Efficacy of multivariate analysis and zone soil sampling to study relationships between site variables affecting crop yield and yield response to phosphorus and potassium fertilization

by

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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:

My wife Nair

My sons, Mateo and Victoria

My parents

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CHAPTER 1.

GENERAL INTRODUCTION

INTRODUCTION

For a long time farmers and researchers have known that crop yields are not uniform across fields. However, in the past, fields were considered and managed as homogeneous units for a number of reasons. Those reasons included (1) the ability to accurately identify and record specific locations within a field was limited, (2) the variability of yield and several soil and crop variables was difficult to measure, (3) the relationships between those variables was not fully understood, and (4) small areas were difficult to manage separately from other field areas.

The advent of precision agriculture technologies, such as differentially corrected global positioning systems (DGPS), yield monitors, geographical information systems (GIS), and variable-rate applicators among others improved the ability to collect large amounts of spatially referenced data for several variables from producer's fields. The combination of these technologies confirmed and uncovered the historic assumptions about the lack of uniform yields or yield responses to different inputs within fields. All these technologies are now becoming more and more popular, and are relatively easy to implement. Yet, researchers are trying to understand the relationships between different crop and soil variables to use these technologies more effectively.

Several factors are known to affect the within-field yield variability for different crops. Differences in soils and related intrinsic soil properties, terrain attributes, nutrient availability, and the complex effects of weeds, diseases, and insects are factors that explain within-field yield variability. The relationships between these variables are often complex to understand using conventional univariate statistical methods. Classical multivariate statistical techniques often applied in social sciences, may provide a more rational framework to study the interrelation between variables that affect yields or yield responses to specific inputs. A better understanding of these relationships could result in a more efficient use of the inputs commonly used in agricultural fields.

A more rationale use of fertilizer is an issue being addressed by researchers. Surveys indicate that approximately 70 % of Iowa fields test above optimum for P and K levels for corn and soybean. Many farmers, agricultural scientists, and even the society as a whole are concerned about potential and real environmental problems associated with P fertilization practices commonly used in production agriculture. This issue is not easy to address partly because both P and K levels in the soil usually show a high within-field variation. This spatial variability is well documented in the literature and arises through complex interactions between soil-forming and management factors. Management practices such as tillage, fertilization, manure applications, and others can affect variability patterns for these nutrients. While the use of precision farming technologies may uncover part of this variability, agricultural scientists need to develop nutrient management strategies that optimizes economic and environmental benefits.

Soil testing is the most commonly used tool to determine the P and K fertilizer needs for corn and soybean. Soil-test P and K levels, the removal of these nutrients in harvested products, and the need to replace these nutrients with fertilizers is not uniform over an entire field. A successful use of precision agriculture technologies relies on the ability of soil sampling to identify areas that will likely respond to added fertilizer and areas that will not respond. This issue must also take in account cost-benefit relationships when attempting to accurately describe the within-field variation in soil-test levels. Past research has shown that an intensive grid sampling, while uncovering part of this variability, is expensive and time consuming. Several researchers have proposed the use of a zone or targeted sampling approach based on relatively stable soil properties with the main goal of reducing sampling costs. Another goal obviously is to be able to identify much of the soil-test variability across a field with fewer samples. While several approaches have been proposed, these approaches have rarely been tested in terms of yield response to P and K. It is not known if these approaches would really identify responsive from non-responsive areas within a field, and what approaches are the most effective.

This research involved two different studies. The first study used two multivariate techniques, factor analysis and principal component analysis, to study the relationship between several crop and soil variables and to determine their importance in explaining soybean yield variability in several Iowa fields. The second study applied various zone sampling approaches and assessed their efficacy on the basis of measured corn and soybean yield response to P and K within zones delineated with each approach.

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 "Identifying factors affecting soybean yield variability using multivariate techniques". The title of the second paper is "Relating soil tests and within-field response to phosphorus and potassium using various zone sampling approaches". Each paper is divided in sections that include 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.

IDENTIFYING FACTORS AFFECTING SOYBEAN YIELD VARIABILITY USING MULTIVARIATE TECHNIQUES

A paper to be submitted to Agronomy Journal

Jorge Sawchik and Antonio P. Mallarino

ABSTRACT

Site-specific crop management requires an understanding of relationships between soil and crop measurements in relation to within-field yield variability. The objectives of this study were to identify underlying associations of soil and crop properties using multivariate techniques and to determine their importance in explaining soybean (*Glycine max* [L.] Merr.) yield variability on five producer's fields. Soil, terrain, and crop variables measured included soil texture, soil organic matter, soil pH, exchangeable Ca and Mg, cation exchange capacity, soil-test P and K; elevation; early growth and early P and K uptake; crop height, plant population, and the incidence of several weeds and diseases. These measurements often were highly correlated and the correlations varied across fields. Factor analysis (FA) grouped correlated site variables into at least three common factors for all fields: conditions for early growth, the interaction between landscape position and soil properties of intrinsic origin, and soil P and K availability. Multiple regression of yield on new variables derived from FA or principal component analysis (PCA) showed that the importance of grouped variables in explaining yield variability varied from field to field. Use of FA or PCA resulted in a similar prediction of within-field yield variability. The explained yield variation was 65 % in one field with large yield variation (35.1 % coefficient of variation) and 10 to 42 % in four fields with small yield variation (< 10 % coefficient of variation). Non-measured variables, such as soil water

availability during soybean development and others, may account for the non-explained yield variability.

Abbreviations: ANOVA; analysis of variance; CV, coefficient of variation; FA, factor analysis; GIS, geographical information systems; GPS, global positioning systems; ISU, Iowa State University; PCA, principal component analysis; SOM, soil organic matter; STP, soil-test P; and STK, soil-test K.

INTRODUCTION

Site-specific crop and nutrient management has the potential to improve profitability minimizing negative effects to the environment. A successful site-specific management program requires, however, a quantitative knowledge of the factors and interactions that affect yields. Precision agriculture technologies allow for collection of large amounts of georeferenced data from producer's fields. These data can then be further analyzed in several ways to improve decision making in crop management issues. To be effective, management schemes must address both soil variability and soil and crop properties affecting yield.

Soil properties, soil nutrient availability, terrain attributes, crop parameters, the incidence of diseases, pest and weeds, and crop yields are examples of the most common measurements usually collected. Variables such as landscape position, soil physical properties, and terrain attributes have been described as examples of relatively permanent spatial factors affecting crop yields directly or indirectly (Kravchenko and Bullock, 2000). The incidence of weeds, diseases, and insects are examples of transient spatial factors affecting grain yields in specific field areas (Kaspar et al., 2003) and might or might not be present in the same areas every year. Variability of grain yields usually do not occur only across space but the spatial patterns vary among years as well (Lamb et al., 1997; Jaynes et al., 2003).

The relationship between yield and soil properties or terrain attributes have been extensively studied. For example, Kravchenko and Bullock (2000) reported that the combination of soil properties and topographical land features explained 10 to 78 % of corn (*Zea Mays* L.) and soybean yield variability in several Midwestern fields. In general, under moderate and dry weather conditions larger yields were observed at lowland positions. Under these climatic conditions larger yields were also observed at locations with small slope. Another study (Kravchenko et al., 2000) under these climatic conditions also showed larger yields at locations with small slope but during wet growing seasons lower yields prevailed at location with low slopes. Kaspar et al. (2003) developed a multiple regression model based on terrain attributes such as relative elevation, slope, and curvature that explained 78 % of corn yield variability for a set of four moderately dry years.

Soil nutrient supply is another important factor affecting yield variability. Soil testing is the most widely used tool to assess P and K fertilizer needs for soybean. Soil types and several soil properties and management practices that influence nutrient supply are known sources of soil-test P and K variability. Several authors have attempted to study the spatial distribution of soil P and K availability (Cambardella et al., 1994; Wollenhaupt et al., 1994; Mallarino, 1996a) and P and K nutrient uptake (Borges and Mallarino, 1997). The results showed that the spatial distribution of these variables varied greatly within and across fields and was affected by the sampling scale.

Different approaches have been used to determine the importance of many site variables in determining within-field yield variability. Simple correlation analyses show that some site variables are often correlated among themselves and with crop yield (Mallarino et al., 1999). However, the use of highly correlated variables as input to multiple regression analysis can lead to interpretation errors. When one or more the predictor variables are nearly linearly related to the others multicollinearity is said to exist (Neter et al., 1996). In these situations, regression on all of the predictor variables can provide good predictions, but the estimated regression coefficients may have large standard errors and may not accurately reflect the actual influence of some variables on the mean response. The interpretation of the regression coefficient as measuring the effect of one variable while the rest of the predictor variables is held constant is not applicable (Neter et al., 1996).

Multivariate statistical techniques provide a rational framework to study site correlated variables and deal with collinearity. Also, because several variables are included simultaneously, more useful interpretations can be made compared with univariate techniques (Brejda, 1998). Two classical multivariate techniques are useful and are commonly used in several disciplines in that sense: principal component analysis (PCA) and factor analysis (FA). Although closely related, these two techniques have different objectives.

Principal component analysis and FA attempt to explain the variance-covariance structure of a set of variables through a few linear combinations of these variables that are not correlated (PCA) or that may be correlated (FA) (Johnson and Wichern, 2002). The objective of PCA is to reduce the number of variables to a few components, the new variables, that explain a large proportion of the variance in the data (Sharma, 1996). The objective of FA, on the other hand, is to identify underlying factor(s) that can explain the intercorrelation among the variables (Sharma, 1996). While PCA groups variables by emphasizing the variance explained by the new linear combination of variables, FA groups highly correlated variables by emphasizing the covariance structure. Both techniques can reveal relationships between variables that were not previously suspected and thereby allow interpretations that would not ordinarily result (Johnson and Wichern, 2002). The new variables derived from PCA or FA can be used as independent variables in multiple regression analysis, thus the interpretation problems of these analyses when using correlated variables would be minimized (Neter et al., 1996).

Factor analysis has been applied to discriminate soil types and vegetation (Brejda, 1998), or to identify soil quality factors from a large set of soil properties (Brejda et al., 2000). Wander and

Bollero (1999) used PCA to determine which soil quality factors were affected by the introduction of no-tillage in several Illinois fields. Mallarino et al. (1999) identified three common factors: soil fertility, weed control, and conditions for early plant growth that influenced corn yields in five Iowa fields. Johnson et al. (2002) identified three to four factors form a large set of soil properties. These factors, however, were not successfully related to cotton (*Gossypium hirsutum* L.) fiber yield and quality.

The objectives of this study was to use two different multivariate techniques (PCA and FA) to study relationships between several crop and soil variables collected using precision agriculture technologies and to determine their relative importance in explaining within-field yield variability in several Iowa soybean fields.

MATERIALS AND METHODS

The study was conducted in five Iowa fields managed under a 2-yr corn-soybean crop rotation. Field 1 was located in Boone County, Fields 2 and 3 in Linn County, and Fields 4 and 5 in Carroll County. Data for soybean were collected in 1997 from Fields 1, 2, and 4 and in 1998 for the other fields. Soil series present in the experimental areas varied across fields and were representative of major agricultural soils of Iowa (Table 1). Soil series map units for each field were identified using digitized soil survey maps on a 1:12000 scale (Iowa Coop. Soil Survey, 2001). Management practices were those selected by each farmer; thus, soybean varieties, planting dates, seeding rates, herbicide management and tillage varied across fields (Table 2).

Areas of 12-20 ha located at least 40 m away from border areas were selected in each field. Soil samples were collected in the spring before planting following an unaligned grid-point sampling scheme (Wollenhaupt et al., 1994). Cell size was 0.2 ha, and smaller sampling points (80 m^2) were randomly selected within each cell using a geographic information system (GIS) software. There were 100, 60, 60, 57 and 59 sampling positions for Fields 1 through 5, respectively. Composite soil samples (20 to 24 cores from a 15-cm depth) were collected from each sampling point. Elevation was determined with conventional land survey equipment (a transit) at each sampling position. Elevation data were expressed relative to the lowest position in each field.

The soil samples were dried in a forced-air oven at 35°, and ground to pass a 2-mm sieve. Duplicate soil samples were then analyzed for pH, organic matter, P and K and other nutrients using routine soil-test methods. Soil-test P (STP) was determined using the Bray-P_1, Olsen and Mehlich-3 extractants following procedures described by Frank et al. (1998). Field 1 had a high percentage of soil samples with pH > 7.4. Under these conditions, both the Olsen and Mehlich-3 extractants are more reliable than the Bray-P_1 method to estimate plant-available P in Iowa soils (Mallarino, 1997). Soil-test K (STK), and exchangeable Ca and Mg were determined with the 1 *M* ammonium acetate method (Warncke and Brown, 1998), soil organic matter (SOM) with the Walkley-Black method (Combs and Nathan, 1998), and pH with the 1:1 (vol/vol) ratio soil/water method (McLean, 1982). Cation exchange capacity (CEC) was estimated by the sum of K, Ca, Mg and exchangeable acidity (Warncke and Brown, 1998). Exchangeable acidity was estimated from measurements of pH and buffer pH. Extractable Zn was measured with a DTPA extraction technique (Whitney, 1998). Particle size distribution for the < 2mm soil fraction was determined by the standard pipette method (Walter et al., 1978). Iowa State University (ISU) soil-test interpretation classes for P and K in soybean production (Sawyer et al., 2002) were used to classify soil-test ranges. Five STP classes were (i) Very Low (≤8 mg kg^{-1}), (ii) Low (9-15 mg kg^{-1}), (iii) Optimum (16-20 mg kg^{-1}), (iv) High (21-30 mg kg^{-1}), and (v) Very High (≥31 mg kg^{-1}). Five STK classes were (i) Very Low (≤ 90 mg kg^{-1}), (ii) Low (91-130 mg kg^{-1}), (iii) Optimum (131- 170 mg kg^{-1}), (iv) High (171-200 mg kg^{-1}), and (v) Very High (≥201 mg kg^{-1}).

Several crop measurements were performed at each soil sampling position. The aboveground part of 10 soybean plants was sampled when plant height averaged 15 to 25 cm (V5 to V6 growth stage). Plant population was also measured at this time. Plant height was recorded at this time, and also at the R5 stage of development except for Field 1. Samples were dried in a forced air-oven at 60° C, weighed and ground to pass a 2-mm screen. Total P and K in the tissue was extracted by digesting samples with H_2SO_4 and H_2O_2 (Digesdahl Analysis System, Hatch Inc., Boulder, CO). Phosphorus in the extracts was measured by colorimetry (Murphy and Riley, 1962) and K was measured by flame photometry. Total P and K uptake were calculated from plant dry weights and nutrient concentrations and were expressed on a plant basis.

The presence of broadleaf and grass weeds was visually determined for the entire area of each cell at the VE to V1 soybean growth stage of development. A scale from 1 to 5 was developed, where 1 depicted the absence of weeds, and 5 represented an extremely dense weed pressure (more than 3/4 of the grid cell with weeds). Soybean cyst nematode (SCN) (*Heterodera glycines*) population density was determined for Field 1 in the fall and spring from samples collected from the sampling points areas before soybean planting following the procedures described by Tylka and Flynn (1999). Fall and spring eggs counts were averaged and data were expressed on a per volume basis as number of SCN eggs per 100 cc of soil. Data were collected only in Field 1, because the other fields did not have a substantial SCN infestation. Brown stem rot infection caused by *Phialophora Gregata* was visually evaluated when soybean reached the reproductive stages of development and data were expressed as the percentage of plant stems infected at each sampling position. The percentage of soybean plants affected by *Phytophtora* was also determined at each sampling position in the spring after planting.

Soybean grain yield was measured using combines equipped with yield monitors and real-time DGPS receivers. Yield monitors used were impact flow-rate sensors Ag Leader (AgLeader Technology, Ames, IA) or Green Star (John Deere, Moline, IL). Differential correction were obtained through the U.S. Coast Guard AM signal. Yield data were unaffected by field borders because at least 40 m from any border were harvested but not used. Grain moisture was determined on-the-go by a sensor located in the combine auger, and grain yield was corrected to 130 g kg^{-1} H_2O. The raw yield data was then exported into ArcView (Environmental Systems Research Inst., 380 New York St., Redlands, CA). The yield monitor data were carefully analyzed for common errors such as incorrect geographic coordinates due to partial loss of differential correction, the effect of waterways, and incorrect setting times in the time lag for the grain path through the combine. Affected data were corrected (such as grain path lags) or deleted (yield points near waterways or where the combine stopped within the trial area). Yield input data represented the mean of all yield monitor points recorded at 1-s intervals (9-s intervals in Field 1) for an area equivalent to the cell size. Yield data was then exported to the SAS statistical package (SAS Inst., 2000) for further statistical analyses.

Data Analysis

Descriptive statistical analysis for all site variables was performed using conventional univariate statistics (SAS Inst., 2000). Pearson's correlation coefficients (*r*) between site variables were computed to identify significant relationships among measured variables. Groups of correlated site variables, excluding soybean grain yield, were defined for each field separately using FA with the FACTOR procedure of SAS (SAS Inst., 2000). This approach has been used before to study relationships among correlated site variables in cornfields (Mallarino et al., 1999). Factor analysis was performed on the correlation matrix instead of the variance-covariance matrix to eliminate effects of the soil, crop and other properties' different measurement units. Principal factor analysis was utilized as the method of factor extraction and only factors with eigenvalues greater than one were retained for further analysis (Dillon and Goldstein, 1984; Sharma, 1996).

Identified factors were rotated to achieve a simpler factor structure and to aid in data interpretation (Sharma, 1996). A Promax (oblique) factor rotation of the loading matrix was used in order to redistribute the factor loadings for the measured variables in each factor (Johnson and Wichern, 2002). An orthogonal rotation preserves the original orientation between factors so they are still perpendicular after rotation and uncorrelated (Dillon and Goldstein, 1984) while in an oblique transformation the axes do not necessarily remain perpendicular after the rotation, thus factors can be partially correlated (Sharma,1996).

Rotated factor loadings were used to compute factor scores. Factor scores are linear transformations of the original variables and represent estimates of values for the unobserved factors (Johnson and Wichern, 2002). Factor scores were estimated by two different procedures. Procedure 1 estimated factor scores for each sampling point using the regression method of SAS (SAS Inst., 2000), considering all site variables for each individual factor. In Procedure 2 factor scores were estimated by a simpler method based on the size of the rotated loadings (Rencher, 1995). New variables for each sampling position of each field were created by standardizing and averaging selected variables from each retained factor. The basis for selecting measured variables was in the factor loadings (Johnson and Wichern, 2002). Only variables with loadings higher than + - 0.5 within each factor were selected to create these variables (Haq and Mallarino, 1998; Mallarino et al., 1999). This new set of variables are called latent variables to denote that they attempt to represent underlying unobservable factors (Mallarino et al., 1999). The effect of soil series on factor scores calculated by Procedure 1 was then assessed by analysis of variance, and residuals from this analysis were tested for normality. Factor analysis was also performed across all fields including only soil and crop variables measured across all fields.

Principal component analysis was also performed for each field by computing the eigenvectors and eigenvalues of the correlation matrix using the PRINCOMP procedure of SAS

(SAS Inst., 2000). The eigenvectors represent the direction of maximum variance while the eigenvalues specify the length or the magnitude of the variances (Johnson and Wichern, 2002). Principal components are linear combinations of the original site variables and present some important characteristics: the PC are uncorrelated, the first PC accounts for as much of the variance in the data as possible, and each succeeding PC accounts for as much of the remaining variability as possible (Johnson, 1998). Only PC with eigenvalues greater than one were retained (Sharma, 1996). In a correlation matrix the variance of each variable is equal to one and if a PC cannot account for more variation than a single variable by itself, then it is probably not relevant (Johnson, 1998).

To study the relationships between site variables and soybean grain yield, multiple linear regression models were fit for each field using SAS (SAS Inst., 2000) following three different procedures. In Procedure 1, soybean grain yield was regressed on all individual site variables using a stepwise regression procedure with a criteria of probability (*P*) equal to 0.05 for variable addition or deletion. This procedure was used as a reference for comparison with the regression models using FA and PCA. The inclusion of a large number of variables in a regression model often results in multicollinearity, which is defined as a high degree of correlation among independent variables (Freund and Littell, 2000). The degree of multicollinearity was assessed using three statistics: (i) the significance of the model and parameter estimates, (ii) the variance inflation factors (VIF) and (iii) the Condition Index (CI). The VIF are useful to determine which variables may be involved in multicollinearity, and measures how much the variances of the estimated regression coefficients are inflated as compared to when the predictor variables are not linearly related (Neter et al., 1996). The CI is derived from the study of the eigenvalues and eigenvectors of the correlation matrix, and is the square root of the ratio of the largest to smallest eigenvalue (Freund and Littel, 2000). Large variability among the eigenvalues suggests a greater degree of collinearity. In Procedure 2 soybean grain yield was regressed on the latent variables derived from the oblique factor loadings. In a few instances a single variable that was not included in any factor but was still highly correlated with yield was included in the model as an additional independent variable. In Procedure 3, soybean grain yield was regressed on the PC scores calculated from PCA.

RESULTS AND DISCUSSION

Rainfall during the growing seasons was highly variable across fields (Table 2). Rainfall during the early growth period (in late spring) was below the 50-yr average in Field 1 and above the 50-yr average in Fields 3 and 5. In mid-summer, when soybean reached the critical reproductive stages of development, rainfall was well below average in Fields 1 and 4.

The mean values and the variability for most site variables are shown in Table 3. There was large within-field soil nutrient variability in most fields. Soil-test P showed the highest coefficient of variation (CV) and soil pH the lowest across fields. In Fields 1, 2 and 4, STP values encompassed all ISU soil test interpretation classes (Sawyer et al., 2002). Only two fields had STK values in the Very Low class, but all fields except Field 5 had STK values in the Low class (Table 3). This suggests that most fields had limiting levels of P and K according to current recommendations for soybean (Sawyer et al., 2002). Several studies (Cambardella et al., 1994; Wollenhaupt et al., 1994; Mallarino, 1996a; Nolin et al., 2000) have also reported a high within-field spatial variability for P and K with CV ranging from 30-85% for STP and 35-60% for STK.

The lowest observed soil pH values in all fields were below the minimum recommended levels (pH < 6.0 or < 6.5) for soybean according to Iowa recommendations depending on the soil series (Sawyer et al., 2002). Field 1 presented the highest within-field variability in soil pH and soil Ca (Table 3). The highest pH values (8.03) were explained by the presence of the Canisteo (Typic Haplaquolls) and Harps (Typic Calciaquolls) soil series at lowland positions having $CaCO_3$-affected surface soil.

Correlations Among Site Variables

The degree of correlation between measured variables varied markedly across fields. Variables correlated in one field were not always correlated in other fields (Table 4). In all fields, SOM showed positive or negative correlations ($P \leq 0.05$) with most other site variables (Table 4). All fields except Field 4 had higher SOM content at lower landscape positions as denoted by the negative correlation between SOM and elevation. Topography is a major factor influencing SOM content through a modification of climate, soil texture and redistribution of water (Baldock and Nelson, 2000). Soil organic matter was positively correlated with clay content in three fields and with CEC in four fields. The positive correlation between SOM and clay content might be related to a higher SOM stability with finer textures (Baldock and Nelson, 2000). There were significant correlations between elevation and other soil properties (like clay content or CEC) in some fields but not in others. In Field 3 for example, elevation was positively correlated with clay content. Previous studies suggested that the lack of consistent correlation between elevation and some soil properties relates to differences between fields in parent material variation through the landscape (Kravchenko and Bullock, 2000). Soil organic matter was not correlated with soybean yield in any field. Most of the soils in this study were Mollisols and presented high mean SOM contents (Table 3). Kravchenko and Bullock (2000) emphasized that SOM content is likely a more important yield-affecting factor for corn in soils with low (< 30 mg kg^{-1}) SOM contents.

Within-field ranges of STP and STK values were large enough to expect significant ($P \leq 0.05$) positive correlations with soybean yield in most of the fields (Table 3). For example, the positive correlation between STK and grain yield in Field 1 (Table 4) was expected because STK classes ranged from Very Low to Very High. However, yield was not correlated with STP or STK in some fields with soil test values ranging from below optimum to above optimum values. The lack of correlation in some fields might be explained by several reasons. First, soybean yield response to P and K fertilization should be a better indicator of nutrient sufficiency than absolute yield because of high within-field variation in other growth factors. Other non-measured variables such as soil moisture, soil compaction, which affects root growth, might affect P and K uptake and could mask expected responses to STP and STK. Second, even the dense grid sampling approach used may have misrepresented P and K availability in the fields due to a large small-scale variability of these nutrients (Mallarino, 1996a). Different fertilization histories, or differences in soil types can explain the lack of correlation between any two site variables within a field (Mallarino et al., 1999). Also, the fact that some variables were correlated may imply that another measured or non-measured variable would be responsible for this correlation. Examining a correlation table to identify groups of correlated variables is not a clear-cut task. Highly correlated variables can be grouped into homogenous sets of variables representing single underlying factors (Johnson and Wichern, 2002).

Factor Analysis

Factor analysis for each field.

Oblique rotated factor loadings and the first four eigenvalues of the correlation matrix are presented in Table 5. Factor loadings indicate the correlation between a variable and an underlying common factor. Four factors were extracted in Fields 1, 2, and 3 whereas five and six factors were retained in Fields 4 and 5, respectively. The last two factors in Fields 4 and 5 only explained a small proportion of the variance in site variables, loaded highly on just one variable, or were not easily interpreted and are not shown. A high factor loading for a particular site variable suggests a high association between this variable and the factor. Variables with high positive or negative loadings within a factor indicate that a possible common factor exists that makes them vary together within a field. The first four factors accounted for 86, 80, 84, 74 and 69 % of the variance in Fields 1 to 5 respectively. That portion of the variance of a particular variable contributed by the retained factors is called the communality (Johnson and Wichern, 2002). A high communality for a soil or crop attribute indicates that a high proportion of its variance is explained by the factors. In contrast, a low communality for a soil or crop attribute indicates that much of that attribute's variance remains unexplained (Brejda et al., 2000). Less importance should then be assigned to attributes with low communalities when interpreting the factors. The remaining non-explained variance is called specific or residual variance (Rencher, 1995). For example, in Field 1 more than 80 % of the variation in clay, sand, pH, early growth, early P uptake or early K uptake was explained by a four-factor model (Table 5).

The first factor identified in all fields had consistent high positive loadings (> 0.75) for early growth, early P uptake, and early K uptake. This factor was the most relevant in Fields 3 and 5 based on the magnitude of the eigenvalue and was the second most relevant in Fields 1 and 2. We named this factor *conditions for early growth.* It is likely that differences in soil moisture, soil temperature, residue cover (specially in fields under no-tillage), affected by landscape position and soil series may have resulted in a wide range of conditions for early growth across fields. Furthermore, variables highly associated with this factor had a high within-field variability in all fields (Table 3). A similar common factor has also been identified before in a study involving corn in different fields (Mallarino et al., 1999). This factor was also associated with soil pH in Field 1 and with tissue K concentration in Field 3. The high negative loading of soil pH in Field 1 reflects the negative effect of a wide range of soil pH values (5.30-8.03) on early growth. It is remarkable that neither STP nor STK presented high loadings for this factor. However, previous studies suggested that a high variation in early growth for soybean is not necessary related to variations in STP or STK (Borges and Mallarino, 1998).

Another factor that showed the largest eigenvalue in Fields 1 and 2 (Table 5) but was less relevant in the rest of the fields involved the interaction of landscape or topographic position with stable soil properties such as CEC, SOM, and clay content. We named this factor as *landscape position - soil properties* and resulted from the interrelations between site variables of intrinsic origin. Some authors have referred to this group of variables as a soil texture factor (Brejda, 1998; Brejda et al., 2000). Nolin et al. (2000) suggested that these variables are mostly influenced by soil-forming factors or landscape and termed this factor as an "inherent soil fertility factor". In Field 1 this factor had high positive loadings for clay content, SOM, exchangeable Ca and CEC and a high negative loading for elevation and sand content. The same factor loading structure was also observed in Field 2. However, variables with large positive or negative loadings were not always consistent across fields. For example, in Field 3 only elevation, sand and clay content were present in this factor and the other stable soil properties were present or had high loadings in other factors. Elevation data were collected in all fields only at the sampling positions (approximately five points per ha) thus detailed terrain attributes like slope, profile, curvature and aspect could not be properly derived. Several studies have reported a strong relationship between these terrain attributes and soil properties or grain yields (Timlin et al., 1998; Kravchenko and Bullock, 2000; Kravchenko et al., 2000; Pachepsky et al., 2001). Some of these attributes could have been related to this factor especially in Fields 4 and 5 because they presented the largest variation in elevation (Table 3).

Soil-test P and STK were grouped together in one factor in four fields (Table 5), sometimes together with variables such as tissue K concentration or soil pH. The only exception was Field 1 because only STP had a loading > 0.5. We termed this factor *soil nutrient availability*. This factor had high loadings for tissue K concentration in Fields 2, 4, and 5; for tissue P concentration in Field 5 and for soil pH in Fields 1 and 2. A positive correlation (0.45-0.73) between STP and STK was observed in all fields (Table 4). Also, STK showed a positive correlation ($P \leq 0.05$) with K uptake and plant K concentration in all fields. In most fields there was a linear relationship between STK and plant K concentration. Soil-test P and P uptake or plant P concentration were correlated ($P \leq$

0.05) only in Fields 2, 3 and 4, and the relationship was curvilinear (decreasing increments with increasing STP). These results partially agreed with those reported by Borges and Mallarino (1998). These authors suggested the capacity of significant accumulation of K in young soybean plants over an important range of STK values but little for P (Mallarino, 1996b). The grouping of STP and STK in the same factor might have several explanations. It is likely that in the long term, crop nutrient removal might be an important source of variability driving both nutrients in the same direction. Also, these nutrients are usually applied together and this may also result in similar variation. Moreover, P and K had low mobility in soils and soil erosion and sedimentation processes might affect their availability similarly across the landscape. This would have probably been confirmed with a more detailed terrain survey.

The high negative loading for soil pH in Field 1 reflects the effect of high soil pH (> 7.4) and $CaCO_3$ content probably reducing P availability because of precipitation of insoluble calcium phosphate compounds (Bohn et al., 2001). A high positive loading for soil pH in the same factor that included STP and STK (Field 2) agreed with positive correlations with both STP and STK (Table 4). The range of soil pH values observed in this field (6.05-7.33) likely affected P availability.

The lack of relevant correlation between soil nutrient availability and other intrinsic soil properties poses the question of how effective are those soil properties when defining efficient sampling schemes for P and K. This is particularly important in those fields with long histories of P, K, and lime applications because there is both small and large scale nutrient variability. Mallarino and Wittry (2003) reported that in these fields a grid sampling approach was more effective for STP, while a sampling scheme considering soil series was more effective for SOM.

Transient variables such as plant diseases usually had low loadings in most factors for all fields. However, in Field 1 a factor that we named *conditions for SCN incidence* was identified. This factor had high positive loadings for SCN, SOM, soil pH, Ca, and CEC and negative loadings for elevation and tissue K concentration and early K uptake (Table 5). Higher SCN counts were observed in calcareous soils (Canisteo and Harps soil series) also characterized by a very poor drainage. It is likely that SCN infection was not the only variable affecting soybean yield but rather a combination of SCN incidence, reduced early growth, and higher weed pressure. It is remarkable that all variables related to early growth had also moderate negative loadings indicating the negative effect of lowland soils with high pH values on early growth.

Effect of soil series on factor scores.

There was an important within-field variation in soil series across fields. This variable was not included in the FA because the number of samples was too small for soil series with small areas and because we wanted to focus on measurable soil properties across an entire field. It is likely, however, that some extracted factors might be linked with a particular spatial location or soil series. To test a possible effect of soil series on factor scores we conducted an ANOVA for individual factor scores and fields (Table 6). Factor scores represent the values of the factors for each subject or observation. The absolute size of a score for a determined factor is an index of the strength between a particular observation and the factor. Factor scores were significantly ($P \leq 0.05$) affected by soil series in all fields. For example in Field 1, Factors 1 (*soil properties*), 2 (*conditions for early growth*) and 3 (*conditions for SCN infestation*) showed the highest positive scores for the Harps soil and the highest negative scores for the Clarion soil. Harps soils were highly associated with lowland positions, had higher pH, higher SCN cysts counts and reduced early growth. Moreover, this soil had high negative scores for Factor 4 (*nutrient availability*) probably because STP values were reduced in areas of high soil pH values. Factor 1 (*soil properties*) scores in Field 2 were highly negative for the Kenyon soil because this soil is located at upland positions, and exhibited the highest and lowest sand and SOM contents respectively. These observations coincide with the signs of the rotated loadings for this factor (Table 5).

In Field 3, the Kenyon and Dinsdale soils had contrastingly different scores for Factor 2 (*soil properties*) (Table 6). Kenyon soils are located at upland positions and had lower SOM contents and CEC than Dinsdale soils. That was reflected by the highly negative scores for these variables for the Kenyon soil and the positive scores for the Dinsdale soil. There were also differences in soil nutrient availability across soil types in Field 4. The Colo soil had significantly ($P \leq 0.05$) higher Factor 1 scores. This factor represented the combined effect of P and K availability and soil pH (Table 5). The Colo soil showed a high positive score associated with this factor, while upland soils with higher slopes such as Marshall soils had negative scores for this factor.

Factor analysis across fields

When data from all fields were pooled together (Table 7), a three-factor model accounted for 76 % of the variance of the site variables (Table 7). A *soil properties* factor accounted for 36 % of the total variance. This factor had high positive loadings on clay content, SOM, exchangeable Ca and Mg, and CEC; and had a high negative loading on sand content. A second common factor was named *conditions for early growth* because had high (> 0.75) positive loadings for early growth, and early P and K uptake. A third factor that explained an additional 13 % of the variance between site variables grouped together STP, STK, and both tissue P and K concentrations.

Of course, the structure of the covariance for the measured variables differs across fields, and these results cannot be generalized. However, it is remarkable that some factors were consistently observed across fields in this soybean study and in a previous Iowa study with corn based on different fields and years (Mallarino et al., 1999).

Principal Component Analysis

Principal component analysis was performed including all site variables, except soybean yield, for all fields. Five PC were extracted in Fields 1 and 3 and six PC were extracted in the rest of the fields. The first four PC accounted for 70, 67, 71, 60, and 56 % of the total standardized variance for Fields 1 through 5, respectively (Table 8). Fields 4 and 5 had the largest non-explained variability for all site variables. These fields had low values (< 0.6) of the Kaiser's measure of overall sampling adequacy (MSA). This indicator provides a mean to assess the extent to which the indicators of a PC or factor belong together (Sharma, 1996). For the purpose of this discussion as an example of interpretation of PCA, only all the PC's of the first three fields will be discussed because approximately similar interpretations apply to PC's for other fields.

In Field 1, the first PC (PC1) represented a contrast between some stable soil properties and early growth, early P and K uptake. This contrast likely reflects the negative effect of soils located at lowland positions, with high soil pH, SOM, exchangeable bases and SCN counts reducing early growth and early nutrient uptake. The second PC (PC2) represents different contrasts between STP, STK, exchangeable Mg and sand content, soil pH, and SCN infestation. First, the negative effect of high soil pH values on STP and STK in this field is reasonable and was also observed with the FA approach. Second, both soil pH, and SCN infestation are positively related (as denoted by the signs of the PC) which also coincided with the results from the FA. Third, there is a contrast between sand content and several variables. For example we would expect a reduction in the severity of *Phytophtora* with an increase in sand content due to an improvement of aeration and internal drainage. However it is not clear the effect of sand content on STP or STK. The third PC (PC3) is likely an indicator of early growth and early P and K uptake but also showed a contrast between this group of variables and *Phytophtora* which is reasonable because this plant disease directly affects early growth. The fourth PC (PC4) is difficult to interpret because several variables had high positive or negative loadings, but no clear contrasts could be interpreted.

In Field 2, PC1 is mostly composed of stable soil properties. It had positive loadings for clay content, SOM, exchangeable Ca and Mg, CEC and the height of the crop at the R5 stage of development and high negative loadings for elevation and sand content. This represents the contrast between several stable soil properties and topographic position. This relationship was also identified using FA. The second PC (PC2) is an indicator of early growth and early P and K uptake and had a negative effect of soil Ca. Probably, high Ca levels in this field (the highest except for Field 1) would have an effect reducing early growth. The third PC (PC3) clearly represented an index of nutrient availability because it had high positive loadings for STP, STK, and soil pH. The fourth PC (PC4) is difficult to interpret and is not discussed.

The first PC (PC1) in Field 3 represented a contrast between relatively stable soil properties (SOM, Ca, Mg, CEC, and soil pH) and an index of early growth and early P and K uptake. The second principal component (PC2) represented a weighted average effect of several variables that in general were negatively related to sand content. The negative effect of sand content on stable soil properties like SOM, Ca, Mg, or CEC seems reasonable. However, the contrast between sand content and early growth is not so clear nor is the contrast of sand content with STP and STK. The third principal component (PC3) does not provide a clear interpretation, while PC4 represented an index of nutrient availability because it had high loadings for both STP and STK and also a contrast with topography and some stable soil properties.

Relationships Between Site Variables and Soybean Yield

The use of FA and PCA to study the variance-covariance structure of different attributes should be regarded as a tool to better understand relationships among several site variables. Factor analysis grouped correlated variables into different factors and similar factors often were identified in all the fields. On the other hand, PCA provided information about the positive or negative effects of different variables to delineate the PC. In some cases a particular PC was only representing a weighted average of the different measured variables and was difficult to interpret. However, in other cases PCA revealed the contrast between variables (given by the positive or negative signs of the eigenvectors) and aided in data interpretation. Additional useful information is provided by study of relationships between site variables or groups of variables (from FA and PCA) with crop yield.

A stepwise multiple regression procedure was used to relate single site variables with soybean yield within each field. The reduced regression models for predicting soybean yield are presented in Table 9. Coefficients of determination (R^2) for the models ranged from 0.25 to 0.67. In Field 1 there was a negative relationship between yield and a model including pH, SCN, and the incidence of brown stem rot. All these variables showed a negative ($P \leq 0.05$) correlation with soybean yield (Table 4). There was a positive relationship between soil pH and Mg with yield in Field 2. Soil pH was positively correlated with STP and STK (Table 4) and FA grouped these three variables in the same factor. The positive effect of Mg on yield in Field 2 could not be clearly explained because this variable was not significantly correlated with yield, however Mg levels in this field were one of the lowest across fields, only higher than Field 3. It is likely that a possible Mg deficiency may have occurred in this field. There was a positive effect of elevation and sand content on yield in Field 3. This field had above average rainfall during the most of the growing season. Kaspar et al. (2003) also found a positive relationship between corn yield and increasing elevation in wet years. Factor analysis revealed that both elevation and sand content were included in the same factor for this field. The negative relationship between yield and elevation in Field 4 is reasonable because this field had below average rainfall during most of the growing season. The negative relationship between yield and SOM in Fields 4 and 5 could not be explained. A positive relationship between yield and plant K for Fields 4 and 5 is reasonable because plant K concentration was among the lowest in these fields even though STK was not the lowest. There was no evidence of collinearity between independent variables for any final stepwise regression model (VIF values were < 10 and CI values were < 30). However, strong evidence of collinearity was observed when a full model used to select the highest coefficient of determination was applied (data are not shown) and these results introduce uncertainty about the variables chosen for the final model.

Multiple regression analyses were conducted using soybean grain yield as the dependent variable and the latent variables derived from FA (Table 10) as independent variables. Coefficients of determination of models based only on latent variables ranged from 0.10 to 0.65 (Table 11). Roughly similar range of explained yield variability has been previously reported for corn (Mallarino et al., 1999), cotton (Johnson et al., 2002), and sorghum (Machado et al., 2002). Although FA analysis identified several groups of correlated variables within and across fields, only some latent variables significantly contributed to explain soybean yield variability.

Two latent variables significantly ($P \leq 0.05$) contributed to explain soybean yield variability in Field 1 (Table 11). A latent variable named *conditions for SCN infestation* (derived from Factor 3) was negatively related with soybean yield, which was in agreement with a negative correlation ($P \leq 0.05$) between SCN incidence or pH and yield. A latent variable named *P and K availability* (derived from Factor 4) was positively related with yield. This was probably related to the effect of a high within-field variation in STP and STK with values encompassing most of the soil-test interpretation classes. This latent variable was the only one that significantly ($P < 0.05$) contributed to explain soybean yield variability in Fields 2 and 5, and represented the combined effect of pH, and P and K availability. Soil-test P ranged from Very Low to High or Very High in these fields (Table 3), whereas STK ranged from Very Low to Very High in Fields 1 and 2. No latent variable was significantly related with yield in Field 3.

In Field 4 there was a negative relationship between the *soil properties -landscape position* latent variable (derived from Factor 2) and soybean yield. Higher yields were frequently observed at lower landscape positions, which is denoted by a negative correlation (*r* -0.55) between relative elevation and yield (Table 4). This field and also Field 5 had the highest range in elevation (Table 3). Also, Field 4 had a period of markedly below average precipitation during soybean reproductive stages (Table 2). Year and monthly weather conditions have considerable influence on yield-topography relationships and higher corn and soybean yields for downslope positions have been previously reported in dry years (Kravchenko and Bullock, 2000; Kaspar et al., 2003). These results have been attributed to the effect of erosion and terrain attributes on soil properties affecting soil water availability (Kaspar et al., 2003). Field 1 also had a period of drought during mid-summer, but relative elevation and yield were positively ($P \leq 0.05$) correlated. Moreover, relative elevation was one of the variables identified in the *conditions for SCN infection* latent variable, which negatively affected soybean yield. Perhaps the occurrence of higher soil pH and higher SCN incidence at lower landscape positions masked the positive correlation between elevation and yield in this case.

The incidence of brown stem rot in Field 2 and the presence of weeds in Fields 4 and 5 had a negative ($P \leq 0.05$) correlation with yield and were not grouped by FA in any factor. Thus, they were included as additional independent variables in the regression models, which improved soybean yield prediction (Table 11).

Principal component regression analysis could provide a better prediction of yield variability than FA because it identifies successive linear combination of all the variables that explain the maximum amount of variance in the data. However, the regression of soybean yield on PC provided similar yield prediction compared to the FA model (Table 12) in Fields 1 and 3. In Fields 2, 4, and 5, the FA and PCA models resulted in similar R^2 values when one independent variable was added to the FA model (Table 11). Coefficients of determination for multiple regression models relating PC with soybean yield ranged from 0.14 to 0.65 (Table 12).

The first four PC's significantly ($P \leq 0.05$) contributed to explain soybean yield variability in Field 1. The first PC (PC1) was negatively correlated to yield. It is likely that poorer early growth conditions prevailed at lowland positions, with high SOM contents, high soil pH, and SCN infestation and this had a negative effect on yield. The second PC (PC2) was positively correlated to yield. As it was previously discussed this PC represented a contrast between several site variables (Table 8), but in this case the positive sign of this PC in the regression model is reflecting the positive effect of variables associated with P and K availability (STP and STK). The third PC (PC3) was negatively correlated to yield. It represented the negative effect of plant diseases such as *Phytophtora* on early growth and Brown stem rot on yield (Table 8). The fourth PC (PC4) also was negatively correlated to yield however this PC could not be easily interpreted. In Field 2 a portion of soybean yield variability was also explained by four PC's. The PC that highly contributed to the regression model was PC3 and represented an index of nutrient availability because STP, STK and soil pH had the highest positive loadings in this PC (Table 8). Factor analysis had also revealed a significant relationship of these variables with soybean yield for this field (Table 11). The second most important PC in the regression model for this field was PC 5. This PC had a high loading for brown stem rot and was negatively correlated with soybean yield. Inclusion of this variable as an additional independent variable in the regression models of soybean yield on the latent variables resulted in similar R^2 to the PCA model (Table 11).

The regression model for Field 3 was not significant, therefore no discussion of the effect of PC's is presented for this field. Three PC's contributed to explain soybean yield variability in Field 4. The most important was PC1 which represented a contrast between STK, plant K concentration, and early K uptake (a measure of K availability) and exchangeable Mg, and CEC (with negative signs). The positive sign for this PC in the model reflects the positive effect of K availability on soybean yield. The second most relevant PC in the regression model was PC4. This PC reflected the positive effect of crop height (H1 and H2) as an indicator of biomass production and the negative effect of elevation (Table 8). The positive sign of this PC in the regression model reflects a poor crop growth at higher elevations which affected soybean yield. This observation agreed with the observed rainfall pattern for this field. Three PC contributed to explain soybean yield variability in Field 5. The first PC (PC1) represented a positive effect of early growth and early P and K uptake on soybean yield. However the most important PC in the regression model (PC3) represented the contrast between the crop height at the R5 stage of development as an indicator of biomass and early growth and early P uptake. The positive sign for this PC in the model reflects the positive effect of a high biomass production on soybean yield, but also the lack of correlation between early growth measured at the V6 stage of development and the biomass production later in the season (data are not shown).

Overall, FA and PCA identified similar groups of variables that had positive or negative relationships with soybean yield variability, especially when a single independent variable not included in any factor from FA was added to the regression models. On the other hand, additional relationships between variables uncovered by PCA had little effect on yield. Despite the large number of measured variables in each field, there was a large spatial variability in soybean yield that remained unexplained either by stepwise regression, FA, and PCA models in some fields. However, all fields except Field 1 had a relatively low yield variability (CV < 10 %) and part of the unexplained variability is probably due to measurement error for yield, soil, and crop properties. Perhaps some variables relevant to yield were not measured directly. For example, soil water availability during soybean reproductive stages was not measured. However, in Field 1 which exhibited the highest yield variability (Table 3), both FA and PCA accounted for 65 % of this variability.

SUMMARY AND CONCLUSIONS

Factor analysis provided a rational criterion to group correlated soil and crop variables into at least four factors in each field. The importance of each factor in explaining yield variability varied from field to field, although factors with similar loading structure were observed in all fields. One factor grouped variables related to early growth conditions. A second factor represented the interaction between topography and stable soil properties not likely to be affected in the short term by soil management practices that reflect or are related to other properties such as soil water holding capacity or nutrient release dynamics. A third factor grouped soil variables that reflected correlations between STP and STK availability and in some fields their interaction with soil pH. These factors were also partially correlated in some fields which is reasonable aiding in data interpretation. The results from PCA were more difficult to interpret because in most cases they represented weighted averages of several variables. However, for some fields PCA reflected contrasts between variables that were consistent with the FA approach and aided in data interpretation.

Regression models of soybean yield on latent variables derived from FA, in some fields together with a single site variable having no strong association to any factor, explained 10-65 % of soybean yield variability. About 90 % of the yield variability was unexplained in one field, but yield variability was very low (CV 6.2 %). Approximately 50-60 % of the yield variability was unexplained in three fields, but the yield variability was also low (CV 6 to 9 %). In the field with largest yield variability (CV 35 %), the FA regression model accounted for 65 % of the yield variability. The relative importance of each factor varied from field to field. The factors with more impact on yield variability were P and K availability (represented by STP and STK), the effect of topographic position in relation with other soil properties and for a particular field (Field 1) the effect of SCN infestation. Principal component regression analysis showed a similar prediction of soybean yield variability to FA, although the effect of single PC's on soybean yield was more difficult to interpret.

Overall, the results of this study showed that single variables seldom can explain yield variability and that complex tables of simple correlation coefficients are very difficult to interpret because of the inter-correlations among variables. A multivariate approach that considers the relationship between many site variables by grouping them in a few factors or PC's is more reasonable. These groups of variables may not always explain a large proportion of yield variability because although they may represent some important underlying factor or variable (such as soil moisture availability), not all relevant variables are measured and some may not be measured with the most appropriate method.

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Table 1. Site locations and predominant soils for five soybean fields.

Field	County	Year	N[†]	Dominant soil			Second dominant soil		
				Series	Subgroup[‡]	Area	Series	Subgroup	Area
						%			%
1	Boone	1997	100	Clarion	T. Hapludolls	33	Nicollet	A. Hapludolls	25
2	Linn	1997	60	Klinger	A. Arguidolls	38	Kenyon	T. Hapludolls	33
3	Linn	1998	60	Clyde-Floyd	T. Haplaquolls	27	Dinsdale	T. Argiudolls	25
4	Carroll	1997	57	Marshall	T.Hapludolls	70	Exira	T.Hapludolls	19
5	Carroll	1998	59	Marshall	T.Hapludolls	68	Judson	C.Hapludolls	12

† Number of sampling positions for each field.

‡ A, Aquic; C, Cumulic; T, Typic.

Table 2. Soybean varieties, planting dates, tillage practices and rainfall for five soybean fields.

				May		June		July		August	
Field	Variety†	Planting date	Tillage‡	Rain	Avg.§	Rain	Avg.	Rain	Avg.	Rain	Avg.
				mm							
1	M-APACHE V	11 May	CH	81	106	96	120	33	99	28	106
2	S2870	12 May	NT	137	114	125	124	24	113	134	109
3	S2254	12 May	NT	120	114	210	124	13	113	221	109
4	SOI 237	9 May	NT	76	105	154	124	42	103	39	92
5	SOI 2807	3 May	NT	134	105	204	124	101	103	72	92

† M, Merschmann Seeds; S, Stine Seed Company; SOI, Sand Seed Service, Inc.

‡ CH, disk-chisel tillage; NT, no tillage

§ 50-yr average rainfall for the corresponding sites.

Table 3. Descriptive statistics for selected site variables in five soybean fields.

	Variables†															
Field	REL	Clay	Sand	SOM	P	K	Ca	Mg	CEC	pH	EG	PLP	PLK	PUP	KUP	Y
	m	kg kg^{-1}		g kg^{-1}	mg kg^{-1}				cmol kg^{-1}		g pl^{-1}	g kg^{-1}		mg pl^{-1}		Mg ha^{-1}
	Mean															
1	2.46	0.256	0.368	46.0	17	143	2791	261	17.4	6.57	1.96	3.7	26.3	7.3	52.6	2.28
2	5.24	0.268	0.188	32.2	19	114	1725	163	10.3	6.75	1.14	3.8	26.5	4.4	30.1	4.29
3	4.95	0.275	0.139	46.7	20	165	1730	173	11.0	6.82	1.21	3.6	32.0	4.3	39.8	4.05
4	8.12	0.329	0.024	35.4	13	162	1460	461	13.4	5.88	1.45	3.4	23.8	4.9	34.6	3.27
5	8.54	0.314	0.063	28.3	14	182	1400	465	14.6	6.31	0.84	3.6	22.5	3.1	19.0	2.96
	Maximum															
1	5.63	0.359	0.634	80.0	32	267	3994	470	28.1	8.03	3.60	4.6	34.6	12.9	115.3	4.03
2	9.55	0.310	0.482	60.0	44	200	2605	292	15.0	7.33	1.49	4.5	32.4	5.8	44.8	4.69
3	9.79	0.315	0.366	75.0	40	235	2548	325	15.6	7.30	1.85	4.2	43.6	7.0	72.4	4.49
4	16.40	0.369	0.038	45.0	33	341	2120	686	17.9	6.85	2.32	4.0	34.0	7.1	62.7	4.24
5	19.74	0.356	0.295	39.0	27	226	1781	688	19.7	6.86	1.19	4.7	29.8	4.4	29.8	3.52
	Minimum															
1	0.0	0.129	0.207	13.0	4	68	1576	132	9.7	5.30	0.81	3.1	16.2	2.9	15.9	0.34
2	0.0	0.197	0.041	20.0	6	81	1086	95	6.8	6.05	0.76	3.3	17.7	3.1	19.5	3.51
3	0.0	0.206	0.042	31.0	11	128	1109	87	6.7	6.30	0.55	2.0	17.0	1.1	12.5	3.52
4	0.0	0.242	0.018	25.0	6	104	1069	298	9.8	5.43	0.91	2.9	18.7	2.6	17.7	2.66
5	0.0	0.225	0.020	14.0	7	148	1022	296	9.3	5.43	0.50	2.4	14.6	1.5	10.1	2.37
	Coefficient of variation (%)															
1	49.1	19.1	26.1	29.1	35.3	26.6	24.6	23.4	21.3	12.9	26.0	8.1	15.2	24.7	35.4	35.1
2	49.1	10.4	69.1	26.1	36.8	15.8	20.3	23.9	18.4	4.1	15.8	5.3	11.7	13.6	18.6	5.4
3	44.6	9.5	60.4	21.4	30.0	13.3	20.9	29.5	19.1	2.8	23.1	11.1	15.9	27.9	34.7	6.2
4	52.5	7.6	16.7	11.6	30.8	28.4	13.0	19.5	11.9	4.9	20.0	5.9	14.7	18.4	27.5	8.9
5	61.7	8.6	98.4	20.1	28.6	10.4	12.8	16.3	14.4	4.4	15.5	11.1	16.0	19.4	22.1	8.1

† REL, elevation relative to the lowest point; SOM, soil organic matter; P, soil-test P; K, soil-test K; CEC, cation exchange capacity; EG, early growth; PLP, plant P concentration; PLK, plant K concentration; PUP, P uptake; KUP, K uptake; Y, grain yield.

Table 4. Pearson's correlation coefficients for selected site variables measured in five soybean fields†.

Field	Variable‡	REL	Clay	Sand	SOM	P	K	Ca	Mg	CEC	pH	EG	PLP	PLK	PUP	KUP
1	Clay	-0.57														
	Sand	0.54	-0.92													
	OM	-0.73	0.77	-0.75												
	P	-0.05	-0.08	-0.02	0.06											
	K	0.00	0.08	-0.18	0.16	0.53										
	Ca	-0.54	0.46	-0.39	0.52	0.07	0.14									
	Mg	-0.37	0.50	-0.59	0.49	0.33	0.28	0.29								
	CEC	-0.53	0.48	-0.49	0.57	0.17	0.33	0.84	0.52							
	pH	-0.60	0.47	-0.36	0.54	-0.26	-0.17	0.62	-0.01	0.39						
	EG	0.46	-0.43	0.37	-0.47	0.22	0.17	-0.42	-0.21	-0.35	-0.53					
	PLP	-0.21	0.33	-0.35	0.36	0.15	0.13	0.25	0.23	0.27	0.21	-0.27				
	PLK	0.53	-0.32	0.24	-0.38	0.27	0.31	-0.42	-0.10	-0.30	-0.73	0.50	0.03			
	PUP	0.41	-0.33	0.26	-0.37	0.28	0.23	-0.36	-0.13	-0.26	-0.49	0.96	0.02	0.52		
	KUP	0.54	-0.42	0.35	-0.48	0.27	0.26	-0.46	-0.21	-0.36	-0.66	0.93	-0.19	0.77	0.90	
	Y	0.34	-0.23	0.10	-0.20	0.31	0.38	-0.38	0.20	-0.15	-0.70	0.42	-0.11	0.65	0.40	0.55
2	Clay	-0.70														
	Sand	0.78	-0.88													
	OM	-0.84	0.65	-0.74												
	P	-0.28	0.07	-0.09	0.26											
	K	-0.24	0.10	-0.17	0.27	0.66										
	Ca	-0.51	0.65	-0.56	0.61	0.31	0.19									
	Mg	-0.64	0.54	-0.62	0.62	-0.06	-0.05	0.36								
	CEC	-0.58	0.70	-0.63	0.66	0.26	0.19	0.98	0.52							
	pH	0.17	-0.24	0.20	-0.13	0.36	0.39	0.08	-0.26	0.00						
	EG	-0.36	0.20	-0.25	0.13	-0.03	0.12	-0.16	0.18	-0.10	-0.13					
	PLP	0.14	-0.05	0.18	-0.08	0.33	-0.01	0.37	-0.18	0.31	0.23	-0.49				
	PLK	0.05	-0.05	0.03	-0.03	0.30	0.35	0.03	-0.10	0.01	0.36	-0.10	0.22			
	PUP	-0.33	0.19	-0.19	0.10	0.10	0.12	-0.04	0.11	0.00	-0.05	0.92	-0.11	-0.00		
	KUP	-0.25	0.11	-0.17	0.08	0.15	0.30	-0.14	0.08	-0.10	0.13	0.75	-0.24	0.56	0.76	
	Y	-0.09	-0.03	-0.08	0.09	0.19	0.05	0.01	0.11	0.01	0.49	-0.10	0.09	0.27	-0.08	0.09

† Correlations differ significantly from zero ($P<0.05$) if the coefficient is greater than 0.20 for Field 1, 0.25 for Field 2, 0.26 for Field 3, 0.26 for Field 4 and 0.27 for Field 5.

‡ REL, elevation relative to the lowest point; SOM, soil organic matter; P, soil-test P; K, soil-test K; CEC, cation exchange capacity; EG, early growth; PLP, plant P concentration; PLK, plant K concentration, PUP, P uptake; KUP, K uptake; Y, soybean yield.

Table 4 (continued).

Field	Variable	REL	Clay	Sand	SOM	P	K	Ca	Mg	CEC	pH	EG	PLP	PLK	PUP	KUP
3	Clay	0.42														
	Sand	-0.52	-0.70													
	OM	-0.26	0.46	-0.31												
	P	0.07	0.37	-0.23	0.18											
	K	0.25	0.43	-0.42	0.28	0.73										
	Ca	-0.20	0.47	-0.34	0.81	0.28	0.32									
	Mg	-0.14	0.54	-0.41	0.74	0.32	0.41	0.88								
	CEC	-0.10	0.52	-0.42	0.77	0.24	0.42	0.94	0.89							
	pH	-0.05	0.08	-0.07	0.17	0.10	-0.00	0.37	0.32	0.13						
	EG	0.22	0.09	-0.12	0.03	0.05	0.27	-0.22	-0.09	-0.01	-0.53					
	PLP	0.24	-0.11	-0.00	-0.24	0.03	-0.13	-0.40	-0.41	-0.41	-0.27	0.39				
	PLK	0.34	-0.07	-0.14	-0.15	-0.07	0.25	-0.30	-0.19	-0.07	-0.56	0.68	0.42			
	PUP	0.28	0.06	-0.12	-0.06	0.04	0.20	-0.30	-0.20	-0.13	-0.53	0.95	0.64	0.71		
	KUP	0.29	0.02	-0.12	-0.08	0.00	0.29	-0.30	-0.17	-0.05	-0.60	0.94	0.43	0.87	0.93	
	Y	0.44	0.08	0.00	-0.23	0.09	0.04	-0.10	-0.10	-0.11	-0.15	0.12	0.20	0.19	0.16	0.14
4	Clay	0.15														
	Sand	-0.16	-0.39													
	OM	-0.20	-0.18	0.15												
	P	0.35	-0.17	0.23	0.26											
	K	-0.10	-0.38	0.26	0.27	0.53										
	Ca	0.41	0.05	0.04	0.61	0.34	0.15									
	Mg	0.34	0.55	-0.17	0.62	0.04	-0.28	0.59								
	CEC	0.56	0.43	-0.24	-0.37	0.14	-0.17	0.69	0.75							
	pH	-0.25	-0.34	0.33	-0.13	0.37	0.42	0.36	-0.12	-0.32						
	EG	-0.19	-0.01	0.11	0.13	-0.02	0.13	0.00	0.00	0.05	0.04					
	PLP	0.21	0.06	0.05	-0.08	0.38	0.10	0.17	0.11	0.10	0.21	-0.18				
	PLK	-0.04	-0.56	0.31	-0.03	0.41	0.76	0.04	-0.39	-0.22	0.27	0.19	0.17			
	PUP	-0.14	0.00	0.12	0.10	0.10	0.16	0.05	0.03	0.07	0.11	0.93	0.18	0.25		
	KUP	-0.21	-0.33	0.25	0.08	0.18	0.53	-0.00	-0.24	-0.12	0.18	0.82	-0.06	0.71	0.80	
	Y	-0.55	-0.15	0.07	-0.11	-0.01	0.16	-0.21	-0.14	-0.38	0.29	-0.03	-0.11	0.17	-0.06	0.10

Table 4 (continued).

Field	Variable	REL	Clay	Sand	SOM	P	K	Ca	Mg	CEC	pH	EG	PLP	PLK	PUP	KUP
5	Clay	-0.05														
	Sand	0.28	-0.81													
	OM	-0.40	0.18	-0.40												
	P	0.28	-0.06	0.14	-0.07											
	K	0.21	0.04	-0.02	0.07	0.45										
	Ca	-0.20	0.14	-0.24	-0.05	-0.11	0.06									
	Mg	0.12	0.52	-0.38	-0.23	-0.05	0.01	0.40								
	CEC	0.05	0.32	-0.39	0.26	-0.04	0.08	0.37	0.41							
	pH	-0.24	0.01	-0.00	-0.28	-0.10	-0.10	0.30	0.09	-0.68						
	EG	-0.11	0.19	-0.16	-0.07	-0.08	0.01	0.04	-0.07	0.03	-0.01					
	PLP	0.00	0.04	0.05	-0.20	0.21	0.23	-0.10	-0.03	-0.08	-0.05	0.19				
	PLK	-0.09	-0.05	0.03	0.43	0.17	0.50	-0.10	-0.30	0.09	-0.31	-0.01	0.49			
	PUP	-0.09	0.20	-0.14	-0.13	0.03	0.13	-0.03	-0.07	0.00	-0.05	0.86	0.65	0.24		
	KUP	-0.15	0.14	-0.14	0.27	0.04	0.35	-0.02	-0.25	0.10	-0.21	0.72	0.46	0.67	0.80	
	Y	0.17	-0.10	0.19	-0.00	0.25	0.32	0.20	-0.11	0.10	-0.12	-0.01	0.21	0.35	0.11	0.25

Table 5. Oblique factor loadings and final communalities for selected site variables in five soybean fields.

		Factor Loadings†				
Field	Variables§	1	2	3	4	Communalities
1	REL	-0.61‡	0.47	-0.68‡	-0.01	0.59
	Clay	0.94‡	-0.41	0.46	-0.13	0.87
	Sand	-0.94‡	0.33	0.08	-0.03	0.85
	SOM	0.68‡	-0.42	0.62‡	-0.01	0.74
	Soil-test P	-0.07	0.34	0.29	0.57‡	0.42
	Soil-test K	0.16	0.33	0.25	0.41	0.41
	pH	0.43	-0.55‡	0.76‡	-0.53‡	0.88
	Ca	0.48	-0.34	0.87‡	0.10	0.76
	Mg	0.60‡	-0.18	0.32	0.40	0.67
	CEC	0.57‡	0.05	0.77‡	0.34	0.77
	Zn	0.33	-0.12	0.19	0.14	0.30
	Early Growth	-0.44	0.88‡	-0.47	-0.04	0.88
	Plant P	0.54‡	0.28	0.24	-0.20	0.37
	P Uptake	-0.28	0.94‡	-0.41	-0.09	0.93
	Plant K	0.14	0.40	-0.55‡	0.27	0.73
	K Uptake	-0.40	0.83‡	-0.61‡	0.06	0.96
	SCN	-0.11	-0.43	0.59‡	-0.46	0.62
	Eigenvalues	6.91	3.16	1.34	1.07	
2	REL	-0.83‡	-0.22	-0.05	-0.01	0.79
	Clay	0.88‡	0.14	-0.07	0.04	0.77
	Sand	-0.92‡	-0.20	0.02	0.16	0.84
	SOM	0.86‡	0.10	0.08	-0.01	0.74
	Soil-test P	0.10	0.07	0.61‡	0.38	0.53
	Soil-test K	0.18	0.18	0.68‡	-0.01	0.51
	pH	-0.15	-0.08	0.69‡	0.02	0.52
	Ca	0.70‡	-0.20	0.14	0.63‡	0.87
	Mg	0.74‡	0.14	-0.22	-0.09	0.60
	CEC	0.77‡	-0.14	-0.09	0.41	0.89
	Zn	-0.08	0.01	-0.05	0.46	0.18
	Early Growth	0.09	0.93‡	-0.08	-0.11	0.96
	Plant P	-0.22	-0.08	0.22	0.89‡	0.86
	P Uptake	-0.02	0.96‡	0.01	0.27	0.95
	Plant K	-0.07	0.09	0.75‡	0.01	0.59
	K Uptake	0.01	0.83‡	0.41	-0.07	0.90
	Height 1	0.37	0.15	-0.02	-0.08	0.16
	Height 2	0.76‡	0.20	0.09	-0.19	0.58
	Eigenvalues	5.91	2.99	2.53	1.26	

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† Rotated factor loadings from an oblique transformation.

‡ Indicates variables with larger loadings selected within each factor to construct latent variables.

§ REL, elevation relative to the lowest point in the field; SOM, soil organic matter; CEC, cation exchange capacity; Plant P, plant P concentration; Plant K, plant K concentration; SCN, soybean cyst nematode counts; Height1 and Height2, crop height at the V6 and R5 stages of development respectively.

Table 5 (continued).

Field	Variables	Factor Loadings 1	2	3	4	Communalities
3	REL	0.29	-0.20	0.72[‡]	0.09	0.66
	Clay	-0.07	0.31	0.77[‡]	0.45	0.74
	Sand	-0.01	-0.37	-0.80[‡]	-0.30	0.69
	SOM	-0.10	0.84[‡]	0.16	0.29	0.69
	Soil-test P	0.02	0.24	0.28	0.86[‡]	0.75
	Soil-test K	0.22	0.39	0.34	0.81[‡]	0.76
	pH	-0.32[‡]	0.22	0.08	0.06	0.44
	Ca	-0.21	0.94[‡]	0.19	0.38	0.93
	Mg	-0.34	0.91[‡]	0.28	0.09	0.86
	CEC	-0.14	0.96[‡]	0.22	0.45	0.94
	Zn	-0.38	0.32	0.03	-0.08	0.29
	Early Growth	0.93[‡]	0.01	0.18	0.02	0.89
	Plant P	0.45	-0.40	0.17	-0.18	0.47
	P Uptake	0.95[‡]	-0.13	0.23	-0.03	0.90
	Plant K	0.87[‡]	-0.15	0.18	-0.05	0.76
	K Uptake	0.99[‡]	-0.09	0.19	0.01	0.97
	Height 1	0.43	-0.11	0.18	-0.01	0.20
	Height 2	0.31	0.64[‡]	0.06	-0.04	0.44
	Eigenvalues	5.62	4.35	1.66	1.09	
4	REL	-0.05	0.75[‡]	-0.22	-0.02	0.64
	Clay	-0.64[‡]	0.35	-0.04	0.03	0.49
	Sand	0.42	-0.19	0.11	0.15	0.22
	SOM	0.32	-0.43	0.21	-0.32	0.34
	Soil-test P	0.61[‡]	0.33	0.02	0.39	0.56
	Soil-test K	0.83[‡]	-0.08	0.21	0.09	0.70
	pH	0.47	-0.17	0.10	0.71[‡]	0.75
	Ca	0.10	0.72[‡]	0.02	0.45	0.66
	Mg	-0.40	0.77[‡]	-0.01	0.34	0.78
	CEC	-0.31	0.88[‡]	0.03	0.07	0.84
	Zn	0.01	0.37	0.18	0.19	0.19
	Early Growth	0.11	-0.05	0.98[‡]	-0.05	0.97
	Plant P	0.18	-0.28	-0.05	0.56[‡]	0.38
	P Uptake	0.18	0.03	0.97[‡]	0.15	0.96
	Plant K	0.91[‡]	-0.10	0.30	-0.06	0.87
	K Uptake	0.43	-0.14	0.88[‡]	-0.10	0.97
	Height 1	-0.08	0.07	-0.19	0.32	0.15
	Height 2	-0.13	0.14	0.20	0.53[‡]	0.36
	Eigenvalues	4.51	3.20	2.28	1.29	

Table 5 (continued).

		Factor Loadings				
Field	Variables	1	2	3	4	Communalities
5	REL	-0.12	-0.13	0.25	-0.57[‡]	0.44
	Clay	0.18	0.80[‡]	0.02	0.11	0.69
	Sand	-0.14	-0.79[‡]	0.11	-0.37	0.77
	SOM	-0.05	0.11	-0.08	0.82[‡]	0.79
	Soil-test P	-0.05	-0.13	0.54[‡]	-0.23	0.52
	Soil-test K	0.10	-0.01	0.66[‡]	0.05	0.46
	pH	-0.05	0.12	-0.17	-0.01	0.92
	Ca	0.01	0.55[‡]	-0.13	-0.03	0.36
	Mg	-0.11	0.70[‡]	-0.09	-0.38	0.69
	CEC	0.02	0.52[‡]	-0.02	-0.02	0.85
	Zn	-0.14	-0.01	-0.26	-0.27	0.15
	Early Growth	0.95[‡]	0.11	0.01	-0.12	0.97
	Plant P	0.40	-0.11	0.74[‡]	0.02	0.74
	P Uptake	0.96[‡]	0.06	0.38	-0.06	0.97
	Plant K	0.23	-0.23	0.67[‡]	0.61[‡]	0.87
	K Uptake	0.85[‡]	-0.04	0.45	0.36	0.95
	Height 1	-0.04	-0.01	-0.08	-0.05	0.55
	Height 2	-0.24	-0.14	0.07	0.26	0.63
	Eigenvalues	3.68	2.72	2.28	1.74	

Table 6. Effect of soil series on rotated factor scores in five soybean fields.

	Soil classification		Mean factor scores				
Field	Series	Subgroup†	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
1	Clarion	T. Hapludolls	-0.85a‡	0.45a	-0.73a	-0.23a	
	Nicollet	A. Hapludolls	-0.05b	0.34a	-0.38b	0.55b	
	Canisteo	T. Haplaquolls	0.42c	-0.41b	0.63c	0.22bc	
	Harps	T. Calciaquolls	1.09d	-0.78b	1.07d	-0.57d	
2	Klinger	A. Argiudolls	0.59a	0.41a	0.02a	-0.09a	
	Kenyon	T. Hapludolls	-0.86b	-0.32b	-0.15a	0.02a	
	Dinsdale	T. Argiudolls	0.29a	-0.25ab	0.21a	0.13a	
3	Clyde	T. Haplaquolls	-0.38a	-0.15a	-0.59a	-0.05a	
	Dinsdale	T. Argiudolls	-0.20a	0.61b	0.22b	0.13a	
	Kenyon	T. Hapludolls	0.32b	-0.59a	-0.02ab	-0.23a	
	Klinger	A. Argiudolls	0.62b	-0.02ab	0.72c	0.13a	
4	Marshall	T. Hapludolls	-0.21a	0.11a	-0.46a	-0.40a	-0.43a
	Exira	T. Hapludolls	-0.29a	0.29a	0.30b	-0.05b	0.71b
	Colo	C. Haplaquolls	1.68b	-0.09a	-0.60a	-0.38a	0.79b
5	Marshall-a§	T. Hapludolls	-0.12a	0.22a	-0.17a	0.06a	-0.02a
	Marshall-b	T. Hapludolls	0.14a	0.07a	-0.14a	0.14a	-0.25a
	Judson	C. Hapludolls	0.06a	0.05a	-0.51b	0.80b	0.76b

† A, Aquic; C, Cumulic; T, Typic.

‡ Values within columns and fields not followed by the same letter are significantly different at the 0.05 level of probability.

§ Marshall-a, 2-5 % slope; Marshall-b, 5-9 % slope.

Table 7. Rotated factor loadings and communalities for standardized site variables measured across five soybean fields.

	Factor Loadings[†]			
Variables[‡]	1	2	3	Communalities
REL	-0.40	0.07	0.09	0.17
Clay	0.76	0.02	-0.06	0.59
Sand	-0.72	-0.05	0.03	0.52
SOM	0.58	-0.04	0.11	0.35
Soil-test P	0.09	0.01	0.56	0.32
Soil-test K	0.15	0.13	0.63	0.43
pH	0.13	-0.38	0.09	0.17
Ca	0.68	-0.27	0.25	0.60
Mg	0.68	-0.05	0.02	0.46
CEC	0.78	-0.11	0.21	0.66
Zn	0.25	-0.15	0.01	0.09
Early Growth	-0.01	0.96	-0.01	0.92
Plant P	0.01	-0.07	0.53	0.28
P Uptake	-0.02	0.91	0.19	0.86
Plant K	-0.29	0.40	0.69	0.72
K Uptake	-0.14	0.89	0.37	0.95
Eigenvalues	3.86	2.88	1.34	
% of Variance[§]	36.3	27.1	12.6	

† Factor loadings obtained from an oblique (Promax) factor rotation.

‡ REL, elevation relative to the lowest sampling point in the field; SOM, soil organic matter; CEC, cation exchange capacity; Plant P, plant P concentration; Plant K, plant K concentration.

§ Proportion of variance explained by each factor.

Table 8. Eigenvectors of the correlation matrix and proportion of total variance explained by the first four principal components derived for five soybean fields.

		Principal component			
Field	Variable†	PC1	PC2	PC3	PC4
1	REL	-0.29	-0.07	-0.03	-0.07
	Clay	0.28	0.16	0.09	-0.41
	Sand	-0.26	-0.24	-0.05	0.39
	SOM	0.30	0.17	0.10	-0.17
	Soil-test P	-0.05	0.34	0.07	0.41
	Soil-test K	-0.01	0.36	0.22	0.17
	pH	0.29	-0.20	0.26	0.10
	Ca	0.27	0.09	0.17	0.36
	Mg	0.16	0.37	-0.22	-0.03
	CEC	0.25	0.23	0.10	0.29
	Zn	0.19	0.15	-0.03	-0.11
	E. Growth	-0.29	0.13	0.33	0.02
	Plant P	0.13	0.14	0.27	-0.13
	P Uptake	-0.26	0.18	0.42	-0.03
	Plant K	-0.26	0.22	0.04	-0.19
	K Uptake	-0.31	0.18	0.28	-0.07
	Phyt.	-0.04	0.29	-0.40	0.12
	Br. Stem	-0.09	0.26	-0.35	0.19
	SCN	0.21	-0.26	0.20	0.30
	Eigenvalue	7.05	3.46	1.54	1.27
2	REL	-0.36	0.05	-0.01	-0.05
	Clay	0.35	0.03	-0.10	-0.06
	Sand	-0.37	0.02	0.08	0.11
	SOM	0.35	0.08	-0.01	-0.01
	Soil-test P	0.10	0.15	0.42	0.17
	Soil-test K	0.11	0.02	0.42	-0.13
	pH	-0.06	0.13	0.43	-0.26
	Ca	0.29	0.31	0.04	0.12
	Mg	0.29	-0.02	-0.18	0.05
	CEC	0.32	0.28	0.28	0.13
	Zn	0.01	0.12	0.11	0.49
	E.Growth	0.13	-0.51	0.07	0.13
	Plant P	-0.04	0.37	0.19	0.38
	P Uptake	0.12	-0.43	0.17	0.31
	Plant K	0.01	0.02	0.42	-0.09
	K Uptake	0.10	-0.42	0.33	0.06
	Phyt.	0.15	0.03	0.02	-0.41
	Br. Stem	0.05	-0.09	-0.22	0.35
	Height1	0.17	-0.06	-0.04	-0.11
	Height2	0.31	-0.03	-0.01	-0.15
	Eigenvalue	6.04	3.02	2.72	1.52

† REL, relative elevation; SOM, soil organic matter; CEC, cation exchange capacity; Phyt, Phytophtora; Br.Stem, brown stem rot; Height1, Crop height at V6; Height2, Crop height at R5.

Table 8 (continued).

Field	Variable	Principal component			
		PC1	PC2	PC3	PC4
3	REL	-0.13	0.15	-0.48	-0.36
	Clay	0.15	0.30	-0.30	-0.22
	Sand	-0.09	-0.29	0.33	0.37
	SOM	0.24	0.25	0.23	-0.01
	Soil P	0.10	0.20	-0.32	0.47
	Soil K	0.07	0.32	-0.24	0.32
	pH	0.25	-0.12	-0.13	-0.20
	Ca	0.34	0.21	0.16	-0.03
	Mg	0.31	0.26	0.12	-0.02
	CEC	0.29	0.29	0.19	0.04
	Zn	0.21	-0.04	0.09	-0.30
	E. Growth	-0.27	0.30	0.15	0.05
	Plant P	-0.27	0.05	-0.09	-0.06
	P Uptake	-0.30	0.27	0.09	0.01
	Plant K	-0.29	0.24	0.08	0.01
	K Uptake	-0.30	0.29	0.12	0.05
	Phyt.	0.20	0.01	-0.18	0.43
	Height1	-0.02	0.14	-0.05	-0.01
	Height2	0.01	0.24	0.40	-0.17
	Eigenvalue	5.73	4.49	1.91	1.38
4	REL	-0.24	0.23	0.14	-0.38
	Clay	-0.30	0.01	-0.21	0.11
	Sand	0.21	0.07	0.16	0.09
	SOM	0.25	-0.11	-0.09	-0.18
	Soil-test P	0.08	0.34	0.33	-0.05
	Soil-test K	0.30	0.21	0.21	-0.17
	pH	0.19	0.18	0.27	0.27
	Ca	-0.15	0.38	0.16	-0.01
	Mg	-0.34	0.26	-0.07	0.10
	CEC	-0.31	0.29	-0.08	-0.21
	Zn	-0.08	0.25	-0.04	0.01
	E.Growth	0.18	0.23	-0.50	0.07
	Plant P	-0.03	0.23	0.21	0.14
	P Uptake	0.17	0.31	-0.43	0.13
	Plant K	0.34	0.20	0.14	-0.25
	K Uptake	0.33	0.26	-0.29	-0.09
	Phyt.	0.27	-0.06	0.09	0.08
	Br. Stem	-0.14	0.17	-0.02	-0.22
	Height1	-0.08	0.02	0.21	0.34
	Height2	-0.06	0.20	-0.06	0.51
	Eigenvalue	4.68	3.34	2.40	1.57

Table 8 (continued).

Field	Variable	Principal component			
		PC1	PC2	PC3	PC4
5	REL	-0.05	0.09	0.05	0.52
	Clay	0.20	-0.43	-0.01	0.05
	Sand	-0.18	0.45	-0.02	0.13
	SOM	0.11	-0.12	0.39	-0.43
	Soil-test P	0.08	0.17	0.24	0.34
	Soil-test K	0.23	0.12	0.19	0.26
	pH	-0.16	0.02	-0.34	-0.11
	Ca	0.01	-0.29	-0.08	0.01
	Mg	-0.01	-0.42	-0.14	0.33
	CEC	0.16	-0.36	0.22	0.22
	Zn	-0.18	-0.06	-0.06	0.06
	E. Growth	0.32	0.01	-0.33	-0.15
	Plant P	0.32	0.21	-0.11	0.15
	P Uptake	0.41	0.10	-0.29	-0.04
	Plant K	0.32	0.19	0.27	-0.09
	K Uptake	0.46	0.12	-0.04	-0.18
	Phyt.	-0.24	0.18	-0.20	-0.24
	Br. Stem	0.11	0.15	-0.01	0.21
	Height1	-0.06	-0.01	0.26	-0.08
	Height2	-0.12	0.08	0.42	-0.13
Eigenvalue		3.77	2.90	2.46	2.06

Table 9. Coefficients and statistics of stepwise multiple regression models relating grain yield with site variables for five soybean fields.

Field	Regression model[†]	Model R^2
1	Y= 3715 + 3.4*STK - 236.1*pH - 4.4*Br. stem - 4.2*SCN	0.67^{**}
2	Y= 3034 + 168.8*pH + 0.6*Mg - 1.2*Br. stem	0.39^{**}
3	Y= 2611 + 56.1*Elev + 718.0*Sand	0.25^{**}
4	Y= 4062 - 24.0*Elev - 15.4*SOM + 104.9*Plant K	0.47^{**}
5	Y= 2208 - 9.2*SOM + 256.6*Plant K + 3615.2*H1	0.36^{**}

**Significant at the 0.01 level of probability

[†] Regression models derived from each field; Y, soybean yield; Elev, relative elevation; Br.stem, brown stem rot; SCN, soybean cyst nematode counts; Plant K, plant K concentration; H1, Height of the crop at the V6 stage of development.

Table 10. Latent variables constructed from rotated factor loadings derived for five soybean fields.

	Latent Variables[†]			
Field	1	2	3	4
1	Soil properties-Landscape position	Early growth	SCN infection	P availability
2	Soil properties-Landscape position	Early growth	P and K availability	ni[§]
3	Early growth	Soil properties	Texture	P and K availability
4	P and K availability	Soil properties - Landscape position	Early growth	ni
5	Early growth	Soil Properties	P and K availability	Landscape position

[†] Latent variables selected from each factor with rotated loadings >+ - 0.5 in each factor.

[‡] na, latent variable not constructed because this factor presented an eigenvalue < than 1.

[§] ni, a latent variable was not clearly associated with this particular factor.

Table 11. Multiple regression models relating soybean grain yield and derived latent variables from factor analysis for five soybean fields.

Field	Regression model[†]	R^2_1[‡]	$P > F$	Other[§]	R^2_2	$P > F$
1	Y = 2309 - 390 (SCN) + 506 (PAV)	0.65	0.01	na[¶]	na	na
2	Y = 4285 + 80 (PKAV)	0.18	0.03	Br. stem[#]	0.37	0.01
3	ns	0.10	0.25	na	na	na
4	Y = 3322 - 153 (SOILP) + 75 (CRHT)	0.34	0.01	Weeds	0.41	0.01
5	Y = 3055 + 99 (PKAV)	0.30	0.01	Weeds	0.46	0.01

[†] Latent variables; SCN, soybean cyst nematode infestation; PAV, P availability; PKAV, P and K availability; SOILP, soil properties-landscape position; CRHT, crop height at the R5 stage of development

[‡] R^2_1, coefficient of determination for the regression model including only latent variables; R^2_2, coefficient of determination for the regression model including latent variables and variables with significant ($P \leq 0.05$) correlation with yield.

[§] Represent variables not included in any latent variable with significant contribution to the regression model.

[¶] na = not applicable, no other variables with significant ($P \leq 0.05$) correlation with yield.

[#] Br. stem, brown stem rot infection.

Table 12. Multiple regression models relating soybean grain yield with principal components derived for five soybean fields.

Field	Intercept	Principal Components						R^2	RMSE†	$P > F$
		PC1	PC2	PC3	PC4	PC5	PC6			
1	2309	-135	209	-117	-92	ns	na‡	0.65	420	0.001
2	4316	ns	ns	24	-28	-42	31	0.42	99	0.001
3	4084	-23	ns	ns	ns	ns	na	0.14	219	0.320
4	3322	23	ns	ns	40	ns	-49	0.40	136	0.001
5	3055	22	ns	34	ns	ns	35	0.37	153	0.001

† RMSE, root mean square error.

‡ na, not applicable. Principal component associated presented an eigenvalue < than 1.

CHAPTER 3.

RELATING SOIL TESTS AND WITHIN-FIELD RESPONSE TO P AND K USING VARIOUS ZONE SAMPLING APPROACHES

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ABSTRACT

Zone sampling approaches based on different layers of information have been proposed to assess within-field soil-test variability. Zone sampling could increase the effectiveness of soil sampling compared with soil map unit or traditional grid sampling. The objective of this study was to assess the efficacy of zone sampling approaches for P and K on the basis of soil-test values and crop response to P and K fertilization within and across sampling zones. Replicated P or K strip trials with corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) were established in seven Iowa fields. Treatments were a control and a fixed P or K rate. Soil-test values of samples collected using a dense grid-sampling approach (0.08-ha in P fields and 0.24-ha in K fields) was used as a base to evaluate zone delineation approaches. The approaches were systematic 1.0-ha grid cell (GC), soil series from digitized (1:12000 scale) survey maps (SMZ), elevation (EZ), soil electrical conductivity (ECZ), a combination of elevation and soil electrical conductivity (EECZ), and a combination of these last two attributes with slope (EECSZ). There was large within-field soil-test and crop-response variation in most fields. Within-field crop responses to P and K where higher in low-testing areas identified by the two grid sampling approaches. The results showed differences in absolute crop yield across zones for zone delineation approaches based on terrain attributes or soil survey maps, but soil-test values and crop response to P or K fertilization seldom differed across zones. Zoning approaches were not superior to a systematic, 1.0-ha cell sampling approach (GC) in describing P and K availability nor predicting crop response for different field areas. Long histories of fertilization in the region probably reduced the impact of soil properties variation on within-field soil-test variation and crop response to P and K fertilization.

Abbreviations: ANOVA, analysis of variance; CEC, cation exchange capacity; DGPS, differential global positioning systems; FR, fixed rate; GIS, geographical information systems; ISU, Iowa State University; SD, standard deviation; STP, soil-test P; STK, soil-test K.

INTRODUCTION

Site-specific management (SSM) recognizes that within-field variability in crop yields, soil properties, and other parameters should be assessed to improve nutrient management. This assessment provides an alternative to the use of the whole field as a homogenous management unit. Site-specific management relies on precision farming technologies such as yield monitors, differential global positioning systems (DGPS), geographical information systems (GIS), variable-rate applicators, and input maps to identify within-field zones for monitoring and mapping spatial soil test and yield variability. Yet, the most difficult task is to obtain a correct assessment of the soil fertility status of a field (Cambardella and Karlen, 1999). Soil testing is the most commonly used tool to determine the P and K fertilizer needs of crops. Soil-test P and K levels, the removal of these nutrients in harvested products, and the replacement of these nutrients with fertilizers usually is not uniform over an entire field (Mallarino and Wittry, 2003). A correct assessment of this variation is an important factor to consider when planning on SSM program.

Many researchers have shown that soil test levels of P and K measured at different scales vary considerably within fields (Cambardella et al., 1994; Mallarino, 1996; Cambardella and Karlen, 1999). Variability patterns for these nutrients sometimes are related to soil map units but in most cases fertilization, manure application or other management practices have created new patterns of nutrient variability (Franzen and Peck, 1995; Mallarino, 1996; Cambardella and Karlen, 1999). Furthermore, the spatial structure of soil test variability is site and nutrient specific (Mallarino, 1996).

Traditionally, P and K fertilizers have been applied at a single and fixed rate (FR) throughout a field. Considering the high within-field nutrient variability observed in most fields, uniform fertilizer applications are likely to lead to excessive fertilization in some areas and suboptimal fertilization in others (Wibawa et al., 1993; Mallarino et al., 1998). The development of variable-rate

(VR) technologies allows for fertilizer changes on-the-go and a better control of the amount of inputs applied to specific field areas. This may improve both input use efficiency and farm profitability.

Field studies comparing FR with VR for P and K management have not demonstrated consistent, positive yield in favor of the VR management (Carr et al., 1991; Wibawa et al., 1993; Yang et al., 1999; Wittry and Mallarino, 2003). However, the amount of fertilizer applied usually is less with VR (Yang et al., 1999; Wittry and Mallarino, 2003) and soil-test variability decreases (Wittry and Mallarino, 2003). Among others, one factor affecting the lack of consistency of these results is the sampling strategy used to determine the P or K fertilizer input rates (Weisz et al., 2003; Mallarino and Wittry, 2003).

Different soil sampling schemes can be used to collect samples from fields. The recognition of a high within-field variability in soil-test levels not closely associated with soil-map units or landscape positions has prompted the use of grid soil sampling as an alternative to characterize this variation (Franzen and Peck, 1995; Wollenhaupt et al., 1994). Grid sampling subdivides a field into a systematic arrangement of small areas or cells. Soil samples from these cells are then analyzed and different interpolation techniques may be used to estimate soil-test values at unknown locations. The selection of an optimum cell or sample size and the choice of an appropriate interpolation method have been extensively studied. For example, Wollenhaupt et al. (1994) recommended grids of 60 x 60 m to direct VR fertilizer application of P and K. In fields that received heavy applications of P and K fertilizer, Franzen and Peck (1995) determined that a 66 x 66 m grid was superior than a 100 x 100 m grid size. Mallarino and Wittry (1997) reported that cells larger than 0.8 ha in size did not represent P and K levels appropriately. The sampling intensity required for effective use of VR technology may be different for different nutrients, fields or geographic regions. It is clear however that if grid distances are too large, then important attributes can be missed (Chang et al., 1999) or poor correlations among grid cells of different size may result (Bronson et al., 2000). Furthermore, interpolation predictions may perform poorly at low sampling densities resulting in inadequate fertilizer recommendations (Mulla et al., 2000; Mueller et al., 2001). A 1-ha cell size is most frequently used for grid sampling in Iowa.

In contrast to sampling in a regular grid of small cells, many researchers have proposed the use of zone or targeted sampling to reduce the number of samples and sampling costs while maintaining acceptable information about within-field nutrient variation across a field. Sampling by zone assumes that there is a logical reason for the patterns of the nutrients to appear in the field, and that patterns are likely to remain stable temporally (Franzen et al., 2002). The criteria and attributes or combination of attributes to define sampling zones vary widely.

One of the oldest zone sampling approaches uses county soil surveys which describe soil variability at scales ranging from 1:12,000 to 1:24,000. Steinwand et al. (1996) examined a field in Iowa in a Clarion-Nicollet-Webster association and found that the 1:15 840 and a detailed soil survey at a 1:3305 scale were similar in terms of yield prediction for a 3-yr study. However, several researchers (Kitchen et al., 1998, Franzen et al., 2002; Mallarino and Wittry, 2003) have concluded that this approach may not be adequate for site-specific applications. Mallarino and Wittry (2000) suggested that the efficacy of a soil-map unit sampling approach may vary across fields depending on the amount of small-scale variation (higher in fields with long fertilization and manure application histories), how contrasting the soil map units are in terms of properties that affect nutrient availability and on the detail of the soil survey map used. For some regions very detailed mapping (more detailed than common soil survey maps) would be impractical and expensive (Brevik et al., 2000). This approach would only be justified if a more detailed soil survey produces significant alterations in the way the targeted field is managed.

Another sampling approach uses temporary-stable data such as apparent soil electrical conductivity (EC_a) and landscape features to identify different patterns of soil variability (Fraisse et al., 2001). The relationship between yield and landscape position and derived terrain attributes have been extensively studied. Most of these studies showed higher corn and soybean yields in footslope positions under dry conditions (Kravchenko and Bullock, 2000; Kravchenko et al., 2000). Kaspar et al., 2003) developed a multiple regression model based on terrain attributes such as elevation, slope and curvature that explained 78 % of corn yield variability for a set of four moderately dry years. There is a substantial difference, however, between explaining yield variability and delineating topography-based zones that may influence P and K availability. For example, Franzen et al. (1998) found that P field levels were not related to topographic position when compared with an intensive grid sampling approach (33 x 33 m). However, in another study with different fields a significant correlation was found between P levels from a topography-based sampling (using fewer samples) and the same base grid size (33 x 33 m). Other studies showed that elevation-based sampling zones showed no clear relationships with soil-test P (STP) data (Bronson et al., 2000; Mallarino and Wittry, 2003).

The use of EC_a to delineate sampling zones is gaining popularity. Current techniques using either the direct application of current to the soil or electrical magnetic induction enable instantaneous, in-situ measurements of EC_a (Heiniger et al., 2003). The EC_a consists mainly in two components: (i) contribution of the soil solid particles associated with exchangeable cations and (ii) contribution from the soil solution (Rhoades et al., 1989). Volumetric soil water content of the soil is the most important factor affecting EC_a and tends to mask the effect of the soil solid particles when the soil water content is near saturation (Rhoades et al., 1989). In nonsaturated and nonsaline soils the contribution of the bulk soil is greater due to the contribution of adsorbed ions (Lund et al., 1999). Under these conditions soil texture, bulk density and cation exchange capacity (CEC) are likely major determinants of EC_a (Sudduth et al., 2003) and changes of this property across a field may also reflect changes in nutrient levels. Other authors have used EC_a as a tool to improve soil classification (Anderson-Cook et al., 2002).

A close association between EC_a and yield variability has been observed in several studies (Jaynes et al., 1995; Sudduth et al., 1995). Soil EC_a also provided an estimate of the within-field soil differences associated with topsoil thickness (Kitchen et al., 1999). Landscape attributes and EC_a have been used simultaneously in regression models to explain yield variation in corn, soybean, sorghum [*Sorghum bicolor* (L.) Moench], and winter wheat (*Triticum aestivum* L.) (Kitchen et al., 2003), and in cotton (*Gossypium hirsutum* L.) (Corwin et al., 2003). The use of this attribute alone or in combination with topographic attributes have been used to delineate sampling zones. For example, Chang et al. (2000) used an intensive grid sampling as a base to simulate several sampling schemes based on block sampling, elevation, and EC_a. Dividing the field into four blocks reduced the average within-block variance of STP compared to the whole field variance in three fields. The combination of EC_a and distance (non connected zones were considered separately) reduced the variance only in one field. Fridgen et al. (2000) delineated soil sampling zones for two fields based on EC_a, elevation, and slope using clustering methods. The reduction in variance of soil and landscape attributes due to dividing the field into several sampling zones was investigated. The within-zone variance of soil P and K was reduced only 20 % in one field indicating that the variability of these soil tests was not well accounted for by the zone delineation. However in another field a similar zone delineation approach significantly decreased within-zone for both variables. In general, zones with higher clay content also had higher EC_a and soil K. Other research has emphasized the use of EC_a alone (Johnson et al., 2003) or in combination with elevation and slope (Fraisse et al., 2001; Kitchen et al., 2002) to delineate sampling zones, but used the yield variance reduction as a measure of clustering performance.

The use of yield maps is another approach employed to delineate sampling zones. Long-term yield data is required to reliably discover patterns of within-field yield variation (Lark and Stafford, 1998). Boydell and McBratney (2002) used a fuzzy *c-means* classification algorithm to delineate potential sampling zones based on yield maps and concluded that stable yield-zone patterns may emerge from at least five years of yield data. Jaynes et al. (2003) applied clustering methods to classify six years of corn yield data, and both EC_a and elevation were the primary attributes that discriminate among three of the four clusters. Delineation of soil sampling schemes based on yield data might not be useful for nutrients like N because measuring yield variability provides little information useful to improve N management (Blackmer and White, 1998). If P and K removal are the most important factors affecting soil-test levels then a yield-zone approach would be useful as an auxiliary variable.

Several other approaches have been used to delineate potential sampling zones. These include approaches based on remote sensing, topography and EC_a (Luchiari et al.,2000); cokriging based on remote sensing (Mulla et al., 2000); topography, remote sensing and farmer experience (Fleming and Westfall, 2000); soil color, EC_a and farmer experience (Fleming and Buchlieter, 2002); an integrated zone approach based on soil-map units, elevation, yield zones and aerial images (Mallarino and Wittry, 2003). These authors found that a grid sampling approach was the most efficient for P, which was the most variable nutrient in eight fields, while the grid and integrated zone approaches were similarly efficient for K. Efficiency of the sampling approaches was based on study of within-zone and between-zone soil test variability.

While several zone sampling approaches based on different attributes have been developed to assess within-field soil test variability, few studies have validated these approaches in terms of yield responses to P and K fertilization. The objective of this study was to assess the efficacy of various zone sampling approaches on the basis of crop response to P and K fertilization within and across sampling zones in seven Iowa farmers' fields.

MATERIALS AND METHODS

Sites, Soil Sampling, and Treatments

This study was conducted on seven Iowa farmer's fields located in Boone, Guthrie, Linn and Tama counties that were managed with a corn-soybean rotation. Management practices were those used by each farmer and, thus, corn hybrids, soybean varieties, seeding rates, planting dates and tillage practices varied among fields. All selected fields had histories of uniform P and K fertilization. In Fields 1-4 and 7 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 under continuous no tillage for at least 10 years.

The soil samples used to measure STP and STK were collected using a pattern that matched the experimental design used to assess crop response to P or K fertilization. Thus, the fields and layout of the trials are described first. 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 three to four replications based on a strip-trial methodology. Soil series represented in the experimental areas were among typical agricultural soil series of Iowa (Table 1). The strip width was 18.3 m and was determined by the spreading width of the fertilizer application equipment, which was the same for all fields. The strip length was uniform within fields but varied across fields from 370 to 800 m. 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. Three treatments arranged in a randomized complete-block design (RCBD) were used in all trials. In Fields 1- 4 treatments were a control without P fertilizer, and a fixed rate (FR) or variable rate (VR) P application methods. There were three replications (blocks) in Fields 1 and 2 and four in Fields 3 and 4. These fields are hereon referred to as P fields. In Fields 5-7, treatments were a control without K fertilizer, and a FR or VR K application methods. In all these fields there were four replications, and are hereon referred to as K fields.

Composite soil samples (8-12 cores from a 15-cm depth) were collected before treatment application using a systematic, grid-point sampling method (Wollenhaupt et al., 1994). For the P fields the width of the grid coincided with the width of each treatment strip (18.3 m), and grid lines were spaced 45 m along crop rows resulting in 0.08-ha cells in all fields. For the K trials the width of the grid coincided with the width of a replication (54.9 m). Grid lines along crop rows were spaced 45 m (Fields 5 and 6) and 50 m (Field 7) resulting in 0.24 and 0.27-ha cells respectively. In all instances the soil cores for each composite sample were collected following a random pattern from areas approximately 100-m^2 in size at the center of each grid cell.

Samples from the P Fields 1 and 2 were analyzed with the Mehlich-3 P test (Frank et al., 1998) because of the presence of soils with soil pH values up to 8.0. Samples from the P Fields 3 and 4 (the other two P fields) were analyzed with the Bray-P$_1$ test (Frank et al., 1998). Iowa State University (ISU) STP interpretation classes are similar for the Bray-P$_1$ and Mehlich-3 tests when both are based on a colorimetric determination of the extracted P (Sawyer et al., 2002). However, the Mehlich-3 test is recommended for all Iowa soils while the Bray-P$_1$ test is recommended only for soils with pH < 7.4. Classes for both 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 (Sawyer et al., 2002). In the K fields (Fields 5 - 7) soil samples were analyzed with the 1 *M* ammonium acetate test (Warncke and Brown, 1988). Interpretation classes for this method are ≤ 90 mg kg^{-1} for Very Low, 91 to 130 mg kg^{-1} for Low, 131 to 170 mg kg^{-1} for Optimum, 171 to 200 mg kg^{-1} for High and ≥ 201 mg kg^{-1} for Very High (Sawyer et al., 2002). Soil pH was analyzed in all samples using a 1:1 soil-water ratio as described by Watson and Brown (1998). Organic matter was analyzed in all samples by the Walkley-Black method as described by Combs and Nathan (1998). Table 2 shows descriptive statistics for STP, soil pH, organic matter and the distribution of STP in the five ISU interpretation classes for the P fields. Table 3 shows similar information for STK, soil pH and organic matter for the K fields. The STP data for the K fields and STK data for the P fields are not shown because P fertilizer was applied to the K fields and K fertilizer was applied to the P fields using VR to eliminate deficiencies.

The P and K rates used with both FR and VR treatments followed closely the ISU recommendations (Sawyer et al., 2002) based on STP and STK and average P and K removal in grain for a 2-yr corn-soybean rotation applied once before the first crop (either corn or soybean). For the FR treatment, the recommendations were used to decide the fertilizer rate when the mean STP or STK (as appropriate for the trial) was Optimum or less, but at least a removal-based rate was also applied when the mean or median soil-test values were High or Very High. Across fields, the FR P application rates ranged from 35 to 70 kg P ha^{-1} and the K application rates ranged from 38 to 110 kg ha^{-1}. For the VR treatment, interpolated STP and STK values were used to create P and K application maps using an inverse-distance method with a distance weighing exponent of two (Wollenhaup et al., 1994) and high-testing areas were not fertilized. The VR treatment is not described further because discussion of differences in application methods was not an objective of this study and data from this treatment were not used to assess crop response to fertilization because high-testing areas were not fertilized with VR. Differences between FR and VR are presented and discussed in other articles already published (Wittry and Mallarino, 2003) or in review.

In the P fields, the fertilizer (granulated di-ammonium phosphate or mono-ammonium phosphate) was spread in the fall before planting with commercial broadcast spreaders equipped with DGPS receivers and controllers, and was incorporated into the soil by chisel plowing and disking. No corrective N rate was used to offset the small N rate applied, but an N rate of at least 150 kg N ha^{-1} as anhydrous ammonia (the highest N rate suggested by ISU for corn after soybean) was uniformly applied for corn in all P fields. In the K fields KCl was spread before planting with the same type of equipment. In Fields 5 and 6, the K fertilizer was not incorporated because fields were managed with no-tillage. In Field 7, the K fertilizer was incorporated by chisel plowing and disking. A uniform N rate of at least 150 kg N ha^{-1} was uniformly applied for corn in all K fields.

Experiments in Fields 1 and 2 were established in 1998 and were evaluated for 4 years (two corn-soybean rotation cycles). Experiments in Fields 3, 4, and 6 were established in 1999 and were evaluated for 4 years. The experiment in Field 5 was established in 2000 and was evaluated for 3 years. A field-crop code was constructed that includes a field number (1 to 7), suffixes "a" and "b" to indicate the first and second crop of the corn-soybean rotation, and suffixes "a_2" and "b_2" to denote crops of the second rotation cycle.

New soil samples were collected after harvesting the second crop of the first rotation cycle. This time, samples from all fields were collected from areas approximately 100 m^2 in size from 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 (18.3 by 45 m). One composite sample was collected from each cell (8-12 cores from a 0-15 cm depth). These samples were analyzed as described for the initial soil sampling, except that soil pH and organic matter were not measured.

The treatments were re-applied before planting the first crop of the second rotation cycle. This time, STP or STK data used to define the FR fertilization rates were those from cells of the FR treatment strips, respectively using the same criteria described before for the initial treatment application.

Grain Yield Measurement

Grain yields were measured using combines equipped with commercial impact flow-rate yield monitors and DGPS receivers. The differential correction was obtained through the U.S. Coast Guard AM signal. Grain moisture was determined by a sensor located in the combine auger, and yield was then corrected to 155 g kg^{-1} moisture for corn and 130 g kg^{-1} moisture for soybean. Yield data were unaffected by field borders because the experimental areas were at least 40 m away from any border rows. Yield monitor data were imported to ArcView GIS (Environmental Systems Research Inst. Inc., 380 New York St., Redlands, CA) and analyzed for common yield monitor errors, such as the effect of waterways or grass strips and incorrect settings for grain path time lag through the combine. Affected data were corrected (such as grain path lags) or deleted (such as yield points near waterways or unexpected combined stops).

Delineation of Zones

Soil-test P and STK values derived from the initial, dense grid-point sampling procedure (0.08-ha cells for the P fields and 0.24 to 0.27-ha for the K fields) were used as a base data to assess less dense sampling approaches. This approach has been developed and used previously by others (Franzen and Peck, 1995; Mulla et al., 2000; Bianchini and Mallarino, 2002; Wittry and Mallarino, 2003). Simulated sampling approaches were (i) 1.0-ha grid cells based on a systematic arrangement of square or rectangular cells (GC); (ii) soil series map zones (SMZ); (iii) elevation zones (EZ); (iv) apparent soil electrical conductivity zones (ECZ); (v) a combination of elevation and apparent soil electrical conductivity (EECZ); and (vi) a combination of elevation, apparent soil electrical conductivity, and slope (EECSZ). A vector theme with associated information was created using ArcView GIS for each sampling approach by creating appropriate polygons to represent grid cells or zones. The STP and STK values for all the dense sampling points within a grid cell or zone were averaged to estimate a value for each grid cell or zone.

For the GC approach and the P fields, the STP data were calculated by averaging the data for 12 contiguous sampling points of the dense, grid-point base sampling approach (six points across strips and two points along strips). For the K fields, where the base data was sparser, the STK data were calculated by averaging the data for four contiguous sampling points of the grid-point base sampling approach (two points across strips and two points along strips). The resulting larger cells measured approximately 1.0 ha in both the P and K fields. Soil series zones for the SMZ approach were obtained from digitized and georeferenced (1:12000 scale) Iowa soil survey maps.

Elevation and position measurements were recorded once for all fields after harvest in the fall of 2001 with a real-time kinematic DGPS receiver that was mounted in an all terrain vehicle. Readings were logged every 1 s as the vehicle moved across the field giving measurements about every 3 to 4 m. A stationary base-station GPS receiver located at one side of the field was used to differentially correct the roving GPS receiver. Data points collected were used to create an elevation surface for a 10- by 10-m regular grid across the field using ArcView GIS. From this elevation surface, slope (the rate of maximum change in elevation to surrounding grid cells expressed in degrees) was derived also for a 10- by 10-m regular grid.

Soil EC_a was measured once at the same time elevation measurements were performed. The EC_a measurements were made with a non-contact electromagnetic induction sensor using an EM-38 sensor (Geonics Limited, Mississauga, ON, Canada) in Fields 1-2 and 5-7 while a Veris 3100 (Veris Technol., Salina, KS) sensor was used in Fields 3 and 4. The EC_a data points were used to estimate EC_a for a 10-by 10-m regular grid across the fields using the Spatial Analyst of ArcView GIS.

The EZ, ECZ, EECZ, and EECSZ sampling zones were delineated with a fuzzy *c*-means unsupervised clustering algorithm (Bezdek et al., 1984; Fridgen et al., 2000; Kitchen et al., 2002) with the Management Zone Analyst 1.0 software (USDA-ARS, 2000). This algorithm is based on the minimization of an objective function defined as the sum of squared distances from all data points in the cluster domain to the cluster center (Kitchen et al., 2002). All clustering algorithms require a measure of similarity of a pair of observation or clusters (Sharma, 1996) and grouping of observations is done on the basis of similarities or distances. Thus a quantitative scale on which to measure the association (similarity) between objects needs to be developed (Johnson and Wichern, 2002). The measure of similarity that establishes a rule for assigning individual observations to a particular cluster is usually the calculated distance from an observation to the cluster mean. For the EZ and ECZ sampling approaches, the euclidean distance was used as a measure of similarity. For the combined approaches (EECZ and EECSZ) descriptive statistics for the clustering variables revealed unequal variances and non-zero covariances. Therefore, the Mahalanobis distance was used as a measure of similarity (Fridgen et al., 2000).

For all approaches cluster analysis was used to divide the field into two to eight potential clusters and the outcome was evaluated to determine the optimum number of clusters to use for further analysis. Two clustering performance indices were calculated to assess the outcomes of the unsupervised classification: the Fuzziness Performance Index (FPI) and the Normalized Classification Entropy (NCE). The FPI measures the degree of separation between the *c*-partitions and may range from 0 to 1. It is an index representing the amount of membership sharing that occurs between classes (Lark, 2001; Kitchen et al., 2002). Values closer to zero represent distinct classes with little membership sharing. The NCE is an index representing the amount of disorganization created by dividing a data set into classes (Lark and Stafford, 1997). A classification that minimized both indices was chosen to determine the optimal number of clusters or zones. This procedure could be applied for all zoning approaches in five fields, but in Fields 3 and 4 (and for some zoning approaches) minimal values for both indexes did not coincide. In these instances we selected the optimal number of zones according to the minimum NCE as suggested by Lark et al. (1998). In addition, the variance reduction for an attribute (elevation, EC_a, and slope) due to zone partitioning was calculated with a procedure described by Fraisse et al. (2001). A ratio of the within-cluster attribute variance to the whole-field variance for the same attribute was calculated for each clustering outcome. This method is a practical approach to quantify the relative importance of each attribute for creating the clusters, and as additional information to the FPI and NCE clustering performances indices.

The combined sampling approaches (EECZ and EECSZ) were also delineated using a conventional, nonhierarchical clustering technique based on the *k-means* algorithm. Unlike fuzzy classifications, in conventional clustering techniques each object belongs to one and only cluster. A nonhierarchical clustering technique, the *k-means* algorithm was used. This clustering technique is designed to group items or observations into a collection of *k* clusters, and the number of clusters might be specified in advance or determined as part of the clustering procedure (Sharma, 1996; Johnson and Wichern, 2002). Because the technique requires a priori knowledge about the number of clusters and is sensitive to the initial partition of the data, Sharma (1986) suggested the previous use of a hierarchical clustering technique to form the initial partition of the data. Hierarchical clustering techniques do not require a priori knowledge of the number of clusters or the starting partition of the data. Thus, a hierarchical clustering technique using PROC CLUSTER with the centroid method followed by a *k-means* algorithm (PROC FASTCLUS) was used to delineate the number of clusters or zones. Data for combined attributes (EECZ and EECSZ) were standardized to zero mean and unit variance prior to the analysis. Data analysis was conducted to divide the fields into up to eight clusters, and selection of the final number of clusters or zones was based three indices of cluster performance (Sharma, 1996; Johnson, 1998): the root- mean-square standard deviation of the new cluster (RMSSTD); the R-squared, which measures the extent to which groups or clusters are different form each other; and a pseudo-*F* statistic provided by the FASTCLUS procedure (Johnson, 1998).

Data Analysis

Yield responses

The grain yield response to fertilization at the entire experimental area of each field was assessed by analysis of variance (ANOVA) for a randomized complete-block design (RCBD) assuming fixed treatments and block effects (SAS Inst., 2000). Results and statistics for VR treatment are not shown for reasons explained before. Yield data input were yield means of all yield monitor points recorded at 1-s intervals within each treatment strip (the experimental unit). Treatment effects on yield for field areas with STP (Fields 1 - 4) or STK (Fields 5 - 7) within different interpretation classes according to the initial dense grid-sampling approach were assessed by a procedure developed by Oyarzabal et al. (1996) and later used by Mallarino et al. (2001), Bermudez and Mallarino (2002), and Wittry and Mallarino (2003). Yield input data were means for areas defined by the width of each strip (18.3 m) and the separation distance of the soil sampling grid lines along crop rows (45 m in Fields 1- 6 and 50 m in Field 7). The STP input values used for the first rotation cycle analyses (1st and 2nd crop) were means calculated from the three samples (one for each future treatment strip) collected from areas defined by the width of each replication (54.9 m) and the separation distance of the grid lines along crop rows. The STK input values used for the first rotation cycle analyses corresponded to the only composite soil sample collected from areas defined by the width of a replication (54.9 m). Thus, three yield means (one for each treatment) corresponded to one STP or STK value. For the second rotation cycle, STP and STK input values were those corresponding to the control treatment strips. Treatment effects for field areas within different STP or STK classes were assessed by a separate RCBD ANOVA for each class assuming fixed effects for replications (blocks) and treatments. This analysis was not performed for STP or STK classes that did not have all the treatments represented in at least two replications (blocks).

Evaluation of zone sampling approaches

Crop yield responses to fertilization for different STP or STK classes identified by the GC approach at each field were assessed by a procedure similar to the ones used for classes identified by the initial, dense grid sampling approach. An ANOVA was performed separately for each of the other zoning methods using PROC MIXED (SAS Inst., 2000) to assess fertilization effects on crop yields for SMZ, EZ, ECZ, EECZ and EECSZ zones. Sources of variation were replications (blocks), treatments, zone, and a treatment by zone interaction term. Treatments, zones and the interaction between treatments and zones were considered fixed effects, while replications (blocks) and the interaction between replications and treatments were considered random effects. In this procedure, errors of the fitted mixed model are considered independent (Littell et al., 1996). Zones that were not represented in at least two replications were not considered.

Soil-test values of samples collected using the initial dense grid-sampling approach encompassed by zones of each sampling approach were compared by observation of several descriptive statistics and a separate ANOVA for each zoning approach using PROC MIXED (SAS Inst., 2000). In this ANOVA, input were the STP or STK data for each sampling point and zones were considered fixed effects.

RESULTS AND DISCUSSION

In the P fields, analyses of STP results from samples collected using a dense sampling approach before treatment application showed that values encompassed at least four ISU STP interpretation classes in all fields (Table 2). According to ISU previous research and fertilizer recommendations for corn and soybean (Mallarino et al., 1991; Webb et al., 1992; Sawyer et al., 2002), there is a large probability of yield response to P when STP or STK is Very Low or Low and < 25 % probability when values are Optimum. The proportion of the experimental areas testing Low or Very Low in STP ranged from 36 % in Field 4 to 75 % in Field 1. In the K fields, STK values encompassed at least three ISU STK interpretation classes in all fields (Table 3). The proportion of the experimental areas testing Low or Very Low in K ranged from 30 % in Field 6 to 66% in Field 7. Thus, all fields contained large areas where a yield response to P or K fertilizer would be expected.

Whole-Field Responses

Phosphorus fertilization increased ($P \leq 0.05$) corn yield in all fields except Fields 1b and 4b, and increased soybean yield in all fields except Fields 2b, $2b_2$ (there was a response trend at $P \leq 0.06$) and $4a_2$ (Table 4). Comparisons of yield responses and initial STP values (Table 2) suggests that corn yield responses in these fields were reasonable because median STP values of Fields 1, 2, and 3 were in the Very Low to Low classes and a large proportion of the experimental areas tested in these STP classes. In Field 4, however, both mean and median STP values were in the Optimum class. The lack of crop yield responses in Fields 1b and 2b was not expected because large proportion of the experimental areas tested Very Low or Low. The lack of crop yield responses in Fields $4a_2$ and 4b is reasonable according to mean and median STP values for these fields.

Potassium fertilization increased ($P \leq 0.05$) crop yield in all years for Field 7 but only in some years for Fields 5 and 6 (Table 5). Initial mean and median STK values for Field 7 were in the Low STK class, but STK for Fields 5 and 6 were in the lower range of the Optimum class (Table 3). Results for Fields 5 and 6 could be expected because there is a small probability of yield response for the Optimum class (Sawyer et al., 2002). However, Field 5 presented a higher proportion of the experimental area testing Very Low or Low, and field-average yield responses were observed in the last two crop years.

Responses in Field Areas with Different Soil-Test P and Soil-Test K Classes

The yield response to P and K assessed by whole-field analyses is the net result of different responses in different parts of the field. Soil test results from initial soil samples collected using a dense grid sampling approach were used to study yield response to fertilization for field areas testing within different STP or STK interpretation classes. Analyses for the P fields showed a corn yield response to P ($P \leq 0.05$) when STP was Very Low or Low in most fields and when STP was Optimum in one field (Table 6). No response was observed in high-testing soils. The lack of response in low-testing areas of fields 1b and 4b coincided with the observed lack of field-average yield response. However, the small response in Field $4b_2$ detected by the whole-field analysis was not observed with the separate analyses by STP class. Soybean yield responses (Table 7) occurred in the Very Low class of all fields ($1a_2$, $2b_2$ and $3b_2$). In Field 4, areas testing Very Low were small (4 %), were present in only one replication, and were merged with the Low class for this analysis. Soybean yield responses for the Low class showed a high variability across fields. Yield responses were observed in Fields 1a, 2b, $2b_2$, and were not observed in Fields 3b, $3b_2$, 4a, and $4a_2$. Although STP interpretation classes for corn and soybean do not differ, Mallarino (1999) reported a larger variability in yield response for soybean compared to corn in Iowa, and a higher proportion of lack of response of soybean in low-testing soils.

Analyses of corn yield response for field areas with different STK classes (Table 8) showed a response to K ($P \leq 0.05$) for the low-testing areas of all fields except Field 5b. In all the K fields areas testing Very Low were merged with the Low class because they represented a small area of the field or were present in only one replication. No significant corn yield increases due to K fertilization ($P \leq 0.05$) were observed in field areas testing Optimum or higher in STK. Analyses of soybean yield responses for field areas with different STK classes (Table 9) showed response to K ($P \leq 0.05$) for the low-testing class except for Fields 6a and $7b_2$. No response was observed in soils testing optimum or higher in STK. The lack of response in low-testing areas of Field 6a coincide with results for the whole-field analysis and may suggest that other factors were affecting the response to K. However, the lack of response in the low-testing areas of Field $7b_2$ (second crop in the 2nd cycle) does not seem reasonable because there was a small whole-field average response in this field (Table 5). Experimental error in yield or STK measurements could explain this disagreement. One consideration merits attention when discussing yield responses for the K fields. The initial soil sampling was based on a larger grid (0.24-ha to 0.27-ha) than for the P fields (0.08-ha), thus the within field variation in STK probably was more poorly described.

Characteristics of the Sampling Zones Delineated Using Electrical Conductivity and Topography

Within-field variation in EC_a and topographic properties used for zone delineation (EZ, ECZ, EECZ, and EECSZ approaches) are summarized in Table 10. Fields 1 and 2 showed the lowest range in elevation and probably a zoning method based on elevation would not be justified. Elevation within the rest of the fields ranged from about 6.6 m in Field 4 to 14.5 m in Field 7. The range of slopes varied across fields. Fields 3 and 4 had the highest slope values due to the presence of old waterways that were cultivated, but these values represented only a small proportion of the experimental areas. Elevation and slope were positively ($P \leq 0.05$) correlated in most fields except Field 4. The lack of positive correlation in Field 4 was probably caused by the presence of cultivated waterways with steeper slopes located at relatively lower elevations.

Soil EC_a showed the highest standard deviation (SD) among all attributes and ranged from 1.6 to 156.2 mS^{-1}. Comparisons of EC_a across fields is risky because this is an attribute with significant temporal variability primarily affected mainly by soil profile moisture (Kitchen et al., 2003). In most fields EC_a measurements were made under moderate soil moisture conditions. High

EC_a readings in Field 7 may be explained by the dominance of the Colo-Ely soil complex (Table 1). These series usually have a high water table and could have increased the EC_a even under moderate soil moisture conditions (T.E. Fenton, personal communication, 2003, Dept. of Agronomy, ISU). In most fields, EC_a was higher in the lower portions of the landscape where more poorly drained soils predominated and lower at higher elevations were well-drained soils predominated. There was a negative correlation ($P \leq 0.05$) between EC_a and elevation in Fields 1, 2, 4, and 6, and r ranged from -0.25 in Field 4 to -0.81 in Field 1. The negative relationship between EC_a and elevation has also been observed before (Jaynes, 1996; Jaynes et al., 2003). However in Fields 3 and 7 elevation and EC_a were positively correlated (r 0.18 for Field 3 and 0.43 for Field 7). Positive correlations between elevation and EC_a have also been reported before (Sudduth et al., 1995; Fraisse et al., 2001), and have been associated to lower EC_a in areas of deep topsoil generally located at lower elevations where these is a deposition of eroded topsoil. Field 7 had the highest range in elevation, a uniform and large slope, and was managed under conventional tillage for several years. Thus, erosion could be a factor when considering the positive correlation between elevation and EC_a.

The number of zones was decided upon both the minimal values of the FPI and the NCE. Use of the method suggested by Fraisse et al. (2001) to study which variables (specially for the combined zones EECZ, and EECSZ) had more weight to delineate the zones indicated that in all fields the variance reduction with increasing number of clusters was more important with EC_a, and slope. Also, at least a 60 % in variance reduction was achieved for all attributes considered.

The delineated zones with means and SD for each attribute, as well as the STP or STK averages for each zone, are presented in Tables 11 and 12. The final number of clusters or zones delineated were conservative as suggested by Lark (2001). This author discussed the compromise between defining too many clusters or zones to be readily interpreted and encompassing too much spatial variation within too few zones. For the *k-means* classification, the three performance statistics (reduction in within-cluster variance, the R-squared, and the *pseudo-F* statistic) almost never coincided, so we used the most conservative outcome provided by the combination of the three statistics.

Soil-Test P and K Values for Different Zones

The differences in STP or STK between zones for each zoning approach (GC, SMZ, EZ, ECZ, EECZ and EECSZ) were assessed using ANOVA. These analyses were performed for all fields based on soil-test data from initial soil samples using a dense grid sampling approach collected before any treatment was applied. Therefore, to avoid confusion, no field code suffix will be used in this section when referring to the P fields as 1 to 4 and the K fields as 5 to 7.

Phosphorus fields.

Mean STP differences ($P \leq 0.05$) among zones delineated with each zoning approach were not consistent across fields (Table 11). In Field 1, where 75 % of the area tested Very Low or Low according to the initial dense sampling (Table 2), STP differed only among GC zones, and the resulting map (not shown) followed closely the map for the more dense sampling approach. Initial STP values for the GC approach (Table 13) encompassed three interpretation classes and 75 % of the experimental area tested Very Low or Low. However this approach failed to detect high-testing soils as compared to the base grid sampling. The other zoning approaches did not detect small high-testing areas in this field and STP never differed among the zones. In Field 2, mean STP values differed among zones of various zoning approaches (Table 11). This result could be partly explained by high STP in an area of the field located at a low (and concave) topographic position with high EC_a values, while the rest of the field had mainly low-testing soils. The low-laying area was poorly drained, had consistently lower yields across years, and could have deposition of soil from higher elevations, which could explain higher STP values.

In Field 3, STP differed only among zones of the GC and EECZ zoning approaches (Table 11). This field had a large STP variability according to the base grid sampling (Table 2). In this field, STP values from the original base grid sampling encompassed four STP interpretation classes. The GC approach identified areas with low and optimum STP values but did not identify areas of very low or high-testing soils (Table 13). Although STP differed among zones of the EECZ approach, the mean values ranged from 14 to 20 mg kg^{-1}, which in practical terms would allow for classifying zones in only two STP interpretation classes (Sawyer et al., 2002). In Field 4, STP differed only among zones of the SMZ approach (Table 14). The Canisteo soil series showed the highest STP values with a mean value within the High STP interpretation class. We cannot provide a supported explanation for the results at this field. The fact that this series occupies low-lying landscape positions and had high STP would tend to agree with high STP values for similar positions in Fields 2 and 3. However, zoning approaches based on elevation and (or) EC$_a$ did not produce comparable results. In this field the GC approach encompassed both optimum and high testing soils and the range of STP values (16-29 mg kg^{-1}) was much less than the observed for the base grid sampling (7-62 mg kg^{-1}).

The lack of consistent STP differences among zones of zoning approaches based on EC$_a$ or topography attributes could be explained by several reasons. First, all these fields had low ranges in elevation and slope except for very small areas in Fields 3 and 4. Thus, soil erosion effects (through transport and deposition) on STP would be minimized and no significant effects of elevation would be observed. Second, it is likely that the effect of past management practices, mainly fertilization histories, is masking any effects of topography or stable soil properties on STP. The lack of relationship between topography with STP has been observed before, even in fields with larger differences in elevation and slope (Franzen et al., 1998; Bronson et al., 2000; Kravchenko and

Bullock, 2000; Wittry and Mallarino, 2003). The lack of consistent correlation between EC_a and STP has also been reported before for several fields (Heiniger et al., 2003). Overall the GC approach identified less STP interpretation classes than the base sampling and in general failed to identify areas testing Very Low or Very High.

Potassium fields.

Mean STK sometimes differed ($P \leq 0.05$) among zones delineated with each zoning approach (Table 12) but, similarly to results for STP, the differences were not consistent across fields or approaches. In Field 5, where the dense base grid-sampling approach revealed high within-field STK variability (Table 3), the GC approach detected areas with Low and Optimum STK values and trends across the field followed the trend observed with the base grid-sampling approach (Table 15). However the GC approach failed to detect Very Low or High STK interpretation classes. The SMZ approach also identified areas with different STK values in this field (Table 16). Areas of Klinger soil series had the highest initial STK values (152 mg kg^{-1}) of the three dominant soil series. In Field 6, STK values did not differ among zones delineated with any zoning approach. The GC approach identified 90 % of the experimental area in the Optimum class while in the base grid sampling STK values encompassed at least four interpretation classes. In Field 7, both the SMZ and the EZ approach identified field areas with different STK. Higher STK values were observed at the lowland positions, which coincided with the Colo-Ely soil series complex. Soil transport and deposition through erosion could have played a role in determining higher K availability in lowland positions because this field had the highest range in elevation and a relatively uniform slope. The likely effect of topography on STK observed in this field is consistent with previous research in other regions. For example, Kravchenko and Bullock (2000) reported a negative relation between elevation and STK in Illinois fields with similar ranges in elevation and slope. Although mean STK values for the

GC approach encompassed at least three interpretation classes (Very Low, Low, and Optimum), the results from these large cells showed an important within-cell variation and this likely affect the sensitivity to detect significant effects on initial STK.

The results showed that zoning approaches for STK based on EC_a (ECZ, EECZ and EECSZ) were not useful in identifying field areas with contrasting STK levels. Other research (Heiniger et al., 2003) showed a weak relationship between EC_a and STK across different soil series, but the correlation improved when soil series were considered. It is likely that under moderate dry conditions, EC_a would be a better indicator of variation in soil cation exchange capacity (CEC) and texture (Sudduth et al., 2003). In general the GC approach identified less STK interpretation classes compared to the intensive base grid sampling (Table 3), and there was large within-cell variation.

Crop Yield and Yield Response to P and K for Different Zones

Average crop yield response to P or K across zones of each delineation method for each field showed, as expected, similar results to those observed for the whole-field analyses. Differences in probability levels for the fertilizer effects were minor and, although values will be shown in tables, these new results will not be discussed. Values are not exactly the same for the two analyses because some yield values were excluded for some zoning approaches (for example, when a zone was not represented in at least two true replications). A statistically significant zone effect indicates that crop yields differed across zones of one delineation approach. A statistically significant interaction zone by fertilization effects indicates that the crop response to fertilization was different across the zones of a particular zoning approach. The interpretation of zone effects or the interaction between treatment and zone needs to consider soil-test values and soil properties predominating within each zone, and also rainfall patterns for a particular growing season. Within separate sections for P fields and K fields, we discuss firstly results for absolute yield differences among zones and secondly results for significant interaction zone by fertilization effects.

Phosphorus fields.

Grid cell approach

Corn and soybean grain yield response differed ($P \leq 0.05$) among the GC zones. Corn yield response to P was observed in the Very Low and Low STP interpretation classes for Fields 2a, $2a_2$, 3a and $3a_2$ and were not observed for the Low class in Fields 1b, $1b_2$, and $4b_2$ (Table 17). These results in general agreed with those observed for the intensive base grid sampling with the only exception of Field $1b_2$. However, in this field there was a non-significant response trend ($P \leq 0.07$). These results are reasonable because the GC approach also identified areas with different STP values in Fields 1, 2, and 3. Soybean yield response to P ($P \leq 0.05$) was observed in the Very Low and Low STP interpretation classes for Fields 1a, 2b, and $2b_2$ (Table 18). Although the results are similar to the obtained with the dense grid sampling, fewer STP interpretation classes were identified for the GC approach. For example, Very Low areas could not be identified in Field 3. This field showed a response only in this class for the dense grid sampling approach.

Soil survey map approach.

Corn yield differed ($P \leq 0.05$) across the soil series zones only in Fields 2a and $2a_2$ (Table 19). There was no significant interaction between soil series and P fertilization effects in any field, which indicated no differential yield response to P for different soil series zones. In Field 2a, the higher corn yield was observed for the Webster soil series and the lowest for the Clarion series. Corn responded to P in both soils, although STP was lower for the Clarion soil (Table 14). Rainfall amount and seasonal patterns for this year (1998) and region were near normal, and higher corn yield is expected for the Webster soil because it is located at lower landscape positions than the Clarion soil and has higher soil water availability in normal or dry years. The same explanations apply to results for Field $2a_2$, which was another year for the same field.

Soybean yield differed ($P \leq 0.05$) across the soil series zones in Fields 2b, 3b, and 4a (Table 20). The yield response to P was statistically similar across soil series within all fields. In the three fields where yield differed across soils, the Clarion soil had higher yield than Nicollet, Canisteo, or Webster soils. The Clarion soils occupies higher topographic positions and is the best drained. Rainfall was well above the 50-yr average for Fields 2b and 4a, and was near average for Field 3b. Other research has shown lower soybean yield levels at lower topographic positions in this soil association, especially in normal or wetter than normal seasons. High soil pH and high soybean cyst nematode (SCN) infestation are more frequent in lowland positions and could explain lower yield levels (G. Tylka, personal communication; Sawchik and Mallarino, first paper of this Dissertation).

Elevation approach.

Corn yield differed ($P \leq 0.05$) across EZ zones in Fields 2a, $2a_2$, 3a, 4b, and $4b_2$ (Table 21). In Field 2a, EZ-3 (medium elevation) had higher ($P \leq 0.05$) corn yield than the other two zones. Rainfall amount and patterns were near normal for this site and year (1998). We would expected higher corn yields at EZ-2 (low elevation), but his zone was partially associated with Canisteo and Harps soil series that are poorly drained. In Field $2a_2$ (the same field for the second rotation cycle), EZ-1 (high elevation) had the lowest yield across all EZ zones. This result is reasonable because rainfall for this year was well below the 50-yr average (-183 mm). Moisture deficit was reflected in the observed low absolute yield. In Fields 4b and $4b_2$, EZ-1 (high elevation), had the highest corn yield for both years. This result agreed with rainfall patterns for both years that were near normal during the growing seasons. A significant interaction between EZ zones and P fertilization effect on corn yield response was observed only in Fields 1b and 3a. In Field 1b, a higher yield response to P was observed at higher elevations (EZ-2). Yields were statistically similar across zones at this field.

Soil-test P was lower for the EZ-2 zone (Table 11), but the STP difference was only 2 mg kg^{-1} and values for both zones were in the Low class. In Field 3a, the yield response to P was higher ($P \leq 0.05$) in the lower landscape position (EZ-1). This zone had a lower STP (Low) compared with the upper landscape position (Optimum), so a higher yield response was reasonable.

Soybean yield differed ($P \leq 0.05$) across EZ zones in Fields 2b, $2b_2$, 4a, and $4a_2$ (Table 22). Excess rainfall during the 1999 growing season could explain lower soybean yield at lower elevaions in Fields 2b (the EZ-2 zone) and 4a (the EZ-3 zone). However, low elevations also showed lower yields for a drier year (2001) in both fields (Fields $2b_2$ and $4a_2$). The difference in soybean yield across zones for these two fields agreed with previous research (Kravchenko and Bullock, 2000; Kaspar et al., 2003; Jaynes et al., 2003) showing an interaction of landscape position with yield variability for corn and soybean. However, Kaspar et al. (2003) and Jaynes et al. (2003) found that differences were larger and more consistent in years with below-average rainfall. Although elevation ranges were low in these P fields, other factors probably limited soybean yield at low landscape positions. As was mentioned previously, other research showed that high pH and SCN infestation often limit soybean yield in lowland positions of fields located in the region where the P fields were located. Because the low-laying soils of Fields 2 and 4 have predominantly acid or neutral pH, SCN likely was the main factor limiting yield (SCN infestation was not measured for this study). Only Field $2b_2$ showed a significant zone by treatment interaction for soybean yield. No response was observed for the lower elevation (EZ-2), probably because of the low yield level and much higher STP (Table 11) compared with the other zones.

Electrical conductivity-based approach.

Corn yield differed ($P \leq 0.05$) across ECZ zones in Fields 1b, $2a_2$, and 3a (Table 21). In Field 1b, elevation and EC_a were negatively correlated (r -0.60) and ECZ-1 (medium EC_a) showed the lowest corn yield and the lowest STP value (Table 11). In the region where the P fields were established, soils at lower landscape positions are poorly drained and usually have higher clay content. Both properties can explain higher EC_a values compared with higher elevations. In Field $2a_2$, elevation and EC_a were also negatively correlated (*r* -0.81), and ECZ-2 (higher EC_2) showed the highest corn yield and the highest STP value. In Field 3a there was a significant zone by P fertilization interaction. Corn responded to P only in the ECZ-1 and ECZ-2 zones (with higher EC_a values). Corn yield was similar across zones when P was applied, but was different when P was not applied (yield was lower for ECZ-1 and ECZ-2 zones). Soil-test P was Optimum for the two responsive zones and Low for the nonresponsive zone, but the difference was only 3 mg kg^{-1}. We believe that excess moisture at this site and year (rainfall was 245 mm higher than average) limited corn yield and yield response to P at the lowest elevations which also had high EC_a values.

Soybean yield differed across ECZ zones in Fields 2b, $2b_2$, and 3b (Table 22). In Field 2b the lowest yield was observed for the ECZ-2 zone (high EC). This zone usually coincided with lower elevation, and with poorly drained soils with higher clay content. Although these factors probably limited soybean yield due to the excess of rainfall received that year, lower yield for the ECZ-2 zone was also observed for the dry to normal growing season (2001) in this field (coded as Field $2b_2$). In Field 3b, which also received excessive rainfall during the growing season, the highest soybean yield was observed for the ECZ-3 zone (low EC_a). The soybean yield response to P differed across ECZ zones only in Field 1a. Yield was increased by P fertilization in all zones, but the response was much larger for the ECZ-1 zone (with intermediate EC_a values). The largest yield response is reasonable because his zone had the lowest mean STP value (Table 11).

Combination of topography and EC_a-based approaches.

Crop yield differed ($P \leq 0.05$) across zones delineated using a combination of elevation and

EC_a attributes (the EECZ approach) only in the corn P fields 3a and $4b_2$ (Table 21), and in the soybean P fields 1a, 2b, $3b_2$, and $4a_2$ (Table 22). In general, the yield differences across zones followed results discussed separately for the EZ and ECZ approaches in previous sections and will not be discussed again. A significant interaction EECZ zone by P fertilization was observed only in Field 3a. In this field, the corn yield response to P fertilization was higher for the EECZ-2 zone. This zone had high EC_a, was located at a lowland position, and mean STP was in the Optimum class and was larger than for the two other zones (Table 11). Thus, mean STP cannot explain the larger response. The analysis for the EZ approach for this field and year showed larger corn yield response at low elevations (EZ-1 zone) and mean STP was lower than for higher elevations. The analysis for the ECZ approach showed larger corn yield response for the two zones with higher EC_a (ECZ-1 and ECZ-2 zones) but STP was slightly higher than for the zone with lower EC_a (ECZ-3 zone). If indeed the EECZ-2 zone was a good indicator of wet, low-lying topographic positions, the higher crop response could be explained by excess rainfall that year. It is possible that in the lower-testing, better-drained parts of the field root development and P uptake was not affected while in the EECZ-2 zone the crop became more dependent on P application.

When slope attributes were added to elevation and EC_a to combine all classification attributes into a delineation approach (EECSZ), crop yields for the P fields differed across zones only in Field $2a_2$ (corn, Table 21) and Field 2b (soybean, Table 22). In Field $2a_2$ corn yield was lowest for the EECSZ-2, which had the lowest EC_a reading, the highest elevation, and a small slope. This result was reasonable because in this year there was below-normal precipitation. In Field 2b, soybean yield was lowest for the EECSZ-4 zone, which had the lowest elevation, the highest EC_a, and the smallest slope of all zones. This result agreed with lower soybean yields for lower topographic positions discussed in previous sections. However, no EECSZ zone by P fertilization interaction was observed at any field.

Classification of attributes (elevation-EC$_a$, and elevation-EC$_a$-slope) based on the unsupervised *k*-means clustering algorithm resulted in poorer results compared to the classification based on the fuzzy *c*-means algorithm for both P and K fields and data are not shown. The *k*-mean clustering algorithm resulted in more numerous zones for both approaches (EECZ, and EECSZ) and statistically significant zone or treatment by zone effects were less frequent than those observed for the fuzzy classification.

Summary of crop response to P across zones

The results for the P fields often showed differences in crop yield across zones for most zone delineation approaches. Approaches based on a combination of attributes (EECZ and EECSZ) did not result in zones with contrasting yield levels, probably because in the landscape where the P fields were located they resulted in zones with contrasting EC$_a$ but quite similar elevations. The crop response to P fertilization seldom differed across zones for most zoning approaches, and the results seldom could be related to mean or median STP values of the zones. The STP values most often were similar across zones of all the zoning approaches, except the GC grid approach. Although in a few instances STP differed across zones, usually the values were in the same STP interpretation class. If P removal is a key element to consider for the application of maintenance rates, use of yield maps could be more useful and reliable than elevation or EC$_a$ to delineate removal zones because it will directly measure yield potential variation across a field.

Potassium fields.

Grid cell approach

Corn and soybean yields differed ($P \leq 0.05$) among zones of the GC approach. Corn yield response to K was observed in the Low class of Fields 6b$_2$, 7a and 7a$_2$ and was not observed in the

Low class of Fields 5b and 6b (Table 23). The lack of response in Field 5b agreed with the results obtained with the base grid sampling for this field. The lack of response in Field 6b is likely related to the STK distribution among interpretation classes for the GC approach. Although 10 % of the experimental area tested Low according to the GC approach, the minimum STK value (128 mg kg^{-1}) was borderline between the Low and Optimum classes. Soybean yield response to K was observed in the Low class in Fields $5b_2$ and $6a_2$ (Table 24). There was also a non-significant response trend ($P \leq 0.08$) in Field 7b that is reasonable because this field also showed a significant yield response in the Low class for the base grid sampling. None of the fields showed a significant corn or soybean yield response in the Optimum class.

Soil survey map approach.

Corn yield differed ($P \leq 0.05$) among the soil series zones only in the K fields 5b and $7a_2$ (Table 25). In Field 5b the Kenyon soil, which is located at higher landscape positions and has steeper slopes, showed lower corn yield this year (2001) probably because rainfall was well below the long-term average. There was no response to K for any soil in this field. In Field $7a_2$, although average yields differed across Colo-Ely and Tama soils, yields for the K fertilized treatment were similar. There was a significant treatment by soil series interaction at this field in 1999 (Field 7a) and in 2001 (Field $7a_2$). In both years the Colo-Ely soil series complex showed a larger response to K fertilizer than the Tama soil. Mean STK was higher for the Colo-Ely soil (Table 16) but showed a large SD. The Colo-Ely complex is located at the lower landscape positions. Because rainfall was below average, perhaps the higher response for the Colo-Ely soil complex was reasonable. This series have higher water holding capacity and usually have a high water table (T.E. Fenton, personal communication, 2003, Dept. of Agronomy, ISU).

Soybean yield differed across soil series zones in Fields 5a, $5a_2$, 6a, and 7b (Table 26). We believe that moisture was the main factor explaining soybean yield variation across soil series. Although SCN infestation was not measured, the farmers have not observed it in previous years. In Fields 5a, 5a$_2$, and 6a the highest yield was observed for the Klinger soil series, which is located at lower portions of the landscape. The Kenyon soil usually had the lowest soybean yield, and this soil have less water holding capacity than the other soil series. In Field 7b, soybean yield was higher for the Tama soil than for the Colo-Ely soil complex. This field and crop-year had above-average rainfall (2000), and the lower yield for the Colo-Ely complex could be explained by reasons given above. The soybean response to K fertilization never differed across soil series zones at any field, although there were significant differences in initial STK for Fields 5 and 7 (Table 16).

Elevation approach.

Corn yield differed ($P \leq 0.05$) across elevation zones (EZ) in all K fields except Field 5b (Table 27). In Field 6b, higher yields were observed in EZ-1 (low elevation), which is reasonable for a drier than normal year. In Field 6b$_2$, and a year with above-average precipitation (154 mm), higher yields were observed at higher elevations (EZ-2). Higher corn yields were also observed at lower elevations for Fields 7a, and 7a$_2$, even though they were evaluated during a slightly wetter (+106 mm) or drier (-90 mm) growing seasons compared to the 50 yr-average. A significant interaction zone by K fertilization was detected in Fields 6b$_2$ and 7a$_2$. For field 6b$_2$, the yield response to K was higher at lower elevations (EZ-1). This zone had also higher corn yields than the other zone. Mean STK for this field and crop-year were in the Low class in both zones and had similar SD. The observed larger yield response at lower elevations could be explained by other non-measured soil properties that determined a higher yield potential for this zone. In Field 7a$_2$, a larger yield response to K was observed for the medium and high elevation zones (EZ-2, EZ-3). This result is reasonable because mean STK for EZ-1 was Optimum while mean STK values for the two most responsive zones was Low.

Soybean yield differed across EZ zones in all K fields except Fields $5a_2$, $6a_2$, and $7b_2$ (Table 28). Soybean yield was higher at lower elevations (EZ-2) in Field 5a, which corresponded to a year with near normal rainfall. In Field 6a, yield was also higher at lower elevations (EZ-1), although this crop year had an excess of rainfall (+109 mm). The same tendency was observed in Field 7b. We believe that in these K fields moderate rainfall excess did not affect soybean yields. The soybean response to K fertilizer never differed ($P \leq 0.05$) across EZ zones.

Electrical conductivity-based approach.

Corn yield differed among ECZ zones only in the K Fields 6b and $7a_2$, and no zone by K fertilization interaction was detected at any field (Table 27). In Field 6b, higher corn yields ($P \leq 0.05$) were observed in the ECZ-2 zone (lowest EC_a), which had the highest STK value. Rainfall pattens for this crop year were near normal. In Field $7a_2$, yield was slightly higher for the ECZ-2 zone (which had the highest EC_a value). Rainfall was below average for this crop year. Higher EC_a in Field $7a_2$ values were probably related to a higher clay content, with also higher water holding capacity, and this may explain the results obtained. Consideration of STK, elevation, and rainfall pattern could not explain apparently contradictory results for yield levels in relation of areas of Fields 6b and $7a_2$ with low or high EC_a.

Soybean yield differed across ECZ zones only in K Fields $5a_2$ and 6a (Table 28). In Field $5a_2$, yield were higher for the zone with the lowest EC_a (ECZ-2). Mean STK values for this zoning approach did not differ, and rainfall was above average for this crop year. It is likely that a lower EC_a might be related with more well drained soils. In Field 6a, soybean yield was also higher at ECZ-2 (lowest EC_a). The soybean response to K fertilizer never differed ($P \leq 0.05$) across ECZ zones.

Combination of topography and EC_a-based approaches.

Use a zoning approach that combined elevation and EC_a (EECZ) resulted in crop yield differences in the corn K Fields 6b, $6b_2$, 7a (Table 27), and in the soybean K Fields 5a, $5a_2$, and $7b_2$ (Table 28). The absolute yield differences across zones followed results discussed separately for EZ and ECZ zoning approaches in previous sections and will not be discussed again. A zone by K fertilization interaction was observed only in Field $7a_2$ (corn, Table 27). In this field, there was a higher corn yield response for the EECZ-2 zone, which had intermediate elevation values and high EC_a readings. The different response was reasonable because mean STK was Low for the responsive zone and was Optimum for the other zones.

The combination of all attributes (EECSZ) resulted in crop yield differences in most corn fields (except Field 7a) (Table 27) but only in one soybean field (Field $5a_2$). A treatment by zone interaction was detected only in Field $7a_2$ (corn). The corn yield response was larger in the EECSZ-1 and EECSZ-2 zones. These zones had no clear differences in elevation or slope compared with the other zones, but had the highest EC_a readings and the lowest STK values (Table 12).

Summary of crop response to K across zones

Results from the K fields showed that grain yield differed across zones of most zoning approaches in most fields. For the EZ approach, corn yields differed across zones in four fields (from a total of five) while soybean yields differed in three fields (from a total of six). For the ECZ approach, crop yields differed across zones in two fields for each crop. When elevation, slope, and ECa attributes were combined for the EECZ or EECSZ approaches, corn yields differed across zones in several fields (three for the EECZ approach and four for the EECSZ approach). Soybean yields differed across zones in three fields for the EECZ approach, and in only one field for the EECSZ approach. Compared to the P fields, the K Fields zoning approaches were more sensitive to identify areas with contrasting yield differences. One reason might be the higher range in elevation and in slope for the K fields. However, few significant treatment by zone interactions were observed. In some instances differences in fertilizer response could be related to STK values, while in other instances yield potential differences between zones was a more logical explanation.

The same considerations made for the P fields about the benefit of topography and EC_a-based zone delineation approaches apply to the K fields. While zoning approaches correctly identified high and low yielding areas of the K fields, the crop response to K fertilization seldom differed across zones, and the results seldom could be related to mean or median STK values of the zones. The STK values usually were similar across zones of all the zoning approaches, except the GC grid approach. If yield potential and K removal is a key element to consider for the application of K fertilizer (as results for two fields suggested) use of yield maps will be more useful and reliable than elevation or EC_a to delineate removal zones because it will directly measure yield potential variation across a field.

SUMMARY AND CONCLUSIONS

Field-average yield responses to P and K fertilizer were statistically significant in most fields with below-Optimum median STP or STK. No field-average yield response to P or K fertilizer was observed in soils testing Optimum or higher in STP or STK. Analyses of responses for field areas testing within different soil-test interpretation classes as described by a dense (0.08 to 0.24-ha) initial grid sampling showed that grain yield responses were large and frequent for areas testing Very Low or Low and small and infrequent for areas testing Optimum.

Results from the P fields often showed differences in crop yield across zones for most zone delineation approaches. However the crop response to P fertilization seldom differed across zones except for the GC (1.0-ha cells) approach, and the results seldom could be related to mean or median STP values of the zones. The STP values were often similar across zones of all the zoning approaches, except for the GC approach.

The zoning approaches were more sensitive to identify areas with contrasting absolute yield differences in the K fields compared with the P fields. This could be explained by a higher range of elevation and slope for these fields compared to the P fields. Crop responses to K seldom differed across zones, and the results seldom could be related to mean or median STK values. The STK values were similar across zones of most zoning methods except the GC and SMZ approaches.

Overall, the results showed that various zoning approaches could be used in this region to delineate zones having contrasting terrain and soil properties and, sometimes, different yield levels. However, most zoning approaches except a dense grid-cell sampling approach (1.0 ha or denser) failed to identify areas with contrastingly different STP or STK values. We believe that long histories of P and K fertilization of originally low-testing fields drastically reduced the impact of physical, chemical and mineralogical properties on within-field soil-test variation. The zoning approaches based on elevation and EC_a often identified areas with different yield potential. Because P and K removal is an important element of fertilizer recommendations in the U.S. Midwest, use of these zoning approaches could be a useful tool for long-term P and K management in conjunction with yield maps.

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Table 1. Predominant soil series in the experimental areas of P and K fields.

		Dominant soil series			Second dominant soil series		
	Field	Series	Subgroup†	Area	Series	Subgroup	Area
				%			%
P Fields	1	Clarion	T. Hapludolls	44	Canisteo	T. Endoaquolls	26
	2	Webster	T. Endoaquolls	36	Clarion	T. Hapludolls	33
	3	Nicollet	A. Hapludolls	58	Clarion	T. Hapludolls	17
	4	Webster	T. Endoaquolls	31	Canisteo	T. Endoaquolls	27
K Fields	5	Donnan	A. Hapludalfs	21	Klinger	A. Argiudolls	19
	6	Dinsdale	T. Argiudolls	38	Klinger	A. Argiudolls	25
	7	Tama	T. Argiudolls	45	Colo-Ely	C. Haplaquolls	39

† A, Aquic; C, Cumulic; T, Typic.

Table 2. Descriptive statistics for initial soil-test P, pH, organic matter and soil-test P distribution according to Iowa State University 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

	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

	Descriptive statistics 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

	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

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

‡ VL, very low; L, low; Opt, optimum; H, high; and VH, very high (Sawyer et al., 2002).

Table 3. Descriptive statistics for initial soil-test K, pH, organic matter and soil-test K distribution according to Iowa State University interpretation classes.

	Descriptive statistics for soil-test K †				
Field	Mean	Median	Min.	Max.	SD
	---------- mg kg^{-1} ----------				
5	133	133	84	194	25
6	140	138	117	221	19
7	129	120	70	276	39

	Field area for five soil-test K classes ‡				
Field	VL	L	Opt	H	VH
	---------- % ----------				
5	2	46	46	6	0
6	0	30	65	3	2
7	5	61	27	28	7

	Descriptive statistics for soil pH				
Field	Mean	Median	Min.	Max.	SD
5	6.6	6.6	6.4	7.1	0.2
6	6.8	6.9	6.3	7.3	0.2
7	6.5	6.5	5.8	7.0	0.4

	Descriptive statistics for organic matter				
Field	Mean	Median	Min.	Max.	SD
	---------- g kg^{-1} ----------				
5	37	37	26	48	5
6	45	45	32	70	9
7	47	45	29	70	8

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

‡ VL, very low; L, low; Opt, optimum; H, high; and VH, very high (Sawyer et al., 2002).

Table 4. Corn and soybean grain yield response to P.

Crop	Field[†]	Year	Treatment and grain yield		Statistics
			Check	P	
			------ Mg ha^{-1} ------		P > *F*
Corn	1b	1999	9.52	9.72	0.16
	1b$_2$	2001	8.17	8.85	0.01
	2a	1998	10.05	11.04	0.01
	2a$_2$	2000	7.67	8.83	0.01
	3a	1999	7.77	8.55	0.01
	3a$_2$	2001	7.33	7.91	0.01
	4b	2000	9.61	9.71	0.15
	4b$_2$	2002	11.96	12.21	0.01
Soybean	1a	1998	3.28	3.72	0.01
	1a$_2$	2000	2.31	2.67	0.02
	2b	1999	2.57	2.91	0.17
	2b$_2$	2001	2.32	2.72	0.06
	3b	2000	3.03	3.19	0.01
	3b$_2$	2002	2.99	3.42	0.01
	4a	1999	3.66	3.71	0.03
	4a$_2$	2001	2.30	2.27	0.50

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

Table 5. Corn and soybean grain yield response to K.

			Treatment and grain yield		
Crop	Field†	Year	Check	K	Statistics
			------ Mg ha^{-1} ------		P > *F*
Corn	5b	2001	10.26	10.51	0.01
	6b	2000	8.66	8.94	0.11
	6b$_2$	2002	11.48	11.99	0.01
	7a	1999	10.00	11.14	0.01
	7a$_2$	2001	9.05	10.38	0.01
Soybean	5a	2000	3.11	3.16	0.11
	5b$_2$	2002	3.78	3.99	0.01
	6a	1999	3.22	3.21	0.12
	6a$_2$	2001	3.35	3.59	0.01
	7b	2000	2.98	3.15	0.01
	7b$_2$	2002	3.21	3.34	0.01

† Suffixes "a" and "b" in the field code identify the first and second crop rotation cycle (K fertilizer was applied once before the first crop). Suffixes "a$_2$" and "b$_2$" indicate that treatments were reapplied for a second rotation cycle.

Table 6. 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	P	
			------ Mg ha^{-1} ------		P > *F*
1b	1999	L	9.45	9.67	0.36
		Opt	9.65	9.48	0.70
		H	10.36	10.31	0.93
1b$_2$	2001	VL	7.78	8.85	0.01
		L	8.49	8.82	0.01
2a	1998	L	9.89	10.93	0.05
		Opt	10.01	11.05	0.04
		H	10.60	11.28	0.06
2a$_2$	2000	VL	7.11	8.59	0.01
		L	7.82	8.88	0.01
3a	1999	L	7.82	8.69	0.05
		Opt	7.99	8.55	0.06
		H	7.18	8.45	0.36
3a$_2$	2001	VL	6.93	7.95	0.02
		L	7.33	7.96	0.01
		Opt	7.50	7.95	0.24
		H	7.25	7.74	0.15
4b	2000	L	9.51	9.61	0.58
		Opt	9.62	9.45	0.99
		H	9.64	9.80	0.14
		VH	9.85	9.95	0.44
4b$_2$	2002	L	11.63	12.09	0.27
		Opt	11.71	12.19	0.15
		H	12.05	12.25	0.28
		VH	12.24	12.36	0.33

[†] STP class = soil-test P classes; VL, very low; L, low; Opt, optimum; H, high; VH, very high.

Table 7. 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: Check	Treatment and grain yield: P	Statistics
			------ Mg ha^{-1} ------		P > *F*
1a	1998	L	3.27	3.84	0.04
		H	3.40	3.51	0.19
1a$_2$	2000	VL	2.13	2.71	0.02
		L	2.54	2.65	0.49
2b	1999	L	3.06	3.53	0.03
		Opt	2.15	2.39	0.57
		H	2.43	3.21	0.08
2b$_2$	2001	VL	2.17	2.72	0.04
		L	1.99	2.73	0.05
		VH	3.24	2.91	0.34
3b	2000	L	3.06	3.18	0.29
		Opt	3.01	3.22	0.07
		H	3.03	3.22	0.35
3b$_2$	2002	VL	2.65	3.51	0.03
		L	2.98	3.40	0.30
		Opt	3.25	3.52	0.40
		H	2.93	3.47	0.32
4a	1999	L	3.70	3.76	0.51
		Opt	3.64	3.68	0.77
		H	3.62	3.74	0.33
		VH	3.58	3.69	0.70
4a$_2$	2001	L	2.21	2.27	0.22
		Opt	2.21	2.22	0.69
		H	2.36	2.25	0.10
		VH	2.34	2.32	0.44

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

Table 8. Corn grain yield response to K for field areas testing within different soil-test K interpretation classes.

			Treatment and grain yield		
Field	Year	STK class†	Check	K	Statistics
			------ Mg ha^{-1} ------		P > *F*
5b	2001	L	10.16	10.43	0.26
		Opt	10.34	10.56	0.26
		H	10.83	10.94	0.65
6b	2000	L	8.66	9.01	0.04
		Opt	8.68	8.97	0.26
6b$_2$	2002	L	11.42	11.99	0.01
		Opt	11.77	11.59	0.60
7a	1999	L	9.87	11.07	0.03
		Opt	10.51	11.33	0.08
		VH	10.43	11.85	0.35
7a$_2$	2001	L	8.96	10.36	0.04
		Opt	10.07	10.72	0.31

† STK class, soil-test K classes. L, Low; Opt, Optimum; H, High; and VH, Very High.

Table 9. Soybean grain yield response to K for field areas testing within different soil-test K interpretation classes.

Field	Year	STK class[†]	Treatment and grain yield Check	 K	Statistics
			------ Mg ha^{-1} ------		P > *F*
5a	2000	L	3.10	3.18	0.03
		Opt	3.08	3.13	0.37
		H	3.39	3.22	0.29
5b$_2$	2002	L	3.70	4.02	0.01
		Opt	3.82	3.99	0.14
		H	3.93	4.02	0.20
6a	1999	L	3.17	3.23	0.27
		Opt	3.26	3.20	0.18
6a$_2$	2001	L	3.34	3.58	0.01
		Opt	3.50	3.59	0.58
7b	2000	L	2.97	3.19	0.04
		Opt	3.03	3.11	0.09
		VH	3.11	3.22	0.78
7b$_2$	2002	L	3.22	3.34	0.24
		Opt	3.34	3.33	0.56

[†] STK class = soil-test K classes; L, Low; Opt, Optimum; H, High; and VH, Very High.

Table 10. Univariate statistics for the field attributes used to delineate sampling zones for P and K fields.

Field		Elevation				
		Mean	SD†	Maximum	Minimum	Median
		m				
P fields	1	99.8	0.6	101.1	99.0	99.7
	2	99.8	0.2	100.4	99.4	99.7
	3	345.5	2.0	350.2	341.4	344.9
	4	348.1	1.4	351.0	344.4	348.2
K fields	5	270.5	2.7	276.5	265.1	270.5
	6	264.1	2.4	270.4	260.0	263.7
	7	290.7	3.3	298.7	284.1	290.7
		EC$_a$‡				
		Mean	SD	Maximum	Minimum	Median
		mS m^{-1}				
P fields	1	26.8	10.3	55.4	12.0	22.5
	2	39.1	11.0	64.5	19.8	41.9
	3	29.3	7.7	61.2	16.1	27.7
	4	32.4	9.1	63.3	17.5	30.1
K fields	5	12.6	5.3	35.1	1.6	11.9
	6	17.3	2.4	39.9	5.7	14.9
	7	76.5	26.6	156.2	8.0	75.7
		Slope				
		Mean	SD	Maximum	Minimum	Median
		degrees				
P fields	1	0.5	0.3	1.3	0.0	0.5
	2	0.3	0.2	0.8	0.0	0.3
	3	2.9	2.3	11.5	0.0	2.3
	4	2.3	1.7	7.7	0.0	1.7
K fields	5	2.7	1.0	5.0	0.2	2.8
	6	2.3	0.8	4.7	0.1	2.3
	7	2.7	1.1	6.2	0.1	2.8

† SD, standard deviation.

‡ EC$_a$. apparent soil electrical conductivity.

Table 11. Summary of attributes and soil-test P (STP) values in delineated zones for P fields.

			Variables								
			Elevation		EC$_a$†		Slope		STP		
Field	Zone‡		Mean	SD§	Mean	SD	Mean	SD	Mean	SD	$P > F$¶
			------- m-------		------mS m^{-1}------		-----degrees -----		---- mg kg^{-1}-----		
1	EZ	1	99.5	0.27					14	4.6	0.10
		2	100.5	0.33					12	2.3	
	ECZ	1			31.4	3.81			10	2.2	0.13
		2			46.0	4.50			14	5.3	
		3			19.5	2.78			12	2.2	
	EECZ	1	100.6	0.28	19.7	2.98			13	1.7	0.58
		2	99.4	0.22	42.0	6.38			14	5.7	
		3	99.7	0.31	22.6	5.25			12	2.4	
	EECSZ	1	100.9	0.18	20.2	1.78	0.53	0.22	14	2.3	0.65
		2	99.6	0.30	23.7	5.90	0.37	0.19	12	2.1	
		3	100.1	0.37	21.3	5.39	0.92	0.17	14	4.2	
		4	99.4	0.20	43.3	5.91	0.26	0.14	14	5.8	
2	EZ	1	100.4	0.10					11	1.8	0.01
		2	99.6	0.08					28	15.2	
		3	99.8	0.08					14	5.6	
	ECZ	1			27.9	5.41			11	3.1	0.01
		2			47.3	5.51			25	13.7	
	EECZ	1	99.9	0.17	28.0	5.77			11	4.2	0.04
		2	99.6	0.10	47.6	5.54			24	14.2	
		3	100.1	0.16	33.2	9.05			12	1.6	
	EECSZ	1	99.9	0.17	41.0	7.98	0.46	0.10	15	4.2	0.01
		2	100.1	0.17	25.9	5.23	0.20	0.10	10	2.7	
		3	99.9	0.12	28.9	5.67	0.45	0.12	13	5.9	
		4	99.6	0.10	47.5	5.91	0.17	0.08	26	15.1	
3	EZ	1	344.1	0.90					15	4.6	0.17
		2	347.7	1.03					17	5.4	
	ECZ	1			33.2	3.11			18	5.6	0.22
		2			46.9	5.76			18	5.6	
		3			24.2	2.70			15	4.2	
	EECZ	1	344.1	0.94	26.4	4.46			14	3.6	0.02
		2	345.9	1.99	43.8	6.41			20	5.9	
		3	347.9	1.02	28.0	5.09			17	5.2	
	EECSZ	1	345.3	1.61	27.3	5.19	6.3	1.68	17	4.4	0.16
		2	348.0	0.95	33.4	9.77	2.8	1.52	14	4.1	
		3	344.1	0.94	27.8	6.03	1.5	1.01	15	4.5	

† EC$_a$, apparent soil electrical conductivity.

‡ Zone; EZ, elevation zones; ECZ, apparent electrical conductivity zones; EECZ, elevation and EC$_a$ zones; EECSZ, elevation, EC$_a$, and slope zones.

§ SD, standard deviation.

¶ Probability of the zoning approach effect.

Table 11(cont.)

			Variables								
			Elevation		EC_a[†]		Slope		STP		
Field	Zone[‡]		Mean	SD[§]	Mean	SD	Mean	SD	Mean	SD	$P > F$[¶]
			------- m-------		------mS m-1------		-----degrees -----		---- mg kg^{-1}-----		
4	EZ	1	349.8	0.53					22	6.7	0.86
		2	348.2	0.47					21	10.0	
		3	346.4	0.74					19	5.7	
	ECZ	1			33.6	3.14			21	6.8	0.91
		2			46.5	5.00			20	5.3	
		3			24.7	2.53			20	9.2	
	EECZ	1	349.0	0.81	26.5	4.19			21	9.0	0.57
		2	348.2	1.23	45.7	5.79			20	5.8	
		3	346.8	0.89	32.1	6.42			20	7.3	
	EECSZ	1	347.7	1.42	30.0	6.51	4.96	1.15	21	8.5	0.98
		2	347.8	1.38	44.6	5.81	1.67	0.95	21	7.2	
		3	348.5	1.23	27.1	4.15	1.47	0.85	21	8.9	

Table 12. Summary of attributes and STK values in delineated zones for K Fields.

			Variables								
			Elevation		EC_a†		Slope		STK		
Field	Zone‡		Mean	SD§	Mean	SD	Mean	SD	Mean	SD	$P > F$¶
			------- m-------		------mS m⁻1------		-----degrees -----		---- mg kg⁻¹-----		
5	EZ	1	272.7	1.34					136	18.0	0.17
		2	268.2	1.40					131	31.2	
	ECZ	1			19.2	4.25			139	27.9	0.43
		2			10.1	2.95			132	24.4	
	EECZ	1	267.0	1.17	19.7	4.71			139	36.2	0.84
		2	269.7	1.65	9.4	2.97			133	26.3	
		3	273.4	1.10	15.0	4.15			132	18.4	
	EECSZ	1	273.8	1.14	14.6	4.24	1.75	0.80	106	10.7	0.10
		2	267.6	1.20	14.5	5.73	2.13	0.61	129	27.0	
		3	271.4	1.52	10.6	4.47	3.53	0.51	138	23.0	
6	EZ	1	262.7	1.19					140	14.3	0.77
		2	266.9	1.49					141	26.2	
	ECZ	1			19.9	2.64			137	19.2	0.08
		2			12.4	2.00			149	15.4	
	EECZ	1	267.3	1.58	13.7	2.73			144	28.6	0.09
		2	263.3	1.27	14.4	3.66			134	10.3	
		3	261.9	0.98	29.1	4.98			149	15.4	
	EECSZ	1	267.0	1.58	14.0	2.88	2.92	0.80	143	27.7	0.09
		2	263.3	1.27	14.2	3.70	2.10	0.67	134	10.3	
		3	261.9	0.98	29.2	4.96	1.66	0.60	150	15.5	
7	EZ	1	287.1	1.23					145	46.9	0.05
		2	291.1	1.12					126	36.1	
		3	294.9	1.30					113	19.0	
	ECZ	1			48.6	9.83			130	42.3	0.91
		2			79.0	8.92			128	35.6	
	EECZ	1	287.8	1.76	52.8	12.54			135	40.0	0.44
		2	291.0	2.27	105.7	15.31			132	46.7	
		3	294.3	1.79	76.8	17.06			117	16.9	
	EECSZ	1	289.7	2.34	105.0	19.24	1.54	0.58	148	57.5	0.06
		2	293.1	1.81	88.5	16.50	3.72	0.55	111	21.0	
		3	294.5	2.20	70.8	20.66	2.45	0.76	123	8.6	
		4	287.8	1.79	50.8	10.93	2.59	0.90	127	14.1	

† EC_a, apparent soil electrical conductivity.

‡ Zone; EZ, elevation zones; ECZ, apparent electrical conductivity zones; EECZ, elevation and EC_a zones; EECSZ, elevation, EC_a, and slope zones.

§ SD, standard deviation.

¶ Probability of the zoning approach effect.

Table 13. Descriptive statistics for initial soil-test P and distribution according to Iowa State University interpretation classes for the 1.0-ha grid-cell (GC) approach.

	Descriptive statistics for soil-test P †				
Field	Mean	Median	Min.	Max.	SD
	mg kg^{-1}				
1	13	14	8	17	3
2	19	18	10	36	8
3	16	17	12	19	2
4	21	21	16	29	4

	Field area for five soil-test P classes ‡				
Field	VL	L	Opt	H	VH
	%				
1	12	63	25	0	0
2	0	38	38	0	24
3	0	36	64	0	0
4	0	0	45	55	0

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

‡ VL, very low; L, low; Opt, optimum; H, high; and VH, very high (Sawyer et al., 2002).

Table 14. Initial soil-test P for field areas with different soil series.

		Soil-test P		Statistics
Field	Soil series	Mean	SD[†]	$P > F$[‡]
		-------- mg kg^{-1} --------		
1	Clarion	13	2	0.17
	Canisteo	13	5	
2	Webster	19	17	0.28
	Clarion	13	5	
3	Nicollet	15	5	0.25
	Clarion	16	6	
	Webster	18	5	
4	Webster	19	10	0.01
	Canisteo	24	7	
	Clarion	19	7	

[†] SD, standard deviation.

[‡] Probability of the SMZ approach effect.

Table 15. Descriptive statistics for initial soil-test K and distribution according to Iowa State University interpretation classes for the 1.0-ha grid cell (GC) approach.

Field	Descriptive statistics for soil-test K †				
	Mean	Median	Min.	Max.	SD
	mg kg^{-1}				
5	134	137	94	166	22
6	140	138	128	163	11
7	129	122	102	190	23

Field	Field area for five soil-test K classes ‡				
	VL	L	Opt	H	VH
	%				
5	0	33	67	0	0
6	0	10	90	0	0
7	5	64	27	9	0

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

‡ VL, very low; L, low; Opt, optimum; H, high; and VH, very high (Sawyer et al., 2002).

Table 16. Initial soil-test K for field areas with different soil series.

		Soil-test K		Statistics
Field	Soil series	Mean	SD†	*P* > F‡
		-------- mg kg^{-1} --------		
5	Donnan	132	23	0.04
	Klinger	152	29	
	Kenyon	122	19	
6	Dinsdale	133	11	0.16
	Klinger	144	13	
	Kenyon	150	37	
7	Tama	115	12	0.01
	Colo-Ely	151	54	

† SD, standard deviation.

‡ Probability of the SMZ approach effect.

Table 17. Corn grain yield response to P within different soil-test P interpretation classes according to the 1.0-ha grid cell (GC) approach.

Field	Year	STP class[†]	Treatment and grain yield Check	 P	Statistics
			------ Mg ha^{-1} ------		$P > F$
1b	1999	L	9.47	9.69	0.26
		Opt	9.77	9.90	0.75
1b$_2$	2001	L	8.21	8.85	0.07
2a	1998	L	10.15	11.04	0.05
		Opt	10.05	11.22	0.02
		VH	9.62	10.40	0.37
2a$_2$	2000	VL	7.40	8.52	0.01
		L	7.47	8.81	0.01
		VH	7.95	8.87	0.42
3a	1999	L	7.81	8.54	0.05
		Opt	7.67	8.53	0.05
3a$_2$	2001	L	7.25	7.85	0.01
		Opt	7.40	7.96	0.01
4b	2000	Opt	9.60	9.66	0.64
		H	9.63	9.75	0.25
4b$_2$	2002	L	12.11	12.13	0.14
		Opt	12.13	12.22	0.61
		H	11.81	12.11	0.18
		VH	12.41	12.51	0.53

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

Table 18. Soybean grain yield response to P within different soil-test P interpretation classes according to the 1.0-ha grid cell (GC) approach

			Treatment and grain yield		
Field	Year	STP class†	Check	P	Statistics
			------ Mg ha^{-1} ------		$P > F$
1a	1998	L	3.14	3.74	0.05
		Opt	3.80	3.92	0.07
1a$_2$	2000	L	2.36	2.64	0.17
2b	1999	L	3.22	3.64	0.04
		Opt	2.12	2.54	0.19
		VH	2.30	2.43	0.65
2b$_2$	2001	VL	2.26	2.94	0.01
		L	2.13	2.50	0.05
		VH	2.67	2.76	0.83
3b	2000	L	2.99	3.14	0.19
		Opt	3.07	3.23	0.24
3b$_2$	2002	L	3.00	3.33	0.33
		Opt	3.00	3.49	0.25
4a	1999	Opt	3.65	3.66	0.84
		H	3.66	3.74	0.45
4a$_2$	2001	L	2.31	2.34	0.86
		Opt	2.20	2.24	0.69
		H	2.29	2.21	0.30
		VH	2.32	2.36	0.51

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

Table 19. Corn grain yield response to P for field areas with different soil series.

			Treatment and grain yield		Statistics		
Field	Year	Soil series	Check	P	P effect[†]	Soil[‡]	P x Soil[§]
			------- Mg ha^{-1} -------		---------- P > F --------		
1b	1999	Clarion	9.47	9.70	0.11	0.44	0.99
		Canisteo	9.58	9.82			
1b$_2$	2001	Clarion	8.13	8.86	0.03	0.91	0.83
		Canisteo	8.11	8.92			
2a	1998	Webster	10.26	11.40	0.02	0.01	0.72
		Clarion	9.62	10.67			
2a$_2$	2000	Webster	7.52	8.90	0.01	0.03	0.35
		Clarion	6.99	8.49			
3a	1999	Nicollet	7.99	8.63	0.14	0.13	0.58
		Clarion	7.46	8.49			
		Webster	7.63	8.41			
3a$_2$	2001	Nicollet	7.29	7.96	0.02	0.93	0.40
		Clarion	7.45	7.69			
		Webster	7.30	7.97			
4b	2000	Webster	9.44	9.73	0.16	0.69	0.11
		Canisteo	9.60	9.74			
		Clarion	9.62	9.67			
4b$_2$	2002	Webster	11.71	12.14	0.32	0.07	0.38
		Canisteo	11.92	12.27			
		Clarion	11.88	12.00			

† P effect; probability level of the P main effect.

‡ Soil; probability level of the soil series approach.

§ probability level of the P by soil interaction.

Table 20. Soybean grain yield response to P for field areas with different soil series.

			Treatment and grain yield		Statistics		
Field	Year	Soil series	Check	P	P effect[†]	Soil[‡]	P x Soil[§]
			-------- Mg ha^{-1} -------		----------- P > F ---------		
1a	1998	Clarion	3.12	3.56	0.05	0.86	0.80
		Canisteo	3.20	3.57			
1a$_2$	2000	Clarion	2.31	2.58	0.03	0.68	0.75
		Canisteo	2.20	2.57			
2b	1999	Webster	2.29	2.67	0.10	0.02	0.88
		Clarion	3.11	3.71			
2b$_2$	2001	Webster	2.37	2.63	0.02	0.78	0.09
		Clarion	2.20	3.01			
3b	2000	Nicollet	2.99	3.14	0.22	0.01	0.84
		Clarion	3.14	3.27			
		Webster	3.02	3.23			
3b$_2$	2002	Nicollet	3.05	3.42	0.34	0.39	0.58
		Clarion	2.96	3.34			
		Webster	2.99	3.49			
4a	1999	Webster	3.61	3.68	0.69	0.01	0.60
		Canisteo	3.61	3.68			
		Clarion	3.71	3.80			
4a$_2$	2001	Webster	2.13	2.17	0.27	0.04	0.59
		Canisteo	2.33	2.27			
		Clarion	2.40	2.43			

[†] P effect; probability level of the P main effect.

[‡] Soil; probability level of the soil series approach.

[§] probability level of the P by soil interaction.

Table 21. Corn yield response to P for zones delineated using different zoning methods.

			Treatment and grain		Statistics		
Field	Year	Zone[†]	Check	P	P effect[‡]	Zone[§]	P x Zone[¶]
			------ Mg ha^{-1} -------		-------------- P > F	----------------	
1b	1999	EZ-1	9.73	9.70	0.22	0.12	0.05
		EZ-2	9.19	9.77			
		ECZ-1	8.40	9.49	0.13	0.05	0.12
		ECZ-2	9.72	9.75			
		ECZ-3	9.42	9.72			
		EECZ-1	9.08	9.60	0.21	0.42	0.23
		EECZ-2	9.69	9.80			
		EECZ-3	9.67	9.70			
		EECSZ-2	9.33	9.67	0.24	0.70	0.74
		EECSZ-3	9.62	9.72			
		EECSZ-4	9.67	9.77			
1b$_2$	2001	EZ-1	8.31	8.83	0.05	0.28	0.15
		EZ-2	7.95	8.88			
		ECZ-1	7.74	8.91	0.03	0.72	0.51
		ECZ-2	8.30	8.83			
		ECZ-3	8.09	8.87			
		EECZ-1	7.90	8.89	0.03	0.64	0.43
		EECZ-2	8.22	8.83			
		EECZ-3	8.30	8.83			
		EECSZ-2	8.15	8.97	0.03	0.66	0.80
		EECSZ-3	8.23	8.91			
		EECSZ-4	8.16	8.56			
2a	1998	EZ-1	9.55	10.47	0.04	0.01	0.90
		EZ-2	9.70	10.72			
		EZ-3	10.61	11.59			
		ECZ-1	9.91	10.93	0.03	0.31	0.80
		ECZ-2	10.14	11.11			
		EECZ-1	10.07	11.16	0.01	0.10	0.82
		EECZ-2	10.15	11.15			
		EECSZ-1	9.98	10.93	0.03	0.07	0.93
		EECSZ-3	10.19	11.27			
		EECSZ-4	10.11	10.99			

[†] EZ, elevation zones; ECZ, apparent electrical conductivity zones; EECZ, elevation and EC$_a$ zones; EECSZ, elevation, EC$_a$, and slope zones.

[‡] Probability of the main P effect.

[§] Probability of the zone effect.

[¶] Probability of the interaction between the P effect and the zone effect.

Table 21 (cont.)

			Treatment and grain		Statistics		
Field	Year	Zone	Check	P	P effect	Zone	P x Zone
			---------- Mg ha^{-1} --------		--------------- P > F ---------------		
2a$_2$	2000	EZ-1	7.04	8.36	0.03	0.01	0.80
		EZ-2	7.86	8.97			
		EZ-3	7.81	8.94			
		ECZ-1	7.29	8.70	0.01	0.02	0.15
		ECZ-2	7.96	8.93			
		EECZ-1	7.38	8.79	0.01	0.19	0.72
		EECZ-2	7.91	8.48			
		EECSZ-1	7.54	8.58	0.01	0.03	0.85
		EECSZ-3	7.51	8.80			
		EECSZ-4	7.96	9.00			
3a	1999	EZ-1	7.21	8.38	0.03	0.02	0.05
		EZ-2	8.38	8.58			
		ECZ-1	7.23	8.35	0.04	0.05	0.05
		ECZ-2	7.17	8.54			
		ECZ-3	8.11	8.33			
		EECZ-1	7.95	8.32	0.03	0.04	0.01
		EECZ-2	6.72	8.47			
		EECZ-3	8.30	8.97			
		EECSZ-2	7.76	8.29	0.03	0.21	0.09
		EECSZ-3	6.71	8.46			
3a$_2$	2001	EZ-1	7.34	7.84	0.12	0.64	0.55
		EZ-2	7.32	8.02			
		ECZ-1	7.51	8.14	0.01	0.13	0.94
		ECZ-2	7.16	7.69			
		ECZ-3	7.30	7.87			
		EECZ-1	7.38	7.96	0.02	0.86	0.87
		EECZ-2	7.33	7.83			
		EECZ-3	7.27	7.93			
		EECSZ-2	7.40	8.05	0.01	0.67	0.94
		EECSZ-3	7.20	7.85			

Table 21 (cont.)

Field	Year	Zone	Treatment and grain		Statistics		
			Check	P	P effect	Zone	P x Zone
			------ Mg ha^{-1} -----		--------------- $P > F$ ---------------		
4b	2000	EZ-1	9.86	9.84	0.26	0.01	0.50
		EZ-2	9.60	9.71			
		EZ-3	9.40	9.58			
		ECZ-1	9.49	9.59	0.25	0.22	0.43
		ECZ-2	9.61	9.92			
		ECZ-3	9.62	9.70			
		EECZ-1	9.69	9.72	0.11	0.46	0.23
		EECZ-2	9.42	9.82			
		EECZ-3	9.57	9.57			
		EECSZ-2	9.59	9.79	0.07	0.59	0.46
		EECSZ-3	9.61	9.70			
4b$_2$	2002	EZ-1	12.32	12.38	0.11	0.01	0.09
		EZ-2	11.96	12.26			
		EZ-3	11.57	11.98			
		ECZ-1	12.07	12.25	0.18	0.41	0.90
		ECZ-2	11.83	12.15			
		ECZ-3	11.91	12.17			
		EECZ-1	12.14	12.25	0.10	0.05	0.09
		EECZ-2	11.71	12.06			
		EECZ-3	11.77	12.22			
		EECSZ-2	11.91	12.21	0.23	0.67	0.66
		EECSZ-3	12.01	12.21			

Table 22. Soybean yield response to P for zones delineated using different zoning methods.

Field	Year	Zone[†]	Treatment and grain yield		Statistics		
			Check	P	P effect[‡]	Zone[§]	P x Zone[¶]
			------- Mg ha^{-1} ------		---------------- $P > F$ ----------------		
1a	1998	EZ-1	3.41	3.81	0.17	0.08	0.69
		EZ-2	3.05	3.57			
		ECZ-1	2.99	4.63	0.01	0.34	0.03
		ECZ-2	3.46	3.74			
		ECZ-3	3.14	3.62			
		EECZ-1	2.74	3.20	0.20	0.03	0.98
		EECZ-2	3.35	3.74			
		EECZ-3	3.39	3.84			
		EECSZ-2	3.33	3.60	0.03	0.21	0.11
		EECSZ-3	3.33	4.00			
		EECSZ-4	3.14	3.56			
1a$_2$	2000	EZ-1	2.73	2.90	0.01	0.09	0.12
		EZ-2	2.10	2.75			
		ECZ-1	2.14	2.77	0.04	0.86	0.85
		ECZ-2	2.35	2.80			
		ECZ-3	2.33	2.64			
		EECZ-1	2.24	2.78	0.01	0.80	0.67
		EECZ-2	2.19	2.60			
		EECZ-3	2.40	2.62			
		EECSZ-2	2.20	2.48	0.03	0.15	0.94
		EECSZ-3	2.46	2.93			
		EECSZ-4	2.44	2.79			
2b	1999	EZ-1	3.21	3.71	0.03	0.01	0.15
		EZ-2	1.65	1.74			
		EZ-3	3.02	3.50			
		ECZ-1	3.21	3.64	0.01	0.01	0.59
		ECZ-2	1.99	2.31			
		EECZ-1	3.07	3.67	0.12	0.01	0.54
		EECZ-2	2.02	2.32			
		EECSZ-1	3.11	3.23	0.06	0.02	0.30
		EECSZ-3	3.04	3.62			
		EECSZ-4	1.76	2.06			

[†] EZ, elevation zones; ECZ, apparent electrical conductivity zones; EECZ, elevation and EC$_a$ zones; EECSZ, elevation, EC$_a$, and slope zones.

[‡] Probability of the main P effect.

[§] Probability of the zone effect.

[¶] Probability of the interaction between the P effect and the zone effect.

Table 22 (cont.)

			Treatment and grain yield		Statistics		
Field	Year	Zone	Check	Fixed	P effect	Zone	P x Zone
			------- Mg ha^{-1} ------		---------------- $P > F$ ----------------		
$2b_2$	2001	EZ-1	2.29	3.10	0.05	0.04	0.04
		EZ-2	2.06	2.14			
		EZ-3	2.51	3.18			
		ECZ-1	2.54	2.98	0.03	0.03	0.27
		ECZ-2	2.21	2.38			
		EECZ-1	2.41	3.24	0.01	0.26	0.53
		EECZ-2	2.50	3.05			
		EECSZ-1	2.40	3.23	0.03	0.08	0.14
		EECSZ-3	2.49	3.05			
		EECSZ-4	2.15	2.15			
3b	2000	EZ-1	3.09	3.18	0.14	0.37	0.15
		EZ-2	2.96	3.21			
		ECZ-1	3.11	3.24	0.12	0.04	0.76
		ECZ-2	3.01	3.22			
		ECZ-3	3.01	3.16			
		EECZ-1	3.06	3.19	0.15	0.51	0.81
		EECZ-2	3.04	3.22			
		EECZ-3	2.98	3.17			
		EECSZ-2	3.08	3.22	0.20	0.43	0.78
		EECSZ-4	3.02	3.25			
$3b_2$	2002	EZ-1	3.07	3.48	0.38	0.08	0.88
		EZ-2	2.89	3.33			
		ECZ-1	3.01	3.42	0.26	0.33	0.56
		ECZ-2	2.83	3.40			
		ECZ-3	3.04	3.39			
		EECZ-1	3.08	3.51	0.37	0.04	0.54
		EECZ-2	2.84	3.34			
		EECZ-3	2.98	3.32			
		EECSZ-2	3.15	3.39	0.51	0.26	0.24
		EECSZ-4	2.86	3.40			

Table 22 (cont.)

			Treatment and grain yield		Statistics		
Field	Year	Zone	Check	Fixed	P effect	Zone	P x Zone
			------- Mg ha^{-1} ------		---------------- $P > F$ ----------------		
4a	1999	EZ-1	3.71	3.74	0.58	0.01	0.80
		EZ-2	3.68	3.73			
		EZ-3	3.56	3.64			
		ECZ-1	3.51	3.71	0.42	0.08	0.24
		ECZ-2	3.69	3.70			
		ECZ-3	3.59	3.71			
		EECZ-1	3.70	3.74	0.40	0.01	0.13
		EECZ-2	3.58	3.74			
		EECZ-3	3.62	3.65			
		EECSZ-2	3.61	3.71	0.50	0.08	0.19
		EECSZ-3	3.69	3.72			
$4a_2$	2001	EZ-1	2.54	2.44	0.42	0.01	0.25
		EZ-2	2.23	2.31			
		EZ-3	2.15	2.06			
		ECZ-1	2.18	2.16	0.25	0.22	0.39
		ECZ-2	2.33	2.39			
		ECZ-3	2.29	2.32			
		EECZ-1	2.41	2.38	0.59	0.01	0.98
		EECZ-2	2.24	2.22			
		EECZ-3	2.14	2.11			
		EECSZ-2	2.23	2.23	0.55	0.07	0.53
		EECSZ-4	2.38	2.31			

Table 23. Corn grain yield response to K within different soil-test K interpretation classes according to the 1.0-ha (GC) approach.

Field	Year	STK class†	Treatment and grain yield		Statistics
			Check	K	
			------ Mg ha^{-1} ------		$P > F$
5b	2001	L	10.28	10.48	0.42
		Opt	10.26	10.52	0.18
6b	2000	L	8.99	9.29	0.16
		Opt	8.64	8.90	0.14
6b$_2$	2002	L	11.48	11.99	0.02
7a	1999	L	9.99	11.02	0.05
		Opt	9.84	11.23	0.06
		H	10.58	11.73	0.31
7a$_2$	2001	L	8.95	10.33	0.04
		Opt	10.03	10.89	0.36

† STK class, soil-test K classes. L, Low; Opt, Optimum; H, High.

Table 24. Soybean grain yield response to K within different soil-test K interpretation classes according to the 1.0-ha (GC) approach.

			Treatment and grain yield		
Field	Year	STK class†	Check	K	Statistics
			------ Mg ha^{-1} ------		$P > F$
5a	2000	L	3.15	3.20	0.25
		Opt	3.09	3.14	0.32
5b$_2$	2002	L	3.73	3.99	0.04
		Opt	3.79	3.99	0.09
		H	3.79	3.92	0.14
6a	1999	L	3.10	3.15	0.66
		Opt	3.24	3.22	0.35
6a$_2$	2001	L	3.35	3.59	0.01
7b	2000	L	2.98	3.16	0.08
		Opt	2.92	3.09	0.48
		H	3.16	3.21	0.87
7b$_2$	2002	L	3.21	3.35	0.22
		Opt	3.14	3.11	0.79

† STK class, soil-test K classes. L, Low; Opt, Optimum; H, High.

Table 25. Corn grain yield response to K for field areas with different soil series.

			Treatment and grain yield		Statistics		
Field	Year	Soil series	Check	K	K[†]	Soil[‡]	K x soil[§]
			-------- Mg ha^{-1} ----------		----------- $P > F$ ----------		
5b	2001	Donnan	10.37	10.47	0.23	0.01	0.67
		Klinger	10.58	10.79			
		Kenyon	10.01	10.37			
6b	2000	Dinsdale	8.56	8.87	0.04	0.33	0.61
		Klinger	9.03	9.02			
		Kenyon	8.17	8.89			
6b$_2$	2002	Dinsdale	11.58	12.20	0.03	0.17	0.63
		Klinger	11.60	11.85			
		Kenyon	11.13	11.57			
7a	1999	Tama	10.21	10.93	0.05	0.19	0.01
		Colo-Ely	10.06	11.42			
7a$_2$	2001	Tama	9.58	10.40	0.05	0.01	0.01
		Colo-Ely	8.67	10.36			

[†] K effect; probability level of the K main effect.

[‡] Soil; probability level of the soil series approach.

[§] probability level of the K by soil interaction.

Table 26. Soybean grain yield response to K for field areas with different soil series.

Field	Year	Soil series	Treatment and grain yield		Statistics		
			Check	K	K[†]	Soil[‡]	K x soil[§]
			------ Mg ha^{-1} -----		----------- P > F ---------		
5a	2000	Donnan	3.06	3.07	0.63	0.01	0.07
		Klinger	3.27	3.21			
		Kenyon	3.01	3.15			
5a$_2$	2002	Donnan	3.81	3.99	0.14	0.01	0.95
		Klinger	3.80	3.99			
		Kenyon	3.67	3.87			
6a	1999	Dinsdale	3.18	3.23	0.12	0.03	0.40
		Klinger	3.34	3.25			
		Kenyon	3.07	3.13			
6a$_2$	2001	Dinsdale	3.33	3.60	0.01	0.48	0.63
		Klinger	3.41	3.59			
		Kenyon	3.30	3.53			
7b	2000	Tama	3.05	3.25	0.13	0.01	0.22
		Colo-Ely	2.96	3.04			
7b$_2$	2002	Tama	3.28	3.35	0.26	0.08	0.24
		Colo-Ely	3.16	3.33			

[†] K effect; probability of the K main effect.

[‡] Soil; probability of the soil series approach.

[§] probability level of the K by soil interaction.

Table 27. Corn yield response to K for zones delineated using different zoning methods.

			Treatment and grain yield		Statistics		
Field	Year	Zone†	Check	K	K effect‡	Zone§	K x Zone¶
			-------- Mg ha^{-1} --------		------------------ $P > F$ ----------------		
5b	2001	EZ-1	10.24	10.45	0.18	0.32	0.70
		EZ-2	10.30	10.58			
		ECZ-1	10.19	10.40	0.22	0.39	0.86
		ECZ-2	10.28	10.53			
		EECZ-1	10.33	10.59	0.18	0.15	0.90
		EECZ-2	10.32	10.60			
		EECZ-3	10.16	10.55			
		EECSZ-1	10.49	10.46	0.40	0.01	0.74
		EECSZ-2	10.04	10.33			
		EECSZ-3	10.40	10.66			
6b	2000	EZ-1	8.79	8.99	0.14	0.01	0.32
		EZ-2	8.38	8.84			
		ECZ-1	8.53	8.84	0.14	0.01	0.69
		ECZ-2	9.01	9.18			
		EECZ-1	8.11	8.67	0.20	0.01	0.51
		EECZ-2	8.80	8.97			
		EECZ-3	8.93	9.14			
		EECSZ-1	8.14	8.71	0.13	0.01	0.44
		EECSZ-2	8.92	8.96			
		EECSZ-3	8.93	9.19			
6b$_2$	2002	EZ-1	11.53	12.20	0.01	0.03	0.01
		EZ-2	11.36	11.55			
		ECZ-1	11.49	11.96	0.02	0.76	0.66
		ECZ-2	11.47	12.07			
		EECZ-1	11.10	11.37	0.01	0.01	0.48
		EECZ-2	11.65	12.21			
		EECZ-3	11.54	12.15			
		EECSZ-1	11.17	11.49	0.01	0.01	0.59
		EECSZ-2	11.63	12.20			
		EECSZ-3	11.54	12.16			

† EZ, elevation zones; ECZ, apparent electrical conductivity zones; EECZ, elevation and EC$_a$ zones; EECSZ, elevation, EC$_a$, and slope zones.

‡ Probability of the main K effect.

§ Probability of the zone effect.

¶ Probability of the interaction between the K effect and the zone effect.

Table 27 (cont.)

Field	Year	Zone	Treatment and grain yield		Statistics		
			Check	K	K effect	Zone	K x Zone
			---------- Mg ha^{-1} ---------		---------------- *P* > *F* -----------------		
7a	1999	EZ-1	10.43	11.28	0.04	0.01	0.25
		EZ-2	9.93	11.19			
		EZ-3	9.55	10.87			
		ECZ-1	9.97	11.18	0.05	0.98	0.54
		ECZ-2	10.04	11.11			
		EECZ-1	10.25	11.20	0.05	0.01	0.51
		EECZ-2	10.06	11.31			
		EECZ-3	9.63	10.82			
		EECSZ-1	10.06	11.32	0.05	0.22	0.53
		EECSZ-2	9.70	11.01			
		EECSZ-3	10.04	11.17			
		EECSZ-4	10.22	11.07			
$7a_2$	2001	EZ-1	9.61	10.50	0.04	0.01	0.02
		EZ-2	8.74	10.46			
		EZ-3	8.81	10.09			
		ECZ-1	8.80	10.36	0.04	0.05	0.09
		ECZ-2	9.28	10.40			
		EECZ-1	9.42	10.37	0.05	0.18	0.04
		EECZ-2	8.76	10.48			
		EECZ-3	9.01	10.25			
		EECSZ-1	8.62	10.62	0.06	0.02	0.04
		EECSZ-2	8.70	10.20			
		EECSZ-3	9.19	10.39			
		EECSZ-4	9.61	10.41			

Table 28. Soybean yield response to K zones delineated using different zoning methods.

			Treatment and grain yield		Statistics		
Field	Year	Zone†	Check	K	K effect‡	Zone§	Kx Zone¶
			--------- Mg ha^{-1} --------		------------------ $P > F$ ----------------		
5a	2000	EZ-1	3.03	3.08	0.29	0.01	0.88
		EZ-2	3.20	3.24			
		ECZ-1	3.15	3.19	0.35	0.27	0.87
		ECZ-2	3.10	3.15			
		EECZ-1	3.32	3.29	0.53	0.01	0.48
		EECZ-2	3.15	3.20			
		EECZ-3	2.98	3.05			
		EECSZ-1	2.93	3.12	0.08	0.13	0.15
		EECSZ-2	3.09	3.19			
		EECSZ-3	3.15	3.16			
5a$_2$	2002	EZ-1	3.79	3.98	0.06	0.57	0.34
		EZ-2	3.78	4.02			
		ECZ-1	3.67	3.93	0.05	0.01	0.53
		ECZ-2	3.81	4.01			
		EECZ-1	3.68	3.99	0.04	0.02	0.55
		EECZ-2	3.83	4.03			
		EECZ-3	3.74	3.94			
		EECSZ-1	3.66	3.91	0.03	0.01	0.04
		EECSZ-2	3.69	4.01			
		EECSZ-3	3.87	4.02			
6a	1999	EZ-1	3.24	3.25	0.25	0.04	0.35
		EZ-2	3.18	3.13			
		ECZ-1	3.19	3.17	0.72	0.01	0.71
		ECZ-2	3.31	3.32			
		EECZ-1	3.16	3.08	0.32	0.25	0.22
		EECZ-2	3.21	3.31			
		EECZ-3	3.30	3.22			
		EECSZ-1	3.18	3.05	0.35	0.23	0.42
		EECSZ-2	3.16	3.29			
		EECSZ-3	3.47	3.22			

†EZ, elevation zones; ECZ, apparent electrical conductivity zones; EECZ, elevation and EC$_a$ zones; EECSZ, elevation, EC$_a$, and slope zones.

‡Probability of the main K effect.

§Probability of the zone effect.

¶Probability of the interaction between the K effect and the zone effect.

Table 28 (cont.)

			Treatment and grain yield		Statistics		
Field	Year	Zone	Check	K	K effect	Zone	K x Zone
			-------- Mg ha^{-1} -------		------------------ $P > F$ -----------------		
6a$_2$	2001	EZ-1	3.36	3.60	0.01	0.42	0.56
		EZ-2	3.34	3.56			
		ECZ-1	3.35	3.58	0.01	0.70	0.73
		ECZ-2	3.35	3.61			
		EECZ-1	3.33	3.55	0.01	0.68	0.64
		EECZ-2	3.35	3.59			
		EECZ-3	3.36	3.61			
		EECSZ-1	3.33	3.56	0.01	0.51	0.90
		EECSZ-2	3.35	3.59			
		EECSZ-3	3.38	3.63			
7b	2000	EZ-1	3.07	3.18	0.10	0.05	0.38
		EZ-2	2.99	3.13			
		EZ-3	2.91	3.16			
		ECZ-1	2.99	3.12	0.10	0.49	0.25
		ECZ-2	2.98	3.18			
		EECZ-1	3.02	3.15	0.13	0.57	0.53
		EECZ-2	2.97	3.12			
		EECZ-3	2.96	3.20			
		EECSZ-1	2.98	3.21	0.10	0.07	0.76
		EECSZ-2	2.93	3.09			
		EECSZ-3	2.94	3.18			
		EECSZ-4	3.06	3.22			
7b$_2$	2002	EZ-1	3.22	3.28	0.19	0.29	0.29
		EZ-2	3.21	3.35			
		EZ-3	3.22	3.42			
		ECZ-1	3.19	3.33	0.23	0.34	0.40
		ECZ-2	3.24	3.34			
		EECZ-1	3.23	3.33	0.26	0.01	0.39
		EECZ-2	3.14	3.31			
		EECZ-3	3.29	3.40			
		EECSZ-1	3.23	3.29	0.25	0.46	0.30
		EECSZ-2	3.16	3.37			
		EECSZ-3	3.25	3.38			
		EECSZ-4	3.28	3.34			

CHAPTER 4.

GENERAL CONCLUSIONS

The overall objective of this research was to address the issue of within-field yield and yield response to fertilizer variability from two different perspectives. One study focused on how several soil, crop and other variables are related and what is the effect of these relationships in explaining the yield variability for a particular crop. Specific objectives of this study were (1) to study the relationships between several crop and soil variables using multivariate factor analysis and principal components analysis and (2) to determine their importance in explaining soybean yield variability in several Iowa fields. A second study recognized that within-field variability in yield and yield response to fertilizer occur, and that zones with different soil-test levels and potential response to fertilization can be identified based on selected terrain and stable soil properties. Specific objectives of this study were (1) to compare various zoning approaches for soil sampling and assess their efficacy on the basis of measured corn and soybean yield response to P and K within zones delineated by each approach.

In the first study, five soybean fields were selected and various soil and crop variables were measured at locations following a dense grid-point sampling approach. Many site variables were correlated but the correlations vary greatly and often were not consistent across fields. Using multivariate techniques provided a rationale framework to group correlated variables into at least three common factors in all fields. One factor grouped variables strongly related to early growth conditions (usually early growth, and early P and K uptake). A second factor represented the interaction between soil properties not likely to be affected in the short term by soil management practices (usually soil texture, CEC). A third factor grouped soil variables that reflected P and K availability and, in some fields, their interaction with soil pH. A few new variables representing these groups of correlated variables (latent variables) explained 10-65% of soybean yield variability and their relative importance in explaining yield variability varied across fields. Principal component analysis also was useful to understand relationships among many site variables but its use to explain yield variability was not as straightforward. The results of this study showed that seldom single site variables can explain yield variability and that use of a multivariate approach that considers the interrelation between variables is more appropriate.

In the second study, a 1.0 ha grid cell sampling approach and several approaches were used to delineate sampling zones using attributes such as elevation, soil electrical conductivity, slope, and soil series in several fields. A dense grid-sampling approach (0.08 to 0.24-ha) was used as a base to calculate soil-test P and K levels for each zoning method. The yield response to P or K was evaluated for each zoning approach. This study showed that most zoning approaches usually identified areas of high and low yields for most of the cropping years of this study. Zones based on elevation and (or) soil electrical conductivity were usually the most efficient in identifying zones with different yield. However, these zones seldom detected differences in soil-test P or K that were observed with the two grid sampling approaches. Moreover, crop response to P and K fertilization seldom differed across field zones, which agrees with usually similar mean soil-test values across zones. A 1.0-ha grid-cell sampling approach detected differences in soil-test P and K in most fields and was more useful to identify field areas with different response. We believe that long histories of P and K fertilization of originally low-testing fields drastically reduced the impact of several intrinsic soil properties on within-field soil-test variation. Because yield potential and removal of P and K is an important element for P and K fertilizer management, these zoning approaches based on elevation and (or) soil electrical conductivity would be useful in the long term to establish zones with different potential P or K removal when it is used in conjunction with yield maps.

Overall, the results of these two studies showed that complex combinations of site variables influence crop yield, and that multivariate analysis techniques are useful to identify group of correlated variables that may influence yield in different ways across fields. However, the short term response to P or K fertilizer was related to soil-test levels of these nutrients independently of the variation in many soil properties. Zoning approaches for soil sampling based on inherent terrain or soil properties were not effective in identifying field areas with different soil-test values and crop yield response that were identified by grid-sampling approaches. These results were explained by long histories of P and K fertilization that probably reduced the impact of inherent soil properties on soil-test values.

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