VARIABLE-RATE LIMING FOR THE CORN-SOYBEAN ROTATION

Agustin A. Bianchini and Antonio P. Mallarino

ABSTRACT

Precision agriculture technologies and a strip trial methodology were used to study soil sampling for pH and variable-rate liming for soybean [*Glycine max* (L.) Merr.]-corn (*Zea mays* L.) rotations in two fields with soils of the Clarion (Typic Hapludoll)-Nicollet (Aquic Hapludoll)-Webster (Typic Endoaquoll) association. Treatments applied to replicated long (624 or 900 m) and narrow (18 or 24 m) strips were a control, a fixed lime rate, and a variable lime rate based on grid soil sampling scheme. Soil pH data from samples collected from 0.1-ha cells, aerial photos, and soil survey, elevation, and electrical conductivity maps were used to simulate less intensive sampling schemes, which included sampling of larger cells, soil map units, and management zones. Soil pH (15-cm depth) across the grid points ranged from 5.4 to 8.4 in both fields, and most subsoils were calcareous. Crop yield was harvested with yield monitors in three years for one field and two years for the other. There was only a small response to lime (230 kg ha^{-1} of corn) in one year of one field, and application method did not differ. Yield and pH were negatively correlated in years with excessive rainfall, but positively (for corn) or not correlated (for soybean) in other years. Significantly less lime (56% in one field and 61% in the other) was applied with the variable-rate method. The little or no response to lime and to application method may be explained by a usually high subsoil pH and very high small-scale pH variation. Less intensive sampling schemes would have identified smaller acid and alkaline areas. Variable-rate liming based on any of the sampling strategies considered in this study would apply less lime than the fixed rate method in this soil association. However, the results showed that no lime would be needed in similar soils when topsoil pH is 5.4 or higher.

Abbreviations: CCE, calcium carbonate equivalent; DGPS, differential global positioning system; EC, electrical conductivity; ECCE, effective calcium carbonate equivalent; VRT, variable rate technology.

INTRODUCTION

The value of liming acid soils to increase soil pH to values optimal for crops is well known (Adams, 1984; Black, 1993). McLean and Brown (1984) presented and discussed in a detailed review the beneficial effects of lime in corn and soybean for the United States (U.S.) Corn Belt. Soil testing for pH and other nutrients is a useful tool, but field sampling error generally is large, and larger than chemical analysis error (Cline, 1944). Assessing variability appropriately is a critical first step in precision agriculture (Pierce and Nowak, 1999). High variability in soil test pH, P and K is often observed in farmer's fields (Bullock et al., 1994; Cahn, 1994; Cambardella et al., 1994; Fixen and Reetz, 1995; McGraw and Hemb, 1995; Pierce et al., 1995; Mallarino, 1996). Characteristics of Ca, P, and K in soils suggest that liming and P and K fertilization are very conducive to precision management because residuality of liming or fertilization is high and temporal variability is low compared to N (Rehm et al., 1996; Pierce and Nowak, 1999). The patterns or variability for these nutrients are not always related to soil map units because fertilization and liming often have increased soil test values and created new patterns of variability (Franzen and Peck, 1995; Mallarino and Wittry, 1998). Fields where fertilizers have been banded or where high rates of nutrients and manure were used show large nutrient variability (Peck and Melsted, 1973; Mallarino, 1996). Small scale cyclic patterns (1 m or less) result from banded fertilizer or manure applications, whereas larger scale cyclic trends (15-18 m) result from broadcast fertilization or manuring with commercial bulk spreaders (Mallarino, 1996).

Different sampling techniques can be used to collect soil samples from fields. Grid soil sampling began to be used in the early 1990s in the Corn Belt, and it refers to a process whereby a field is divided into many smaller cells for sampling purposes. The results of analyses are combined with geographical coordinates of each sample to create maps (Pocknee et al., 1996). The sampling intensity required for effective use of variable rate technology (VRT) is not clearly defined and may be different for different soil tests, fields, and geographic regions. Soil sampling for pH, P, and K based on square 1-ha grids were in use in the Corn Belt (Sawyer, 1994). Research (Wollenhaupt et al., 1994; Franzen and Peck, 1995) showed that grid point soil sampling at densities of 0.4 and 0.1 ha further increase soil test mapping accuracy. Mallarino (1996) and Rehm et al. (1996) found that variability of soil test P or K within grid cells of that size can be as great as variability across an entire field. Moreover, others (Wollenhaupt et al., 1994; Mallarino, 1996) found that soil sampling of square grids may lead to loss of spatial variability information if the soil test patterns are long and narrow or if patterns tend to follow cycles.

Zone sampling has recently been suggested to reduce sampling costs while maintaining a reasonably good information about nutrient levels. Sampling by zone assumes that sampling areas can be identified on the basis of zones with different soil or crop characteristics across a field and that patterns are likely to remain temporally stable (Franzen et al., 2000). Criteria used to delineate management zones vary. Topography and soil and crop canopy images can be used to identify management zones because they may reflect different soil properties, are noninvasive, and may be of low cost (Mulla and Schepers, 1997; Franzen et al., 1998; Schepers et al., 2000). Soil electrical conductivity (EC), which can be estimated using noninvasive electromagnetic induction methods, has been useful to estimate topsoil depth (to a claypan or other root growth limiting layer), physical and chemical soil properties, and to explain yield variability (Doolittle et al., 1994; Kitchen et al., 1999; Kitchen et al., 2000; Myers et al., 2000). Yield maps can be used to define different soil productivity areas that together with other layers of information can be used as a basis for variable-rate fertilization (Stafford et al., 1999; Bronson et al., 2000). Colvin et al. (1997) concluded, however, that stable within-field yield patterns may be observed in some fields but not in others.

Benefits from using VRT may include larger yield increases on low-testing or acid soils and fertilizer or lime savings by decreasing application rates on high-testing soils (Sawyer, 1994; Pierce and Nowak, 1999). Large soil test variation within fields pose the problem of determining whether a single fertilizer recommendation can be prescribed for the entire field or whether the variation is so large that different recommendations are required for different parts of the field (Peck and Melsted, 1973). The keys for profitable variable-rate liming are accurate and precise preparation of the lime application map, accurate application control, and a sufficient crop response to offset likely higher soil sampling and application costs (Pierce and Warncke, 2000). Bongiovanni and Lowenberg-DeBoer (2000) simulated crop yield using corn and soybean soil pH response functions from small-plot data and predicted larger annual returns with site-specific pH management. Soil test data from a 8.8 ha field sampled by Borgelt et al. (1994) suggested (crop response was not measured) that 3.4 to 4.5 Mg ha^{-1} of lime were needed, and that a uniform rate would have resulted in over-liming of 9-12 % of the field and under-liming of 37-41% of the field. Mulla et al. (2000) used pH and buffer pH from soil samples collected from a 12 ha field using four sampling strategies (9 x 9 m grids, 18 x 18 m grids, 1-ha grids, and a targeted sampling strategy based on near infrared reflectance images of bare soil and soybean canopy). The two most intensive grid sampling strategies identified acid areas of 1.3 and 3.4 ha respectively, the 1-ha grid strategy identified no acid areas, and the targeted sampling identified 0.6 ha of acid soil that would have required lime. Heiniger and Meijer (2000) used soil samples collected on 1-ha square grids from four states in the U.S. Coastal Plains to estimate amounts of lime required for uniform or variable-rate application. Based on simulated corn yield response and the soil pH data, they concluded that variable-rate lime application would have resulted in an average profit increase of \$4.03 ha^{-1} compared to the fixed lime rate. Pierce and Warncke (2000) applied five lime treatments on the basis of maps interpolated from soil samples collected from 30.5-, 61-, and 91.5-m grids to small field plots (4.5 by 30.5 m) and found that grid soil sampling on regular grids did not accurately predict site specific soil pH or lime requirements for corn or soybean fields. In this study corn did not respond to lime, but soybean did.

Yield monitor maps and differential global positioning system (DGPS) receivers in the combines can be used to evaluate the effects of VRT and other site-specific management practices (Oyarzabal et al., 1996; Colvin et al., 1997). Treatments are applied to narrow (usually the width is a multiple of the equipment width used to apply the treatments) and long strips (generally the length of the field), and crops are harvested with combines equipped with yield monitors and DGPS receivers. Precision agriculture technologies can be successfully adapted to these types of field trials used for on-farm research (Oyarzabal et al., 1996; Mallarino and Wittry, 1997). However, the yield monitor flow meter data cannot be expected to resolve detailed yield variation over spatial intervals of less than approximately 15 m, and 20 to 25 m may be a more realistic scale of resolution (Lark et al., 1997).

Much of the research on variable-rate liming discussed previously focused on describing soil pH variation using various sampling strategies and simulated responses to lime. Moreover, when lime was applied, yield data were gathered from small plots and not by actually comparing yield response to fixed-rate and variable-rate application using VRT equipment used by farmers. The objectives of this study were to evaluate impact of intensive soil sampling and variable-rate lime application on soil pH and yields of corn and soybean using equipment commonly used in production agriculture, and to implement a management zone sampling method that was compared with other sampling strategies to describe pH values over a field.

MATERIALS AND METHODS

The study was conducted over a 3 year period (1998, 1999 and 2000) in one field (Field 1) and over a 2 year period (1999 and 2000) in the other (Field 2). The two fields were located in Boone County, Iowa, had soils of the Clarion-Nicollet-Webster soil association, and were managed with a two-year corn-soybean rotation. Areas of approximately 15 ha in Field 1 and of 18 ha in Field 2 were selected for the experiments. The width of each experimental area was divided into four blocks measuring 54 m in width in Field 1 and three blocks measuring 72 m in Field 2. The blocks corresponded to the replications of the experimental designs. Each block was further subdivided into strips to fit three treatments. Experimental units were strips 18 m wide and 624 m long in Field 1, and 24 m wide and 900 m long in Field 2. The measurements were done with measuring tape and georeferences were recorded using a hand held differential global positioning system (DPGS) receiver. Treatments were applied once before the first soybean crop was planted, and they were a control, a fixed lime rate, and a variable lime rate based on a surfaced map from a 0.2-ha random grid-point soil sampling scheme (Wollenhaupt and Wolkowski, 1994). Each composite sample was made up of 12 cores collected from a 15-cm depth from an area approximately 80 m^2 in size located randomly within each 0.2 ha cell. Soil samples were dried in a forced-air oven at 35º C, ground to pass a 2-mm screen, and analyzed in duplicates. Soil pH was measured potentiometrically in a slurry using an electronic pH meter (McLean,1982), 1:1 (wt/vol) soil:deionized water ratio, and a 10 min shaking time. Lime requirement was calculated using the SMP buffer method (Shoemaker et al., 1961; Watson and Brown, 1998).

The agricultural lime used had 23% Ca and 2.5% Mg. All material passed through a 4.75-mm screen, 93 % though a 2.36-mm screen, and 34 % though a 0.25-mm screen. The calcium carbonate equivalent (CCE) and the Effective CCE (ECCE) of the lime were determined following the procedure used at the Iowa State University Soil and Plant Analysis Laboratory (SPAL). The State of Iowa and the SPAL use a fineness factor to determine ECCE. Briefly, CCE is measured by adding 43 ml of a HCl solution to 1 g of crushed lime, heating the mixture for 30 minutes, adding 4 to 5 drops of phenolphthalein indicator, and titrating with a NaOH solution. Moisture is determined by drying the lime until constant weight was achieved. The ECCE was calculated with Equation 1.

$$\text{Percent ECCE} = (\text{Fineness factor} \times \text{CCE}) - \%\ \text{moisture} \qquad \text{[Eq. 1]}$$

The lime used had 91% CCE and 53% ECCE. Lime rates were calculated to raise the pH to 6.5 using Equation 2, which is the formula used by Iowa State University (ISU) lime recommendations (Voss et al., 1999).

$$\text{Pounds per acre of ECCE} = [49886 - (7245 \times \text{BpH})] \times [6 \times 0.167] \qquad \text{[Eq. 2]}$$

No lime was applied by the variable-rate treatment where pH was at or above 6.3 as suggested by Voss et al. (1999). The fixed rates were 5.8 Mg CCE ha^{-1} in Field 1 and 4.6 Mg CCE ha^{-1} in Field 2, and the variable rates ranged from 0 to 8.2 Mg CCE ha^{-1} in both fields. The ECCE fixed rates were 3.4 Mg ha^{-1} in Field 1, 2.7 Mg ha^{-1} in Field 2, and the variable rates ranged from 0 to 4.8 Mg ha^{-1} in both fields.

The fixed rates were not decided on the basis of average soil pH of the fields. They were rates normally used by the cooperative and the farmers for this soil association. The lime was applied with a commercial broadcast spreader equipped with a variable-rate controller and a DGPS receiver and was incorporated to a 15-cm depth by chisel plowing and disking. Uniform rates of N, P and K were applied by the farmer following local recommendations.

A set of soil samples was collected immediately before the lime application from all treatment strips using a more intensive method than the one used to decide the lime application rates. The objective of this sampling was to have an estimate of initial pH from the same points that would be sampled in the future to evaluate the impact of the lime treatments over time. For Field 1, soil samples were taken in Spring 1998 (the day before liming), Fall 1998 (November), Fall 1999 (November), and Fall 2000 (October). For Field 2, samples were taken in Fall 1998 (the day before liming), Fall 1999 (November), and Fall 2000 (November). Composite samples (12 cores, 15 cm depth) were collected using a systematic grid whose layout followed the field design. The sampling area at each point was approximately 25 m^2 in size located at the center of each of 144 cells in Field 1 and 180 cells in Field 2. The width of each cell coincided with the width of each strip (18 m in Field 1 and 24 m in Field 2) and the length along the strips (and along crop rows) was 52 m in Field 1 and 45 m in Field 2. Thus, the area represented by each sample approximately corresponded to 0.1-ha cells of a grid-point sampling scheme (0.09 ha in Field 1 and 0.11 ha in Field 2).

Composite subsoil samples (three 5-cm diameter cores) were also collected in Fall 1998 from representative areas of each soil survey map unit of both fields (Andrews and Dideriksen, 1981). Fourteen areas were sampled in Field 1 and 23 were sampled in Field 2. Each core was collected to a 91-cm depth and was divided into six 15-cm sections. Soil samples were analyzed for pH, and samples with pH higher than 7.6 were analyzed for calcite and dolomite (Dreimanis, 1962). A percent CCE was calculated from the calcite and dolomite data. In Spring 2000, topsoil samples also were collected along eight transects of selected strips that received the fixed-rate and variable-rate treatments (two fields, two treatments, and two replications). Composite soil samples (8 cores at 15-cm depth from a 4.5-m^2 area) were collected using a 6-m spacing. The transects measured 142-m long in Field 1 and 135-m in Field 2. These samples were analyzed for soil pH.

Grain yield was measured and recorded using combines equipped with impact flow-rate yield monitors (Ag-Leader Technology, 2202 S. Riverside, Ames, IA 50010) and real time DGPS receivers. The monitors recorded yield every 9 s in 1998 and 1999, and every s in 2000. Grain moisture was determined on-the-go by a sensor located in the combine auger. Reported grain yields were corrected to 155 g kg^{-1} for corn and 130 g kg^{-1} for soybean. The yield data were unaffected by field borders because the experimental areas were located at least 90 m from any border. One to two combine passes were used for each soybean treatment strip and two to four passes were used for corn strips. Each combine pass (6.1-m swath in corn fields and 9.1-m swath in soybean fields) was identified with a unique number that was recorded with the georeferenced yield data. The few combine passes that included a mixture of two treatments were deleted and not used in the analyses. The raw yield data recorded by the monitors were exported into ArcView GIS (Environmental Systems Research Institute, Redlands, CA 92373), and carefully analyzed for errors that commonly occur when using yield monitors. This yield map cleaning involved deleting yield points that corresponded to border passes and end rows, and those with obvious problems with grain flow, grain moisture, distance, and header width. In addition, small problematic areas of the field that could obviously affect treatment comparisons (i.e. potholes on wet years that were flooded) were also deleted. The next step was the cell average calculation, which was done by averaging all the yield points that were inside each sampling cell using ArcView GIS. The cell average data was used for yield analysis. Yield, soil pH, and other data were exported from ArcView GIS for analysis with SAS statistical package (SAS Institute, Cary, NC).

Simulations of soil sampling schemes (less intensive than the 0.1 ha grid sampling) were conducted on the basis of this initial 0.1-ha soil sampling. This methodology was previously developed and used by others (Franzen and Peck, 1995; Mulla et al., 2000; Pierce and Warncke, 2000. The simulated sampling schemes were 0.3-ha grid cell, 0.3-ha grid-point, 0.7-ha grid cell, 0.7-ha grid-point, soil map unit sampling, and management zone. A vector map with associated information for each sampling scheme was created using ArcView GIS software either by creating polygons (for the 0.3-, and 0.7-ha grids, and soil map schemes) or by using available layers of information (for the management zone scheme). The 0.3-ha grid-cell data were calculated by averaging the point data for three contiguous cells across each row of cells. The 0.3-ha grid-point data were identified by selecting the point data from the center cell of the same three cells. The 0.7-ha grid-cell data were calculated by averaging the point data for eight contiguous cells in Field 1 (four cells across strips and two along strips) and six contiguous cells in Field 2 (three cells across strips and two along strips). The 0.7-ha grid-point data were identified by randomly selecting the point data from one of the center cells (four center cells in Field 1 and two center cells in Field 2). The soil map sampling scheme simulation was done by calculating the average pH of all the 0.1-ha sampling points that were within each soil map unit.

Several information layers were used to create the management zones map and, as an example, several layers used for Field 2 are shown in Fig. 1. Yield maps from previous years (two soybean and one corn yield map for Field 1, and one soybean and one corn yield map for Field 2) were used to create one yield zone map for each field. In a first step, areas of equal yield in yield maps from each individual year were delineated. In a second step, the maps from each year were overlaid using ArcView GIS and a unique map was created for each field (seven yield zones in Field 1 and six in Field 2). Areas in this map were not necessarily high or low yielding because the yield ranking over time for these areas changed. An Order I soil survey map (Andrews and Dideriksen, 1981) also was used to create the management zones map. In 1998, a vehicle with a high precision DGPS receiver and electromagnetic induction sensors (Veris 3100 (Veris Technologies, 601 N. Broadway, Salina, KS) and EM-38 (Geonics Limited, 1745 Meyerside Drive, Ontario, Canada)) was driven once over both fields to measure and record altitude and EC for approximately 320 positions ha^{-1}. Those measurements were imported into ArcView GIS to create an elevation map and EC map with four elevation and EC zones in each field, which were used as additional layers of information for the management zone scheme. A 1-m resolution georeferenced color aerial photo of the soybean canopy was taken from both fields in June of one year to help create the management zone through visual observations of registered images. All these layers of information were used to create nine management zones for Field 1 and six for Field 2. The pH data for each management zone were calculated by averaging corresponding sampling points of the 0.1-ha cells using ArcView GIS. These means should be approximately similar to the values that would have been obtained by a field sampling procedure that takes similar numbers of composite samples and cores from each zone.

Soil pH data for the different sampling schemes were compared by observation of several descriptive statistics and GIS maps. The area of the field represented by each pH class was calculated for all seven strategies to determine how the schemes would have estimated the size of the area that should receive lime. The two lower pH classes were merged together in one class that corresponded to pH values below 6.3 to represent in one class the area that would have been limed according to each sampling scheme. Average soil pH and SD were determined for the soil map unit, large grid, and management zone schemes and also for the components used to determine the management zones (yield, elevation, and EC). The objective was to determine which of the components of the management zone strategy used had more weight, more variation in the SD within zones, and better described soil pH variability.

The yield responses were analyzed using three statistical procedures. One procedure assumed a randomized complete block design (RCBD) without considering the spatial correlation of yield. The yield data input for this procedure were yield means of each strip (the experimental units). In a second procedure, the spatial correlation of yields was accounted for in the RCBD analysis of variance using nearest neighbor analysis (NNA). Adjusting for spatial correlation or other techniques can reduce experimental error and can make the analysis more sensitive in discerning treatment differences. Previous studies have shown the advantages of using NNA to adjust spatially correlated data in different ways (Hinz, 1987; Bhatti et al., 1991; Hinz and Lagus, 1991; Stroup et al., 1994; Mallarino et al., 1998). In this experiment, NNA was used when calculating the yield residuals by subtracting each yield observation from the mean value of its neighbors and including the residuals as a covariate in the analysis of variance. Four neighbors (one from each N, S, E, and W direction) were used for this study, because previous findings in our research group (A.P. Mallarino and P.N. Hinz, Department of Statistics, Iowa State University, personal communication) found that for this type of study using four neighbors was the most effective in reducing standard errors of treatment means than using up to 12 neighboring observations. The yield input data for this analysis were means of small areas of a width defined by each combine pass (6.1 m for corn and 9.1 m for soybean) and 17.3 (soybean 2000), 22.5 (corn 2000), 45 (soybean 1999), or 52 m (soybean 1998 and corn 1999) in the direction along the crop rows. The individual yield data recorded by yield monitors were not directly considered because of their known lack of accuracy over short distances (Lark et al., 1997).

The third procedure assessed treatment effects separately for parts of the experimental areas with different soil test values following a procedure described by Oyarzabal et al. (1996) and Mallarino et al. (2001). The yield and soil-test input data were means for areas defined by the 0.1-ha point cells. Each yield value was classified according to four soil pH classes (<5.7, 5.7-6.2, 6.3-7.2, and >7.2), that were arbitrarily created using the 0.1-ha point cell initial pH data. The pH 6.3 was used because no lime was applied above this value with VRT. The minimum number of cells for the same pH class was 13 and the maximum was 61. The ANOVA included estimates of soil-test class and interaction treatments by soil-test class effects. The soil-test classes were considered as repeated measures within the experimental units. A significant interaction between soil-test class by treatment (i.e. application method) suggests that treatment effects differed for areas of the field with different soil-test levels. When the interaction was significant, an additional ANOVA estimated the significance of treatment effects for each soil-test class.

The effect produced by the lime application on soil pH was evaluated by ANOVA (RCBD) of pH data from each 0.1-ha sampling point and sampling date. Treatment effects on soil pH were also analyzed for the four pH classes mentioned above. Data from both fields were also pooled to determine the pH change for the four pH classes and was determined by the difference between the soil pH data from the initial sampling date (Spring 1998 for Field 1, and Fall 1998 for Field 2) and the final sampling date (Fall 2000 for both fields).

RESULTS AND DISCUSSION

Lime Effects on Soil pH

Large areas received no lime when the variable rate method was used, so the total lime usage was drastically reduced compared to the fixed-rate method. The variable-rate treatment applied 56% less lime than the fixed-rate in Field 1 and 61% less in Field 2 (Table 1). Although soil pH ranged from 5.5 to 8.2 in Field 1 and from 5.4 to 8.4 for Field 2, large areas had pH 6.3 or higher, which would not require lime according to current ISU recommendations for corn and soybean (Voss et al., 1999). Similar high soil test variation was found in other U.S. Corn Belt states (Bullock et al., 1994; Cahn, 1994; Fixen and Reetz, 1995; McGraw and Hemb, 1995; Pierce et al., 1995). Reducing the amount of lime applied to the field is one of the major advantages of variable-rate lime application, and our results coincide with research conducted in the U.S. Coastal Plains (Heiniger and Meijer, 2000). In the class with lowest pH (<5.7), the rates for the variable-rate treatment were markedly higher than for the fixed-rate in Field 1 (17% higher) and were 1% higher in Field 2. However, in the 5.7-6.2 pH class, variable-rate applied significantly less lime (18% less in Field 1 and 50% less in Field 2).

Table 2 shows soil pH statistics and the significance of treatment effects on soil pH for all sampling dates. Analyses of data from the first sampling date (which were collected before applying the lime treatments) are useful to describe the initial pH values and to detect any possible artificial effect of treatments due to pre-existing variability. Initial soil pH was statistically similar for the three treatments in both fields. In Field 1, application of lime did not affect soil pH significantly (*P*#0.05), but there were increasing trends for both methods of application. An apparently higher pH increase for the variable-rate treatment compared with the fixed-rate treatment in the first sampling date after lime application (a difference of 0.08 pH units) was not statistically significant either. In Field 2, higher pH values in both sampling dates after applying the treatments were statistically significant (*P*#0.05) only for the Fall 1999 sampling date. Although pH was higher for both methods, the variable-rate treatment increased soil pH more than the fixed-rate treatment. The final sampling date for this field showed pH values difficult to explain because only the variable-rate treatment seemed to have increased soil pH. The average lime main effect was not significant (*P*#0.05) and the comparison fixed-rate versus variable-rate was significant only at *P*#0.06. In the Fall 1998 sampling date of Field 1 the pH SD was lower for the variable-rate treatment than for the control or fixed-rate treatments, which suggests that the variable-rate method reduced soil pH variability. This trend was not evident in the Fall 1999 sampling date, but was evident again in Fall 2000. In Field 2 the fixed-rate treatment had the lowest SD in the two sampling dates after the lime application, but it should be noted that the initial SD for plots that would later receive the fixed-rate treatment was lower than for the other treatments (Table 2). A reduction in variability produced by either the fixed or variable-rate treatments would be explained by a larger pH increase due to liming of acid areas than for areas that already had high pH.

Table 3 shows the average soil pH for each one of four pH classes and the level of significance of treatment comparisons. The pH classes were arbitrarily created, and no lime was applied with the variable-rate treatment at or above pH 6.3. Results for the initial soil sampling date before liming (Spring 1998 for Field, and Fall 1998 for Field 2) indicated no significant differences between treatments. As expected, the lime treatments usually increased soil pH significantly (*P*#0.05) in the two acid pH classes, except for the most acid pH class for the Fall 2000 sampling date of Field 2. The variable-rate treatment resulted in higher pH than the fixed-rate treatment in Field 1 but not in Field 2. The difference in soil pH between the fixed and variable-rate treatments in Field 1 was smaller for the 5.7 to 6.2 pH class, probably because the lime rates applied were similar. The fixed-rate lime treatment did not affect soil pH in the neutral or high pH classes.

Treatment effects on soil pH can also be analyzed by calculating the pH change over time. Table 4 shows the average pH change due to liming for each pH class across both fields calculated from the initial (Spring 1998 in Field 1 and Fall 1998 in Field 2) and final (Fall 2000) sampling dates. Both application methods resulted in higher pH for the pH class below 5.7 (*P*#0.05). The highest increase was for the variable-rate treatment, which is reasonable because more lime was applied with variable-rate than with fixed-rate for this pH class. Smaller and not significant pH changes were observed when pH was in the 5.7 to 6.2 range probably because the difference in lime applied was smaller. No significant treatment differences were observed when soil pH was 6.3 or higher.

Yield Response to Lime

The lime treatments had little effect on mean corn and soybean yields along the strips in Field 1 and no effect in Field 2 (Table 5). The means for the RCBD analysis correspond to the observed mean yields. The means for the RCBD-NNA are least square means that were adjusted for the spatial correlation of yield. Comparison of the RCBD means and the RCBD-NNA least square means shows small treatment differences for all site-years. This similarity between observed and spatially adjusted means was observed before (Mallarino et al., 1998). One of the potential advantages of adjusting for spatial correlation using NNA is to remove at least part of the error caused by spatial correlation of yield and therefore to improve the statistical test for treatment effects. The SE always was reduced and levels of significance for treatment effects were increased when the ANOVA accounted for spatial correlation. The corn 1999 was the only crop-year that showed a positive response to lime (approximately 230 kg ha^{-1}), a response that was statistically significant with both methods of analysis. The NNA method of analysis suggested a small negative response to lime for the soybean 1998 crop (*P*#0.1), mainly to the variable-rate method of application.

Tables 6 and 7 show yield means by pH class and treatment for all years of Field 1 and 2. These data make the moderate average positive response to lime of the 1999 corn crop in Field 1 (Table 5) difficult to explain, because the lime effect was not significant (*P*#0.1) for any application method at any pH class in this field. It is possible that a small nonsignificant responsive trend for the 5.7 to 6.2 pH class and field variability explain this result. It must be remembered that the variable-rate treatment was a distinct treatment across the entire field for the two lower pH classes (in which lime was applied), but it provides another estimate of yield without lime for the two highest pH classes because lime was not applied. The corn 2000 crop of Field 2 showed a small yield reduction (*P*#0.01) to the fixed-rate treatment in the 6.3 to 7.2 pH class, which could be reasonable because over-application of lime may have detrimental effects on yield through a reduction in availability of other nutrients (McLean and Brown, 1984), but it is difficult to explain why there were no treatment differences when pH was above 7.2.

Both the general lack of response to the lime application and a small negative response in one soybean crop (1998) can be explained by several reasons. One may be the presence of high pH (calcareous) subsoils in both fields. Eighty-nine percent of the sampling points had soil pH above 7.4 and were calcareous (2% CCE or higher) at some depth (0-91 cm), 38% were calcareous at all depths, and 51% were calcareous at 30 cm or deeper depths. It is possible that low pH of the surface soil layer was offset by high-pH subsoil. Several sampling points revealed acidic soil in the 0-15 cm layer but calcareous subsoil. Current ISU lime recommendations for corn and soybean (Voss et al., 1999) consider a soil pH 6.0 (15-cm depth) sufficient for these crops when subsoils are calcareous, although they recommend increasing topsoil pH to pH 6.3 if lime is applied. Our data suggest that the critical pH level could be even lower.

Another possible reason for the lack of response to lime may be an extremely high small-scale variability in soil pH. Figure 2 shows soil pH data for the intensive sampling conducted along eight transects and the corresponding 0.1-ha grid-point data. Soil pH varied from 5.4 up to 8.0 over distances of about 50 m. In some sections, soil pH varied about two pH units over a 12 m distance, although sometimes changes were more gradual. There was a good agreement between the transect data and the cell data even with such a high small-scale variability in Field 1, which suggests that for this portion of the field the cell data accurately represented the pH of the small area sampled. However, very high variability between the grid-point sampling points was undetected, and no interpolation method could possibly produce a reasonable gridding. In contrast to data for Field 1, there was more discrepancy between the grid-point data and the data from one of the transects (in Transect 2 of the variable-rate treatment). These results may be explained by high soil pH variability along multiple directions, not only along the transect but also across the transect, which coincides with previous research done by Mallarino (1996) with P and K.

Very high small-scale variation suggests that the pH class assignment based on a grid sampling may have not been correct, therefore lime may have been incorrectly applied to some parts of the field, and this may also explain the lack of or a small negative response to lime. For example, in Field 2, soil pH from Transect 2 of the variable-rate treatment indicates that lime should be applied at the section between 40 and 100 m from the beginning of the transect, however, the grid-point data from the same area indicated no lime should be applied (soil pH was at or above 6.3). Although no meaningful statistical analyses for application method can be applied to the transect data because they were replicated only twice, the variable-rate treatment did not result in obviously lower pH variability compared to the fixed-rate. These observations suggest that in these soils (Clarion-Nicollet-Webster soil association) even a very intensive grid soil sampling (0.1 ha) cannot represent the actual soil pH variability. Furthermore, even if soil samples were taken with the extremely high intensity used with the transects, current VRT equipment used by cooperatives or distributors cannot manage such a small scale variation.

The influence of other factors than pH on yield could also explain a lack of detectable response or a small negative response of soybean detected in 1998. There was a negative linear relationship (P#0.05) between soybean yield and soil pH of not limed areas in 1998 and 1999 (data not shown). This negative relationship explained 45% of the yield variability in 1998 (Field 1) and 54% in 1999 (Field 2). No significant correlation was observed between soybean yield and initial soil pH in 2000 (Field 1). Thus an apparent negative effect of lime across an entire field or for high pH classes when lime was applied with the fixed-rate method could be explained by low yield in high pH areas. Correlations between corn yield and soil pH were negative in 1999 and explained 46% of yield variability, but were positive in 2000 and explained 36% of yield variability. These relationships likely are explained by differences in soil moisture. The low lying and high-pH soils of this soil association (such as the series Canisteo, Harps, and

Okoboji) are prone to excessive moisture in years with above-average rainfall. The long-term average rainfall for Boone County is 669 mm (Andrews and Dideriksen, 1981) for the March-September period. The 1998 and 1999 rainfall for the same period was 816 and 827 mm, respectively, so those years were wetter than average. However, the rainfall for the same period of time for the year 2000 was 408 mm, which was far below the average. In wet years, like 1998 and 1999, excessive moisture may likely limit crop growth and reduce yield, but in dry years (like 2000) those lower areas may have an advantage compared to the rest of the field and yields can be higher, especially in corn. Kaspar et al. (2000), who worked on similar soils, found a negative correlation between corn yield and elevation when there was less-than-normal precipitation during the growing season but a positive correlation when there was greater-than-normal precipitation. Moreover, Jaynes and Colvin (1997) found that the yield spatial pattern and structure vary from year to year in the same soil association mainly due to changing rainfall patterns over time.

Soil pH Assessment with Various Soil Sampling Schemes

There was little difference in mean soil pH calculated for each sampling scheme (Table 8). The pH values ranged from 6.64 to 6.93 for Field 1, and from 6.57 to 6.95 for Field 2. However, the pH range and SD within a field were smaller for the soil map unit zone and the management zone schemes than for the more intensive sampling schemes. An *F* test (not shown) that compared the pH variation between zones with the average variation within zones was significant (*P*#0.01) for all the zone schemes (large grid cell, soil map unit zone, and management zone), which suggests that these schemes were effective in separating areas with contrasting pH. The clearly smaller pH range for the sampling schemes with large sampling units suggests, however, that these methods would pool together areas with large pH variation. The soil map unit zone was the least effective in separating areas with distinctly different pH in Field 1 (lower pH range), and the soil map unit and management zone schemes were less effective in Field 2.

The size of field areas that would be classified into four pH classes by each sampling strategy varied markedly (Table 8). The two most acidic classes (<5.7 and 5.7-6.2) were merged in one class (<6.3) because this pH range represents the area of the field that would have been limed according to ISU recommendations (no lime applied where soil pH is at or above 6.3). In Field 1, less intensive sampling schemes resulted in a smaller area that would be limed compared with more intensive schemes. However, in Field 2, this was not always the case, probably because of a large management zone (10.1 ha) with a mean pH of 6.03 that increased significantly the area that would be limed. The least intensive sampling schemes also resulted in smaller high-pH areas, especially in Field 1. Table 9 shows within-zone mean soil pH and SD, as well as ranges for pH and SD across all sampling units for each management zone and for all the layers of information that were used to determine them. In Field 1, the soil map and management zones scheme had the largest pH range between units and the range in SD across units was intermediate. The yield zone scheme had the smallest pH range between units and it was the only scheme that would have resulted in no lime application in all units (soil pH was always higher than 6.3). Although the SD within one yield unit was very low (0.13 in Unit 5), it was very high and ranged from 0.72 to 1.14 in other units, which suggests that this scheme was less effective than others in reducing within zone variability. The elevation zone scheme had the lowest range of SD and an intermediate pH range across the units which suggests that this may be a good source of information to use when delineating management zones. Luchiari et al. (2000) had suggested that elevation was one of the most useful variables when delineating management zones. The range of SD across EC zone units was the second lowest among all zone schemes and the pH range was intermediate. Areas with lower EC values were associated with areas of lower soil pH. Relationships were linear for both fields (P#0.001) and correlation coefficients were 0.67 for Field 1 and 0.70 for Field 2. These results coincide with other research showing that EC maps were useful tools to delineate management zones (Jaynes et al., 1995; Hartsock et al., 2000). In contrast to Field 1, Field 2 had similar pH and SD ranges for all schemes, suggesting that all of them gave similar information about pH variability.

Results of the sampling simulations show that various options are available when farmers need to take soil samples to decide lime application in these soils. One alternative would be to use a 0.7-ha grid (smaller grid sizes would undoubtedly be too costly for extensive crops), which may be effective in representing soil variability but expensive due to the large numbers of samples. Another alternative would be to use less costly schemes that involve collecting fewer composite samples from larger zones, although soil test variability will be less accurately represented. Other layers of information such as aerial photographs could also help define management zones (Schepers et al., 2000). This could be particularly useful in areas where nutrient deficiency symptoms are evident. For example, soybean plants usually show iron chlorosis when grown in calcareous soils. A 1-m resolution color canopy image collected one year from each field (not shown) suggested that it could be used to identify areas with very high pH. Although this may sound like the best alternative in the Clarion-Nicollet-Webster soil association, these areas often are small and very irregular in shape and current VRT may not manage this zones appropriately. Once these areas are identified, however, they can be either sampled separately or not sampled.

Future developments of on-the-go automated soil testing systems should markedly decrease the cost of soil sampling and improve the accuracy of soil nutrient maps (Sudduth et al., 1997). Birrell et al. (1999) and Adamchuk et al. (1999) have developed real-time soil nutrient analysis sensors to determine soil pH that showed good correlation (r^2 0.83) with manually collected soil samples. Although these early automated soil sampling systems provide analysis of soil acidity with lower accuracy than the standard laboratory method, they should improve the quality of the soil maps since much higher spatial resolution of soil sampling can be achieved (Adamchuk et al., 1999). However, when this is achieved, the capacity of VRT equipment to apply large amounts of lime to do a correct and precise variable-rate lime application will likely become a limiting factor.

CONCLUSIONS

Fixed-rate or variable-rate treatments had no meaningful effect on crop yield in these soils of the Clarion-Nicollet-Webster association even though a very intensive soil sampling method showed that 15% of the experimental area had pH 5.4 to 5.7, 35% had pH 5.7 to 6.2, and 50% had pH 6.3 to 8.4. However, the variable-rate method increased pH of acidic areas more than the fixed-rate method and used 56% less lime in one field and 61% less in the other. The lack of yield response could be explained by calcareous subsoil in most areas and by extremely high small-scale pH variability. Irregular patterns with a variation of two to three pH units within 10 to 20 m were common.

The results suggest that even the information provided by a costly 0.1-ha point grid sampling, which is much more intensive than grid sampling procedures used in the Corn Belt, may not be more useful than soil pH estimates from less intensive zone sampling methods. This is due to extreme variation at a scale much smaller than the distance between grid lines. Zone sampling methods based on various criteria may not provide better information about soil pH variability than intensive grid sampling methods, but likely are more cost-effective mainly because the number of samples would be fewer. No sampling scheme will alleviate the serious limitations of current VRT equipment to manage small-scale variability, however, but the results showed that variable-rate liming is a better alternative to fixed-rate liming in these soils because it provides a reasonable way of avoiding lime application to at least some high pH areas.

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Table 1. Field areas and lime rates for the fixed-rate and variable-rate lime treatments.

Field	Treatment	pH class	Field area	Lime rate
			---- ha ----	--Mg ECCE ha^{-1}--
1	Fixed		14.6	3.36
	Variable[†]	Avg. all classes	14.6	1.48
		Below 5.7	1.3	3.92
		5.7 – 6.2	5.7	2.77
		6.3 or above	7.6	0
2	Fixed		18.0	2.69
	Variable	Avg. all classes	18.0	1.05
		Below 5.7	3.6	2.73
		5.7 – 6.2	5.6	1.34
		6.3 or above	8.8	0

[†] Only areas with pH lower than 6.3 received variable-rate lime.

Table 2. Descriptive statistics of soil pH for each treatment across the two fields sampled.

			Descriptive statistics[†]					Lime effect[‡]	
Field	Sampling date	Treatment	Mean	Max	Min	Range	SD	Lime	F vs V
			------------------------ pH ------------------------					------- *P>F* -------	
1	Spring 1998	No lime	6.78	8.18	5.55	2.63	0.96	0.99	0.91
		Fixed	6.81	8.18	5.68	2.50	0.95		
		Variable	6.78	8.20	5.50	2.70	0.95		
	Fall 1998	No lime	6.62	8.10	5.30	2.80	1.10	0.46	0.72
		Fixed	6.80	8.25	5.63	2.62	0.97		
		Variable	6.88	8.50	5.75	2.75	0.92		
	Fall 1999	No lime	6.54	8.05	5.35	2.70	1.03	0.48	0.97
		Fixed	6.78	8.00	5.60	2.40	0.92		
		Variable	6.79	8.13	5.65	2.48	0.91		
	Fall 2000	No lime	6.65	8.18	5.40	2.78	1.06	0.12	0.80
		Fixed	6.95	8.10	5.85	2.25	0.89		
		Variable	6.99	8.15	5.75	2.40	0.83		
2	Fall 1998	No lime	6.62	8.10	5.40	2.70	0.96	0.72	0.53
		Fixed	6.52	8.05	5.28	2.77	0.88		
		Variable	6.61	8.35	5.25	3.10	0.96		
	Fall 1999	No lime	6.65	8.10	5.53	2.58	0.88	0.04	0.05
		Fixed	6.73	8.10	5.60	2.50	0.72		
		Variable	6.90	8.05	5.45	2.60	0.79		
	Fall 2000	No lime	6.69	8.23	5.73	2.50	0.91	0.12	0.06
		Fixed	6.66	8.18	5.45	2.73	0.82		
		Variable	6.89	8.18	5.40	2.78	0.87		

† Max = maximum soil test value, Min = minimum soil test value, SD = standard deviation, CV = coefficient of variation.

‡ Lime effect = comparison of the control vs. the mean of the two limed treatments, F vs V = comparison of the fixed and variable-rate lime treatments.

Table 3. Soil pH for different sampling dates, treatments, and pH classes for two fields.

			Soil pH by sampling date							
			Spring 1998		Fall 1998		Fall 1999		Fall 2000	
Field	pH class	Treatment	pH	*P*>F[†]	pH	*P*>F	pH	*P*>F	pH	*P*>F
1	Below 5.7	No lime	5.63	0.33	5.45	0.01[‡]	5.49	0.01[‡]	5.55	0.01[‡]
		Fixed	5.69		5.65		5.69		5.95	
		Variable	5.61		6.00		5.93		6.23	
	5.7 – 6.2	No lime	5.99	0.91	5.70	0.01[‡]	5.70	0.01	5.78	0.01[‡]
		Fixed	5.97		5.95		5.97		6.13	
		Variable	5.96		6.18		5.98		6.29	
	6.3 – 7.2	No lime	6.76	0.35	6.50	0.12	6.54	0.15	6.59	0.09
		Fixed	6.57		6.86		6.65		6.95	
	Above 7.2	No lime	7.84	0.68	7.76	0.70	7.68	0.47	7.81	0.42
		Fixed	7.87		7.82		7.79		7.92	
2	Below 5.7	No lime	-	-	5.55	0.94	5.78	0.01	5.93	0.27
		Fixed	-		5.51		6.01		5.82	
		Variable	-		5.51		6.12		5.99	
	5.7 – 6.2	No lime	-	-	6.00	0.96	6.15	0.01	6.10	0.02
		Fixed	-		6.03		6.45		6.33	
		Variable	-		6.03		6.34		6.34	
	6.3 – 7.2	No lime	-	-	6.61	0.76	6.75	0.82	6.69	0.90
		Fixed	-		6.58		6.71		6.70	
	Above 7.2	No lime	-	-	7.85	0.56	7.79	0.26	7.89	0.22
		Fixed	-		7.81		7.60		7.66	

[†] *P*>F = Probability of the comparison between the control and the mean of the two lime treatments for the two acid classes, or between the fixed-rate treatment and the mean of the two treatments that received no lime (control and variable-rate) for the two high pH classes.

[‡] A comparison of the fixed versus variable rate treatments was significant at *P*#0.05.

Table 4. Average change in pH by pH class and treatment across both fields.

pH class	Treatment	pH change[‡]	Lime effect[†]	
			Lime	F vs V
			------------- *P*>F	-------------
Below 5.7	No lime	0.23	0.04	0.04
	Fixed	0.29		
	Variable	0.54		
5.7 – 6.2	No lime	-0.08	0.01	0.22
	Fixed	0.21		
	Variable	0.33		
6.3 – 7.2	No lime	0.01	0.28	-
	Fixed	0.22		
Above 7.2	No lime	0.01	0.36	-
	Fixed	-0.06		

† Lime = Probability of the comparison between the control and the mean of the two lime treatments for the two acid classes, or between the fixed-rate treatment and the mean of the two treatments that received no lime (control and variable-rate) for the two high pH classes, F vs V = comparison of the fixed and variable rate treatments.

‡ pH change = pH difference between final pH (Fall 2000) and initial pH (Spring 1998 for Field 1, and Fall 1998 for Field 2).

Table 5. Effect of lime application on corn and soybean yields evaluated by two methods of analysis.

Field	Crop	Treatment and statistics‡	Method of analysis†	
			RCBD	RCBD-NNA
			--- kg ha^{-1} and level of significance ---	
1	Soybean 1998	No lime	3980	3988
		Fixed	3975	3954
		Variable	3887	3896
		SE	71.1	23.2
		Lime effect	0.59	0.07
		F vs. V	-	0.12
	Corn 1999	No lime	11118	11122
		Fixed	11337	11324
		Variable	11376	11386
		SE	101.3	57.9
		Lime effect	0.10	0.02
		F vs. V	0.79	0.48
	Soybean 2000	No lime	3154	3148
		Fixed	3156	3160
		Variable	3143	3145
		SE	22.8	5.1
		Lime effect	0.88	0.45
		F vs. V	-	-
2	Soybean 1999	No lime	3306	3301
		Fixed	3304	3305
		Variable	3277	3281
		SE	31.8	11.5
		Lime effect	0.72	0.61
		F vs. V	-	-
	Corn 2000	No lime	9184	9178
		Fixed	9138	9143
		Variable	9181	9181
		SE	27.0	10.4
		Lime effect	0.49	0.28
		F vs. V	-	-

† RCBD = observed means and statistics for the complete-block design, RCBD-NNA = Least square means and statistics from RCBD analysis combined with nearest neighbor analysis.

‡ SE = average standard error of the least square means, Lime effect = P>*F* of the orthogonal contrast of the control versus the average of the fixed and variable rate treatments, F vs. V = P>*F* of the comparison between the fixed and variable rate lime treatments.

Table 6. Soybean and corn yield by pH class and treatment for three years in Field 1.

		Soybean 1998		Corn 1999		Soybean 2000	
pH class	Treatment	Yield	*P*>F[†]	Yield	*P*>F	Yield	*P*>F
		--kg ha^{-1}--		--kg ha^{-1}--		--kg ha^{-1}--	
Below 5.7	No lime	4513	0.84	11713	0.84	3192	0.98
	Fixed	4477		11716		3226	
	Variable	4603		11583		3163	
5.7 – 6.2	No lime	4228	0.88	11508	0.29	3134	0.22
	Fixed	4287		11674		3166	
	Variable	4196		11637		3180	
6.3 – 7.2	No lime	4089	0.73	11556	0.97	3226	0.96
	Fixed	4031		11587		3230	
Above 7.2	No lime	3497	0.76	10816	0.53	3110	0.99
	Fixed	3537		10923		3110	

[†] *P*>F: Significance for the orthogonal contrast of the control versus the mean of the fixed and variable rate treatments for the two acid classes and between the fixed rate and the mean of the two treatments receiving no lime (control and variable-rate) for the two high pH classes. The comparison of the fixed versus variable-rate treatments never was significant at *P*#0.05.

Table 7. Soybean and corn yield by pH class and treatment for two years in Field 2.

		Soybean 1999		Corn 2000	
pH class	Treatment	Yield	*P*>F[†]	Yield	*P*>F
		--kg ha^{-1}--		--kg ha^{-1}--	
Below 5.7	No lime	3690	0.13	8891	0.47
	Fixed	3539		8913	
	Variable	3609		8685	
5.7 – 6.2	No lime	3485	0.35	9009	0.14
	Fixed	3424		8833	
	Variable	3400		8949	
6.3 – 7.2	No lime	3327	0.57	9196	0.01
	Fixed	3389		8934	
Above 7.2	No lime	2940	0.72	9234	0.28
	Fixed	2979		9315	

† *P*>F: Significance for the orthogonal contrast of the control versus the mean of the fixed and variable rate treatments for the two acid classes and between the fixed rate and the mean of the two treatments receiving no lime (control and variable-rate) for the two high pH classes. The comparison of the fixed versus variable-rate treatments never was significant at *P*#0.05.

Table 8. Area for each sampling unit, number of sampling units, and descriptive statistics of soil pH for different soil sampling strategies.

Field	Sampling scheme	Area[§]	Number of units[†]	Soil pH			Total area by pH class		
				Mean	Range	SD[‡]	<6.3	6.3-7.2	>7.2
		---ha---							
1	Small grid-point	0.1	144	6.81	2.70	0.94	6.9	1.4	6.1
	Medium grid point	0.3	48	6.78	2.63	0.95	6.9	1.5	6.0
	Medium grid cell	0.3	48	6.81	2.38	0.86	6.3	1.8	6.3
	Large grid point	0.7	18	6.93	2.48	0.94	5.6	1.8	7.0
	Large grid cell	0.7	18	6.81	2.08	0.75	4.1	4.8	5.5
	Soil map zones	0.5-4.6	7	6.64	1.75	0.73	5.4	5.1	3.9
	Management zones	0.5-2.1	9	6.68	2.03	0.60	4.5	7.3	2.6
2	Small grid point	0.1	180	6.60	3.10	0.93	9.2	3.1	5.7
	Medium grid point	0.3	60	6.62	2.70	0.95	9.9	2.1	6.0
	Medium grid cell	0.3	60	6.60	2.65	0.87	9.3	2.7	6.0
	Large grid point	0.7	30	6.68	2.70	0.95	10.2	1.1	6.7
	Large grid cell	0.7	30	6.57	2.32	0.72	6.7	6.7	4.6
	Soil map zones	0.9-6.7	6	6.95	1.86	0.80	9.7	4.2	4.1
	Management zones	1.0-10.1	6	6.91	1.82	0.81	11.9	0.0	6.1

[†] Number of sampling units for each soil sampling scheme.

[‡] SD = Standard deviation.

[§] Size of each sampling unit. The two numbers indicate the smallest and largest sampling zones.

Table 9 Soil pH means and standard deviation for soil map yield, elevation, electrical conductivity, and management zone schemes.

	Soil map zone			Yield zone			Elevation zone			EC zone[†]			Management zone		
Field	Unit	pH	SD[‡]	Unit	pH	SD	Unit	pH	SD	Unit	pH	SD	Unit	pH	SD
1	1	6.42	0.92	1	7.08	0.94	1	7.20	0.75	1	6.12	0.65	1	7.01	0.95
	2	6.98	0.89	2	7.39	0.93	2	7.63	0.67	2	6.05	0.53	2	6.24	0.51
	3	5.85	0.15	3	6.39	0.88	3	6.05	0.47	3	7.40	0.74	3	7.17	0.85
	4	7.53	0.68	4	6.72	0.87	4	6.16	0.69	4	7.62	0.56	4	6.48	0.65
	5	6.14	0.64	5	7.85	0.13							5	6.73	0.98
	6	5.97	0.52	6	6.83	1.14							6	5.80	0.23
	7	7.60	0.63	7	6.73	0.72							7	6.68	0.94
													8	6.22	0.75
													9	7.83	0.32
	Range[§]	1.75	0.77	Range	1.46	1.01	Range	1.58	0.06	Range	1.57	0.21	Range	2.03	0.75
2	1	5.99	0.60	1	5.96	0.56	1	7.80	0.26	1	6.04	0.43	1	7.85	0.14
	2	6.65	0.87	2	7.81	0.19	2	6.87	0.93	2	6.17	0.73	2	7.29	0.76
	3	6.14	0.50	3	7.51	0.64	3	5.89	0.45	3	7.35	0.79	3	6.03	0.68
	4	7.49	0.27	4	7.36	0.71	4	6.27	0.23	4	7.80	0.19	4	6.27	0.17
	5	7.60	-	5	6.26	0.17							5	6.28	0.23
	6	7.85	0.30	6	5.99	0.63							6	7.75	0.36
	Range	1.86	0.60	Range	1.85	0.54	Range	1.91	0.70	Range	1.76	0.60	Range	1.82	0.62

† EC zone = Electrical conductivity zones.

‡ SD = Standard deviation.

§ Observed range of values across sampling units for each scheme.

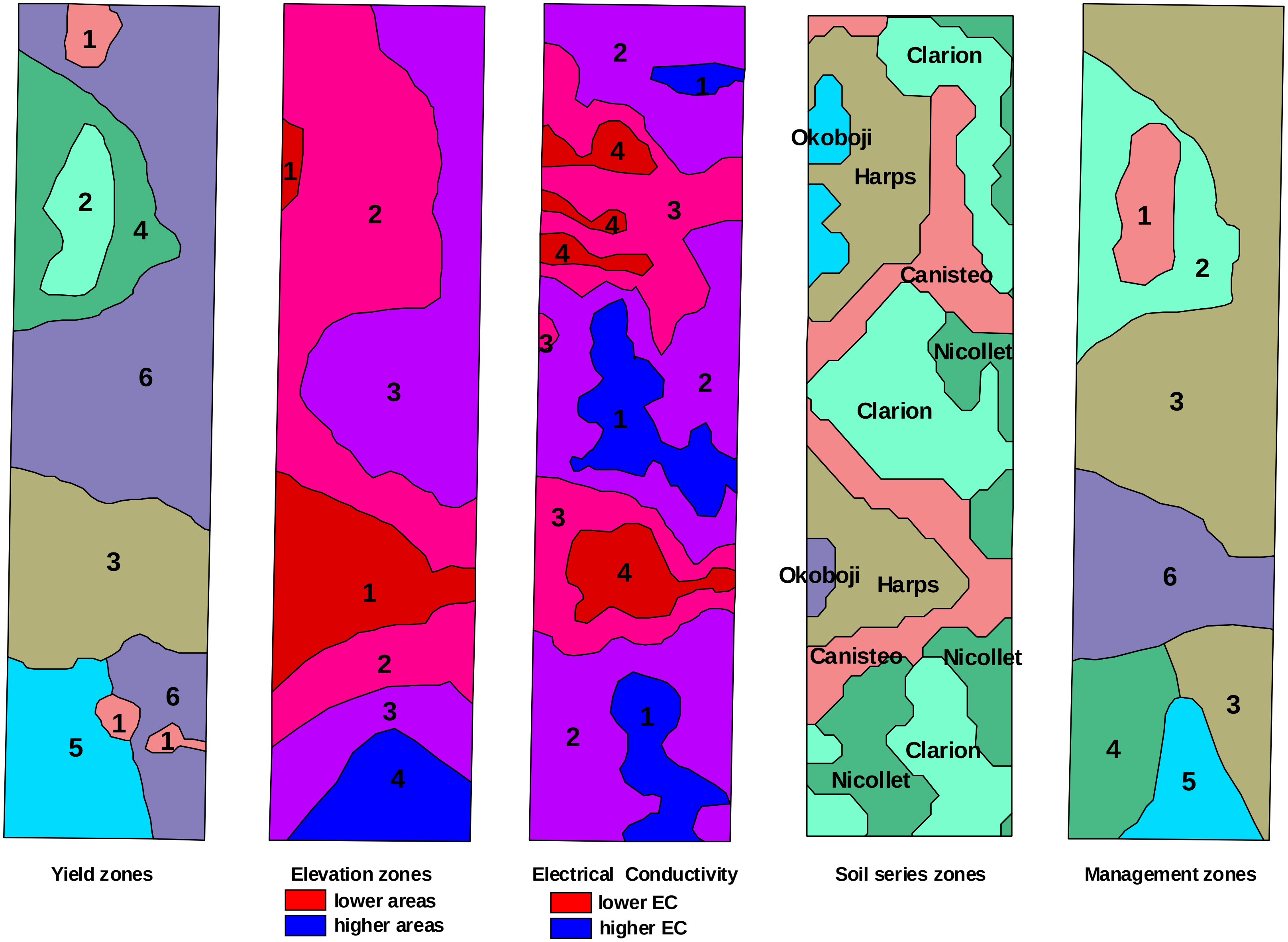

Figure 1. Yield (soybean 1999 and corn 2000), elevation, electrical conductivity, soil, and management zone maps from Field 2.

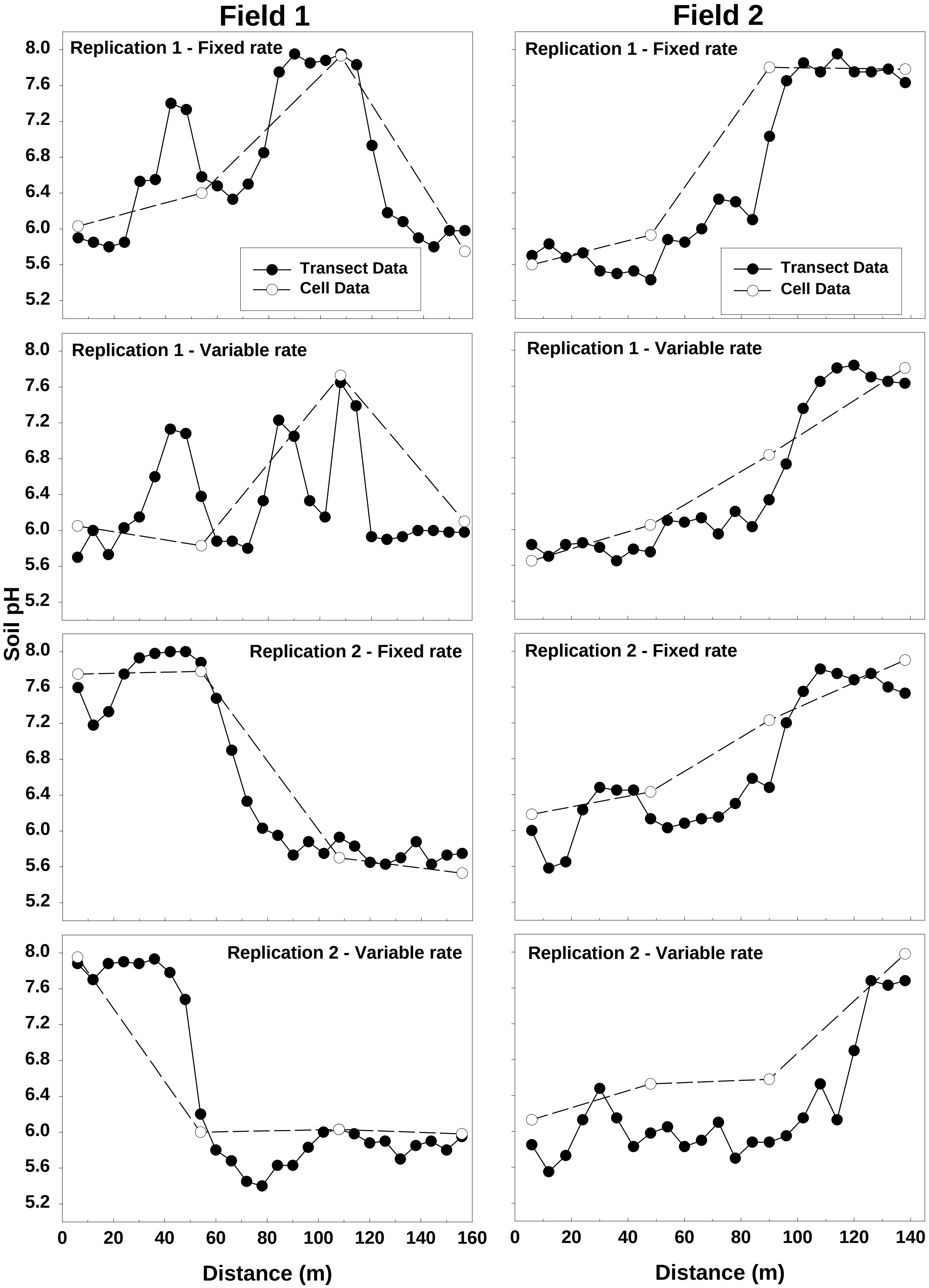

Figure 2. Intensive soil sampling data from transects compared to the cell data for the fixed rate and the variable rate treatments in Fields 1 and 2.