | 2000 | Webster | 7.54 | 8.85 | 8.97 | 0.01 | 0.49 |
| | | Clarion | 7.07 | 8.52 | 8.47 | 0.01 | 0.86 |
| 3a | 1999 | Nicollet | 7.97 | 8.68 | 8.63 | 0.07 | 0.88 |
| | | Clarion | 7.46 | 8.66 | 8.64 | 0.01 | 0.95 |
| | | Webster | 7.87 | 8.03 | 8.46 | 0.27 | 0.49 |
| 3a$_2$ | 2001 | Nicollet | 7.30 | 7.75 | 7.96 | 0.01 | 0.02 |
| | | Clarion | 7.43 | 7.80 | 7.74 | 0.10 | 0.80 |
| | | Webster | 7.12 | 7.63 | 7.93 | 0.04 | 0.27 |
| 4b | 2000 | Webster | 9.40 | 9.35 | 9.73 | 0.40 | 0.08 |
| | | Canisteo | 9.60 | 9.69 | 9.75 | 0.44 | 0.77 |
| | | Clarion | 9.61 | 9.46 | 9.69 | 0.65 | 0.05 |
| 5b | 2000 | Marshall | 7.66 | 7.48 | 7.54 | 0.45 | 0.81 |
| | | Exira | 7.20 | 7.35 | 7.46 | na§ | na |
| 6a | 1999 | Marshall | 10.96 | 11.19 | 10.98 | 0.40 | 0.27 |
| | | Colo | 11.38 | 11.44 | 11.04 | na | na |

† P effect = probability of the P main effect.

‡ F-V = Comparison of fixed-rate and variable-rate fertilization methods.

§ na= not available. Insufficient number of replications to test the significance.

Table 10. Soybean grain yield response to P for field areas with different soil series.

| Field | Year | Soil Series | Treatment and grain yield | | | Statistics | |
|---|---|---|---|---|---|---|---|
| | | | Check | Variable | Fixed | P effect† | F-V‡ |
| | | | ------------ Mg ha$^{-1}$ ------------ | | | ------ $P > F$ ------ | |
| 1a | 1998 | Clarion | 3.12 | 3.78 | 3.56 | 0.01 | 0.03 |
| | | Canisteo | 3.20 | 3.52 | 3.57 | 0.14 | 0.84 |
| $1a_2$ | 2000 | Clarion | 2.31 | 2.64 | 2.58 | 0.18 | 0.81 |
| | | Canisteo | 2.20 | 2.73 | 2.57 | 0.01 | 0.15 |
| 2b | 1999 | Webster | 2.29 | 2.42 | 2.67 | 0.37 | 0.45 |
| | | Clarion | 3.11 | 3.60 | 3.71 | 0.01 | 0.21 |
| $2b_2$ | 2001 | Webster | 2.12 | 2.50 | 2.54 | 0.12 | 0.88 |
| | | Clarion | 2.22 | 2.82 | 3.02 | 0.01 | 0.10 |
| 3b | 2000 | Nicollet | 2.99 | 3.01 | 3.14 | 0.24 | 0.11 |
| | | Clarion | 3.14 | 3.15 | 3.27 | 0.33 | 0.19 |
| | | Webster | 3.02 | 3.06 | 3.23 | 0.23 | 0.15 |
| 4a | 1999 | Webster | 3.61 | 3.68 | 3.68 | 0.20 | 0.97 |
| | | Canisteo | 3.61 | 3.68 | 3.68 | 0.48 | 0.99 |
| | | Clarion | 3.71 | 3.81 | 3.80 | 0.10 | 0.80 |
| $4a_2$ | 2001 | Webster | 2.13 | 2.26 | 2.17 | 0.22 | 0.24 |
| | | Canisteo | 2.33 | 2.26 | 2.27 | 0.53 | 0.92 |
| | | Clarion | 2.40 | 2.26 | 2.43 | 0.36 | 0.05 |
| 5a | 1999 | Marshall | 3.62 | 3.73 | 3.67 | 0.36 | 0.56 |
| | | Exira | 3.64 | 3.71 | 3.57 | na§ | na |
| $5a_2$ | 2001 | Marshall | 3.09 | 3.30 | 3.01 | 0.57 | 0.06 |
| | | Exira | 3.32 | 3.42 | 3.29 | na | na |
| 6b | 2000 | Marshall | 2.73 | 2.76 | 2.74 | 0.38 | 0.62 |
| | | Colo | 2.64 | 2.70 | 2.89 | na | na |
| $6a_2$ | 2001 | Marshall | 3.12 | 3.28 | 3.31 | 0.02 | 0.66 |
| | | Colo | 2.80 | 3.32 | 2.82 | na | na |

† P effect = probability of the P main effect.
‡ F-V = comparison of the fixed-rate and variable-rate fertilization methods.
§ na= not available. Insufficient number of replications to test the significance.

Table 11. Effect of uniform-rate and variable-rate on corn yield variability and spatial structure.

| Field | Treatment | Yield variation† | | | Semivariogram parameters (spherical model)‡ | | |
|---|---|---|---|---|---|---|---|
| | | SD | *P>F* | | Nugget | Sill | Range |
| | | kg ha$^{-1}$ | P effect | F-V | $C_0$ (x10$^3$) | $C_0$ + C (x10$^3$) | m |
| 1b | Control | 734 | 0.01 | 0.37 | 21.7 | 412.0 | 60 |
| | Uniform | 483 | | | 12.0 | 251.2 | 40 |
| | Variable | 502 | | | 11.5 | 219.3 | 40 |
| 1b$_2$ | Control | 640 | 0.38 | 0.13 | 29.0 | 550.9 | 120 |
| | Uniform | 577 | | | 14.6 | 277.1 | 70 |
| | Variable | 658 | | | 24.0 | 455.6 | 120 |
| 2a | Control | 855 | 0.05 | 0.02 | 52.5 | 997.9 | 100 |
| | Uniform | 808 | | | 40.2 | 764.2 | 155 |
| | Variable | 631 | | | 28.4 | 539.6 | 160 |
| 2a$_2$ | Control | 806 | 0.01 | 0.02 | 34.8 | 661.0 | 120 |
| | Uniform | 419 | | | 8.2 | 155.8 | 160 |
| | Variable | 328 | | | 5.8 | 110.6 | 100 |
| 3a | Control | 954 | 0.01 | 0.10 | 28.5 | 542.0 | 100 |
| | Uniform | 564 | | | 14.4 | 273.3 | 75 |
| | Variable | 640 | | | 16.4 | 311.1 | 80 |
| 3a$_2$ | Control | 564 | 0.01 | 0.39 | 21.0 | 398.5 | 125 |
| | Uniform | 709 | | | 25.5 | 484.6 | 110 |
| | Variable | 727 | | | 30.8 | 584.6 | 120 |
| 4b | Control | 395 | 0.26 | 0.16 | 6.1 | 115.0 | 60 |
| | Uniform | 357 | | | 5.1 | 97.0 | 65 |
| | Variable | 389 | | | 5.0 | 91.8 | 65 |
| 5b | Control | 601 | 0.23 | 0.01 | 10.3 | 196.6 | 70 |
| | Uniform | 848 | | | 11.8 | 267.0 | 75 |
| | Variable | 440 | | | 10.2 | 223.8 | 80 |
| 6a | Control | 394 | 0.04 | 0.31 | 7.6 | 145.0 | 95 |
| | Uniform | 329 | | | 2.4 | 44.8 | 35 |
| | Variable | 336 | | | 2.0 | 40.0 | 45 |

† SD = Standard deviation. The number of observations (n) and variances for *F* tests correspond to means of areas delineated by treatment width (18m) and 15m length. The n values ranges from 24 to 44.

‡ The maximum lag distance ranges from 100 to 250 m.

Table 12. Effect of uniform rate and variable-rate on soybean yield variability and spatial structure.

| Field | Treatment | Yield variation† | | | Semivariogram parameters (spherical model)‡ | | |
|---|---|---|---|---|---|---|---|
| | | SD | *P>F* | | Nugget | Sill | Range |
| | | kg ha$^{-1}$ | P effect | F-V | $C_0$ (x$10^3$) | $C_0$ + C (x$10^3$) | m |
| 1a | Control | 700 | 0.29 | 0.27 | 29.2 | 555.6 | 70 |
| | Uniform | 679 | | | 29.3 | 557.6 | 90 |
| | Variable | 632 | | | 28.6 | 542.4 | 90 |
| 1a$_2$ | Control | 350 | 0.01 | 0.16 | 9.4 | 178.4 | 110 |
| | Uniform | 531 | | | 25.3 | 481.4 | 170 |
| | Variable | 471 | | | 14.7 | 280.0 | 110 |
| 2b | Control | 738 | 0.03 | 0.31 | 42.9 | 815.0 | 140 |
| | Uniform | 897 | | | 81.8 | 159.4 | 180 |
| | Variable | 951 | | | 94.5 | 179.5 | 220 |
| 2b$_2$ | Control | 760 | 0.21 | 0.20 | 37.7 | 715.8 | 100 |
| | Uniform | 878 | | | 47.3 | 898.8 | 135 |
| | Variable | 793 | | | 35.9 | 682.5 | 130 |
| 3b | Control | 195 | 0.05 | 0.01 | 9.9 | 40.5 | 160 |
| | Uniform | 202 | | | 6.4 | 24.8 | 75 |
| | Variable | 135 | | | 3.1 | 16.4 | 40 |
| 4a | Control | 182 | 0.01 | 0.30 | 0.4 | 9.2 | 30 |
| | Uniform | 134 | | | 0.0 | 12.2 | 35 |
| | Variable | 128 | | | 4.5 | 11.8 | 70 |
| 4a$_2$ | Control | 303 | 0.11 | 0.38 | 15.2 | 79.6 | 225 |
| | Uniform | 276 | | | 4.9 | 92.6 | 220 |
| | Variable | 269 | | | 0.5 | 60.9 | 115 |
| 5a | Control | 270 | 0.01 | 0.01 | 2.8 | 52.6 | 50 |
| | Uniform | 310 | | | 3.0 | 58.0 | 55 |
| | Variable | 423 | | | 3.8 | 71.3 | 65 |
| 5a$_2$ | Control | 308 | 0.19 | 0.01 | 0.0 | 52.2 | 55 |
| | Uniform | 248 | | | 1.7 | 32.2 | 45 |
| | Variable | 320 | | | 0.0 | 74.0 | 80 |
| 6b | Control | 258 | 0.22 | 0.03 | 0.0 | 40.3 | 45 |
| | Uniform | 260 | | | 0.0 | 28.6 | 45 |
| | Variable | 220 | | | 0.0 | 27.6 | 50 |
| 6a$_2$ | Control | 229 | 0.07 | 0.15 | 0.0 | 49.3 | 60 |
| | Uniform | 296 | | | 3.0 | 57.9 | 80 |
| | Variable | 259 | | | 2.2 | 41.9 | 60 |

† SD = Standard deviation. The number of observations (n) and variances for *F* tests correspond to means of areas delineated by treatment width and 15m length. The n values ranges from 24 to 44.
‡ The maximum lag distance ranges from 100 to 250 m.

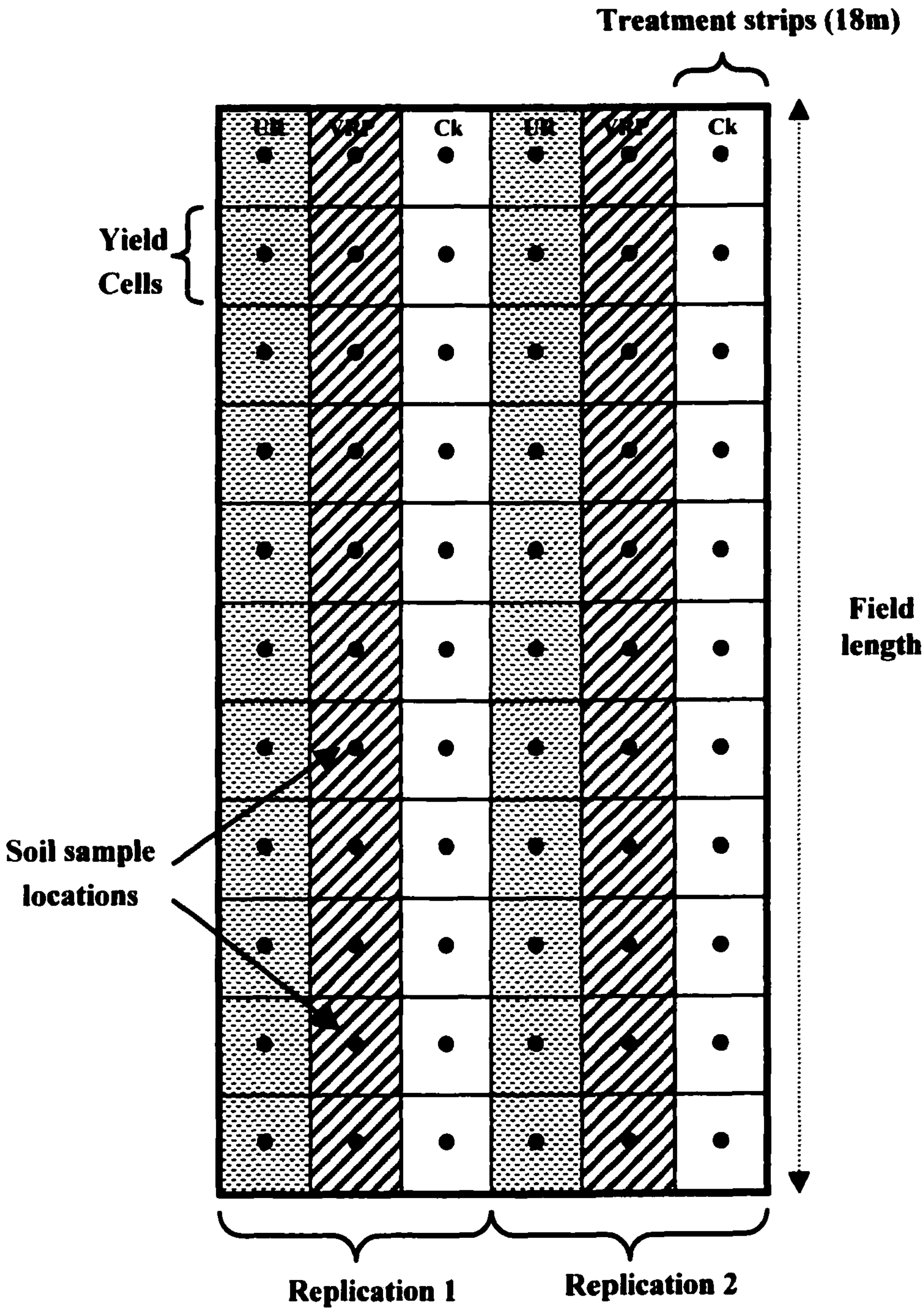


Figure 1. Representative experimental design used in Field 3 showing two of four replications.

# CHAPTER 4.

# GENERAL CONCLUSIONS

The overall objective of this research was to assess the impact of P fertilization methods on crop and soil-test P responses to P. Two distinct studies were conducted to achieve this general objective. Specific objectives of one study were (1) to evaluate yield, early growth, and early nutrient uptake of corn as affected by liquid starter fertilization (mainly N and P mixtures) and reduced spring tillage in no-till fields, and (2) to assess these crop yield responses for field areas with different soil-test values and soil series. Specific objectives of the other study were (1) to evaluate the yield responses of corn and soybean to P fertilizer using uniform-rate and variable-rate application methods, and (2) to assess the effect of these application methods on grain yield variability.

The starter fertilization study involved strip trials on seven cornfields conducted during two years. Treatments applied were no-starter and liquid starter with or without spring tillage. Results from this study showed that grain yield, early plant growth, and early N and P uptake often were greater with tillage than with no-tillage. Frequent and large high early growth and nutrient uptake responses to tillage were not reflected in large grain yield responses. Spring tillage produced higher and more consistent yield responses than starter fertilization. Yield responses to starter fertilization were less frequent and smaller than for tillage, and did not substitute for tillage effects on yield. Early growth and nutrient uptake responses to starter were large and occurred in most areas within the fields. Across all sites, starter fertilization increased yield by 1.3%, early growth by 29%, P uptake by 30% and N uptake by 30%. These responses sometimes were larger when soil-test P was low but were also observed when soil-test P was high. Yield responses in some areas with high soil-test P could partly be attributed to either the P or N in the starter. Overall, the results indicated that frequent and large responses of early corn growth and nutrient uptake to starter fertilization resulted in small and poorly predictable yield responses. The yield response to tillage was more consistent across and within fields than the response to starter fertilization.

The variable-rate P response study involved six fields managed with a corn-soybean rotation. A strip trial methodology and intensive grid soil sampling (0.1 ha cells) were used to evaluate crop and soil-test P responses during three years at each field. Treatments were a check, a variable-rate application method based on soil-test P, and a uniform-rate method based on field-average soil-test P. Results from this study showed that field-average grain yield responses were statistically significant in fields that on average tested Optimum or lower in soil-test P. Variable-rate and uniform-rate application methods seldom differed. The variable-rate method increased yield more than uniform-rate in one field, but the reverse result was observed in another field. The grain yield response was higher for areas within fields having soil-test P testing Very Low or Low compared with areas testing Optimum. The variable-rate method reduced the total amount of fertilizer applied in nine site-years (35% on average) and increased it in three site-years (21% on average). The lack of consistent differences in yield response and amount of fertilizer applied with the two fertilization methods indicate that the variable-rate method will seldom offset additional costs over the traditional uniform-rate application method. However, the variable-rate method should become more cost effective over a long period of time because it will improve nutrient management by applying less fertilizer to high-testing areas and reducing soil test variability. Also, reducing P application to high-testing areas likely reduces the risk of excess P loss to water resources.

Overall, the results of this research showed large soil-test P variation in fields with long histories of uniform-rate P fertilization. Results also showed that use of starter fertilization in addition to broadcast fertilization and use of variable-rate fertilization instead of uniform-rate fertilization would manage P better and could potentially increase yield because significant field areas tested low in soil-test P. However, these theoretically more efficient fertilizer application methods seldom resulted in consistently larger yield responses that could offset increased application costs when commonly used fertilization rates were used. The results suggest that only potentially better environmental P management would justify adoption fo these fertilizer application methods across all Iowa fields.

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