# Dividing cornfields into soil management units for nitrogen fertilization

by

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To my wife, Lisa
With love and gratitude

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## Abstract

The advent of applicators having the capacity to adjust rates of fertilization as they move across fields has created a need to subdivide fields into nitrogen (N) management units, or areas of soil that should receive a common rate of N. This dissertation explores methods for using yield monitors on combines, the Global Positioning System (GPS) , remote sensing, and geographic information systems (GIS) to subdivide fields into N management units. Fertilizer treatments were applied in replicated strips 4.5-6 m wide and >500 m long across fields having several soil types. Combines with yield monitors harvested each strip as a single swath. Geographic information systems were used to divide the field into 28 $m^2$ grid cells and yield responses to treatments were calculated from the appropriate paired cells. Cells within this grid formed a population of yield responses for the whole field or for any subdivision. The field was subdivided into possible management zones by using soil survey maps or spatial pattern in light reflectance from crop canopies. Only when subdivisions resulted in yield responses great enough to pay for the treatment were the subdivisions considered different management units. Analysis showed that yield responses great enough to pay for the treatment were usually statistically significant. The experimental precision attained was considerably better than obtained in conventional small plot fertility trials. Remote sensing of canopy reflectance could identify small areas that differed substantially from the surrounding soil. This information can be used to correct and add important details to soil survey maps and maps of N management units. An important advantage of this method is that populations of yield responses are

characterized for areas of soil having defined ranges of heterogeneity and, therefore, results of experiments can be used to make scientifically defensible N recommendations for areas of soil having the same defined range of heterogeneity. The major advantage, however, is that farmers can conduct trials in their fields at negligible cost and they can see the results.

# Chapter I: General Introduction

Several new technologies have been developed that enable Iowa growers to take more control over the nitrogen (N)-management practices they use to grow corn. These technologies include: the Global Positioning System (GPS), geographic information systems (GIS), variable-rate technology, crop hybrids, remote sensing, yield monitors and other tractor-mounted sensors. These technologies can be used for the site-specific application of nitrogen on cornfields. This has created the need to subdivide fields into N-management units or areas of soil that will receive the same method of N application. The method of application is defined as the rate, time, form and placement of N fertilizer. However, methodology to divide fields into management units and the methods of N applications on these units is not completely understood.

Precision agriculture and, specifically, variable rate application technologies have the potential to increase profits, protect the environment, and sustain the ecosystem. Nitrogen should be applied at a time when plants begin rapid uptake of nutrients. More N taken up by the corn plants leaves less N in a position to be leached. Leaching of N into the groundwater is a source of pollution that can be controlled by better N-management practices. Nitrogen loss impacts both profits and the environment Finally, the ecosystems is protected because fertilizer-N is not going to streams, rivers and lakes contributing to problems such as eutrophication.

This dissertation will explore the use of several precision agriculture technologies to delineate N-management units, characterize variability within and across potential N-management units, and determine the optimal N-application methods to be used in N-management units. Ultimately, it is hoped that the methods explored in this dissertation will have the potential to assist growers in creating their own sets of recommendations on their farms.

## Dissertation Organization

This dissertation is organized into five chapters. The first chapter is the general introduction to the dissertation. Chapters two through four are manuscripts that will be submitted to the Soil Science Society of American Journal for publication. The last chapter is a general conclusion.

# Chapter II: Characterizing Corn Yield Response to Nitrogen Fertilization Within Soil Map Units

A paper prepared for submission to the Soil Science Society of America Journal
J. W. Ellsworth, A. M. Blackmer, and J. Zhang

## Abstract

Lack of practical methods for measuring the variability in yield responses to fertilizer within and between areas within fields seems to be a major problem limiting our ability to estimate fertilizer needs in fields which often have marked variability in soil properties. We explored the possibility of avoiding this problem by using on-the-go yield monitors in field-scale trials where nitrogen (N)-fertilizer treatments are applied in replicated strips 4.5-6 m wide and >500 m in length. Results from 16 trials showed that the method was usually able to detect mean increases as small as 0.25 Mg ha$^{-1}$ for areas of 1-2 ha and as small as 0.17 Mg ha$^{-1}$ whole fields. Each strip was divided into 6-m segments, the probability density of yields and yield responses associated with the effects of fertilizer treatments were displayed and analyzed. The method makes it possible to characterize variability in yield responses within and between areas of soil likely to be used as separate management units by farmers. Knowledge of this variability makes it possible to identify appropriate management zones and compare the reliability of alternative methods for estimating fertilizer needs for these management zones.

## Introduction

Modern methods of estimating fertilizer needs for crop production are based on analysis of previously measured yield responses to fertilization (Black, 1993;

Colwell, 1994; Heady et al., 1955). The responses are measured in field experiments where three or more rates of fertilizer are applied to plots located within areas of soil as homogenous as possible. The optimal size and shape of the plots is known to vary with many factors, including type of equipment used, amount of land available, plant size, and soil heterogeneity (LeClerg et al., 1962; Gomez and Gomez, 1984). Treatments are replicated in experimental designs selected to minimize soil heterogeneity and thereby maximize experimental precision, which refers to the smallness of difference between two treatments that can be detected (Little and Jackson, 1978).

Although fertilizer needs are estimated in relatively small areas of homogeneous soils, the estimates are used to select rates of fertilization for relatively large areas of heterogeneous soils. The larger areas of soil can be described as management units, or areas that will receive a common rate of fertilization. Management units in the past have been fields as defined by farmers. Fields often contain considerable heterogeneity, which is most often characterized by utilizing the results of soil surveys that divide the landscape into areas of soil having somewhat similar properties called soil map units (Soil Survey Staff, 1998). With the advent of variable-rate application technologies there is good reason to subdivide fields into soil management units that may be defined in terms of soil map units provided by county soil surveys.

A problem that has received little attention is the uncertainty associated with extrapolations of estimates of N fertilizer needs from small areas of homogeneous soils to large areas of heterogeneous soils. Indeed, the scientific literature seems to include no quantitative discussions of methods for making such extrapolations amid normally expected heterogeneity within or among soil map units. Despite the great practical importance of estimating the best rate of fertilization for specific management units, quantitative procedures for estimating these rates from response data have not been described. Lack of methods for developing appropriate estimates of fertilizer needs for soil management units should be considered a major factor limiting the benefits of using variable-rate application technologies.

Blackmer and White (1998) recently described field techniques that seem to have great potential for quantitatively estimating N fertilizer needs in cornfields assumed to be heterogeneous. Fertilizer treatments (three rates of N) were applied in replicated strips that crossed several soil map units. Each strip was harvested as a single swath of a harvester equipped with a yield monitor, which recorded mean flows of grain in one second intervals. The harvester also had a GPS receiver, which recorded the position of each flow measurement. With the use of GIS, mean yields for each treatment were calculated for each strip or for portions of strips located within a soil map unit (or any other potential N-management unit). This method offers a way to utilize yield response data to divide fields into management units and to estimate fertilizer needs for each management unit, but the utility of this method needs to be more rigorously evaluated.

Information concerning the smallness of yield responses that can be detected at near-maximum yields is extremely important because measurements in this range are most important when assessing N fertilizer needs. As illustrated by Cerrato and Blackmer (1990), bias imposed during model fitting is a serious problem that complicates the task of identifying optimal rates of fertilization by methods used in the past. This problem occurs because yield increases tend to decrease with each successive increment of fertilizer applied and because economic optimum rates of fertilization occur where changes in fertilization rate have relatively small effects on yield. Yang (2000) pointed out that, because of this problem, researchers usually are faced with the dilemma of calculating economic optimum rates from models that lack statistical significance or are strongly influenced by yields observed at extremely high or low rates of N fertilization.

Yang (2000) recently demonstrated that the profitability of N fertilization was little affected by changes in rate of N fertilization at near-optimal rates of fertilization. He found that this occurs because small increases in yields tend to offset the additional costs of fertilization within a range of about 25 kg N $ha^{-1}$. This observation indicates that it is not necessary to identify an exact rate of fertilization to maximize profits. This observation also suggests that assessments of N fertilizer needs can be attained by merely determining whether small increases in rates are profitable in the near-optimal range. This approach would avoid the need to collect data at rates far above and below those needed to maximize profits. In situations where fertilizer needs are approximately known, this approach makes it possible to conduct studies across large areas of soil without loss of profit due to N deficiencies at low rates of fertilization in some treatments and unnecessary purchases of fertilizer in other treatments.

The objectives of this study were (i) to assess the precision of this method for measuring corn yield response to fertilizer N in trials conducted on areas of soil having various degrees of heterogeneity as indicated by soil survey maps and (ii) to evaluate the ability of this method to characterize variability in yield responses within and among soil survey map units in the same field. The specific studies reported here are considered to be only one step in the overall process of evaluating the merits of this new method of estimating N-fertilizer needs for management units. Both of these factors, however, deserve early attention when exploring utility of this method for estimating fertilizer needs for individual soil map units and both factors should be considered simultaneously.

## Materials and Methods

Data were gathered from N-response trials conducted at 16 sites over a period of two years (1998-99). Trials were conductucted at sites 1-6, 9 and 12 in 1998 and at the remaining sites in 1999. The locations, soil associations, soil map symbols, soil map units and percentages of area covered by the soil map unit at each site are given in Table 1. This information was obtained from digitized soil survey maps (Iowa Cooperative Soil Survey, Ames, IA) using ArcView (v. 3.2, ESRI, Redlands, CA). Table 2 gives the soil classification for each of the soil series given in Table 1.

All sites had average to above average soil variability for the soil association. All had been in a corn-soybean rotation. None of the treatments considered involved extreme deficiency of N, some had fertilizer N (Sites 1-6 and 13) or manure N (Sites 11, 16-17) applied prior to planting to avoid extreme deficiencies. The fertilizer treatments discussed in this paper were applied as urea ammonium nitrate (UAN) in a stratified design with four to seven replications. The three treatments considered at each site were either 0, 56, 112 kg N $ha^{-1}$ or 56, 112 and 168 kg N $ha^{-1}$. To simplify discussion, the three rates at each site are described as R1, R2 and R3 in this paper. Although it is important to know that fertilizer was always applied in 56 kg N $ha^{-1}$ increments, the actual rates applied to each site have no importance to the objectives of this paper.

Each of the trials was planted to corn in late April or early May. The trials were managed according to the grower's normal practices except for N application. After planting, the fields were divided into strips that were the width of the grower's combine and the length of the field. Each strip was numbered consecutively across the field. The fertilizer treatments discussed in this paper were applied in appropriate strips.

The fields were harvested by farmers using their combines equipped with commercially available yield monitors and GPS receivers. Yield data were recorded at ONE SECOND intervals and imported into ArcView for post processing and analysis. For analysis, the experimental areas in each trial were divided into a grid formed by strips (treatments and combine swaths) and tiers that were 6.1 m wide and the width of the experimental area. These tiers were perpendicular to the treatment strips and were numbered consecutively from one end of the field to the other. Yield values for each cell in the grid were calculated (each cell contained an average of two yield points) and qualitative properties such as soil map unit were assigned to each cell. Yield responses were calculated by subtracting the yield in one cell from yields in the appropriate adjacent cell. Cells were treated as individual experimental units. The trials are numbered in order of decreasing magnitude of N response (highest minus lowest yields).

SAS (v. 8.1, SAS Institute, Cary, NC) was used to calculate the means and probability density functions (PDF) of yield and yield response. The PROC GLM procedure was used to calculate means and LSD values. PROC MEANS was used to perform the t-test. Probability density functions were calculated using the PROC UNIVARIATE procedure. The PDF was selected over a frequency distribution because yield is a continuous variable. Sigma Plot (v. 5.0, SPSS Inc., Chicago, IL) was used to present data in graph form.

## RESULTS AND DISCUSSION

### Yields

The mean yield of grain observed at the highest N rate within each of the 16 trials ranged from 7.8 to 11.4 Mg $ha^{-1}$ (Table 3). This range is generally typical of yield levels found in Iowa cornfields, which are usually fertilized to attain near-maximum yields. Mean yields at the lowest rate of fertilization within each trial ranged from 60 to 97% and averaged 82% of the highest. Mean yields at the intermediate rate of fertilization ranged from 88 to 99% and averaged 96% of the highest. The responses observed at these sites are smaller than often observed in non-fertilized fields, but they are appropriate for studies of yield responses to N at near-maximum yields.

Figure 1 illustrates the distributions of yields observed for each rate of fertilization within each of the 16 sites studied. Each line describes the probability of cell-mean yields being a certain values at a single N rate within a trial. For non-responsive trials (e.g., site 16) the three curves essentially coincide, meaning that each cell as an equal probability of being the same value no matter the rate. For responsive trials (e.g., Site 1) three separate curves are observed meaning that cells receiving the high rate of N has a greater probility of having a higher yield than the lower rate. These curves provide information not given in tables of treatment means (Table 3) and tables of distribution parameters (Table 4) because degree of normality or skewness is illustrated. Observations concerning the normality of distributions provide a basis for making inferences concerning the homogeneity of the area studied. They also provide a basis for characterizing the effects of N rate on yield variability, which is important in economic analyses that assess levels of risk associated with a given fertilization practice.

Relatively little is known about the distributions of yields expected within areas of soil commonly used as management units because it has not been practical to harvest enough plots to characterize these distributions. Areas of homogeneous soil should be expected to produce normal distributions of yields, but areas of heterogeneous soil could produce skewed, multi-peaked or non-normal distributions. This information cannot be obtained by pooling data from many sites or years because such pooling confounds the effects of soil factors and weather. It should be noted, however, that decisions concerning N management must be based on observed yield responses to fertilization rather than on yields.

## Yield Responses

The mean yield response observed for the first increase in N rate ranged from 0.2 to 2.9 Mg $ha^{-1}$, and the mean yield response for the second increase in rate ranged from 0.0 to 1.3 Mg $ha^{-1}$ (Table 5). The profits resulting from each increase in rate can be easily calculated for each site if it is recognized that an additional 0.25 Mg of grain usually is needed to pay for the 56 kg N applied with each increase in rate of fertilization. At these prices the first increase in rate was profitable at 15 of the 16 sites, and the second increase in rate was profitable at 9 of the 16 sites.

Precision of the experimental methods for detecting yield responses can be expressed in terms of LSD values, which ranged from 0.07 to 0.30 Mg $ha^{-1}$ and had a mean of 0.17 Mg $ha^{-1}$ (Table 3). The precision obtained, therefore, was sufficient that profitable yield increases usually were statistically significant at the 95% confidence level usually used as the standard for scientific research. Profitable increases in yields were always statistically significant at the 80% confidence level.

The LSD values in this study indicated much greater precision than is usually found in N-response trials. For example, Blackmer (1986) surveyed the literature relating to corn yield response to nitrification inhibitors and found that yield increases of 8 to 81% (mean = 22%) were required before the investigator would have considered the response to be statistically significant. Yang (2000) summarized data from 70 N-response trials having 10 rates of fertilizer N and concluded that regression analysis usually failed to detect statistically significant effects if yield responses were less than 2 Mg $ha^{-1}$, which amounted to 20% of the highest yields. When the LSD values were calculated as percentages of the lowest rates of fertilization within each trial in the present study, yield increases of only 0.8 to 3.6% (mean = 1.7%) were necessary to attain statistical significance at $\alpha = 0.05$.

Within heterogeneous fields, factors such as yield potential (i.e., highest rate that can be attained by adding fertilizer N), N-supplying power of the soil (i.e., mineralization rate and residual inorganic N), and losses of fertilizer N by leaching or denitrification often vary independently with position in the field. One should not expect observed distributions of yield responses to be predictable from observed distributions of yields attained when trials are conducted on areas of heterogeneous soil. For this reason, observed distributions of yield responses within and among areas of soil have unique significance when dividing fields into management units.

The distributions of yield responses observed within each of the 16 trials in this study are illustrated in Fig. 2. The degree of dispersion (and other parameters) describing each distribution are presented in Table 6. An increase in rates that has no net effects on yields (i.e., Site 16) has approximately equal numbers of positive and negative yield responses. These must be considered experimental errors unless areas having net positive or negative yield responses can be separated. However, if areas having net positive and/or negative yield responses can be separated, this information can be used to subdivide an area into two or more management units.

### Dividing Fields into Management Units

Analyses of yield responses observed within the soil map unit covering the greatest percentage of each trial are presented in Tables 7 and 8 and Fig. 3. The results of these analyses are remarkably similar to results for the entire area within each trial (Tables 5 and 6 and Fig. 2). A t-test showed that yield responses observed within the largest soil map unit were not significantly different from those observed within the entire area covered by the trial at 12 out of 16 sites. These observations suggest that the largest soil map unit was reasonably representative of the remainder of the field.

The LSD values for the largest map unit tended to be slightly higher than for the whole field. This increase must be attributed to the size of the area studied because the standard deviations of yields for map units were slightly lower than for the whole field (Tables 5 and 6). Standard deviations for yields should be expected to decrease if dividing the total area into map units decreased variability in soils and, therefore, in yields. The observed differences in LSD and standard deviations were small, so it should be concluded that neither field size and nor division by map unit had significant effects in this study.

Similarity of distribuitons between Fig 2 and 3, if differences among soil map units is not significant, indicates a problem that influenced both the major soil type as well as the remainder of the field. Possible causes of the problem include malfunction of equipment used to measure yields, non-uniform planting density, inaccurate placement of boundaries between map units, or relatively uniform distributions of divergent soil types that are too small to be shown on survey maps. Analysis to determine the most likely causes of these deviations from normal are beyond the scope of this paper but will be addressed in subsequent papers.

Analyses presented in Table 9 reveal that significant differences in yield responses were often observed among soil map units that covered at least 10% of the area within a site. At the 95% confidence level, differences among soil map units at 10 out of 16 sites for the first increase in rate and 7 out of 16 sites for the second increase in rate were significant. At the 80% level, all sites that would have been profitable were significant. At the 80% confidence level, all differences in yield response that were great enough to pay for the additional increment of N were statistically significant. Although adjustments would have to be made for any additional costs of applying two rates of N, the finding of differences in yield response that are both statistically significant and economically practical seem to provide a rational basis for diving fields into different N management units.

## CONCLUSIONS

The data indicate that field trials where only a few fertilizer treatments in the near-optimal range are applied in strips going the length of fields can be used to make relatively precise measurements of corn yield response to N fertilizer. This method involves dividing fields in a grid pattern with more than 350 cells $ha^{-1}$, calculating yield responses from yields observed on adjacent cells with different fertilizer treatments. Geographic information systems make it possible to characterize mean yields and yield responses for the entire area studied or for individual units on digitized soil survey maps. The probability density of observed yields and yield responses can be calculated for the field or for individual soil map units within the field.

The new method of measuring yield response solves a long-standing problem in making fertilizer recommendations because it can characterize the distributions of yields and yield responses on areas of soil having defined limits on heterogeneity. The limits of heterogeneity can be defined by the physical boundaries of the area studied (i.e., a specific field) or by a combination of soil management history and soil survey map units (specific portions of many fields within a region). Collecting yield response data on areas of soil having defined limits of heterogeneity improves ability to utilize data collected in the past to estimate fertilizer needs for specific areas of soil in the future. The specific problem solved is that traditional response trials on small areas of uniform soil essentially represent a single point sample from a poorly defined area of soil known to include considerable heterogeneity. The new method, therefore, makes it possible to calculate the degree of uncertainty for a given estimate of N fertilizer need, something that could not be done in the past.

The results take an important step toward demonstrating that it is practical to estimate N fertilizer needs in trials where two or three rates of fertilizer are applied at near-optimal rates in alternating strips that cross large areas of land in production agriculture. The optimal difference between rates would depend on expected variability in optimal rates, which can be easily assessed by starting with increments that differ by about 50 kg N $ha^{-1}$. For management units where optimal rates have been identified with reasonable certainty, differences between alternating treatments could be reduced enough to avoid significant loss of profit due to lost yields or unnecessary fertilization. Information needed to define appropriate management units and refine recommendations for each management unit could be collected at very low costs. The results of other studies in progress are developing other steps that are needed to fully demonstrate the utility of this method for developing a new generation of N fertilizer recommendations that quantitatively address variability in N fertilizer needs within and among fields.

## References

Black, C.A. 1993. Soil fertility evaluation and control. Lewis Publishers, Boca Raton, FL.

Blackmer, A.M. 1986. Potential yield response of corn to treatments that conserve fertilizer nitrogen in soils. Agron. J. 78:571-575.

Blackmer, A.M. and S.E. White. 1998. Using precision farming technologies to improve management of soil and fertiliser nitrogen. Aust. J. Agric. Res., 49:555-564.

Cerrato, M.E. and A.M. Blackmer. 1990. Comparison of models for describing corn yield response to nitrogen fertilizer. Agron. J. 82:138-143.

Colwell, J.D. 1994. Estimating fertilize requirements: A quantitative approach. CAB International, Wallingford, Oxon, UK.

Gomez, K.A. and A.A. Gomez. 1984. Statistical procedures for agricultural research, 2nd ed. John Wiley & Sons, Inc., New York, NY.

Heady, E.O., J.T. Pesek, and W.G. Brown. 1955. Crop response surfaces and economic optima in fertilizer use. Research Bulletin 424. Agricultural Experiment Station, Iowa State College, Ames.

Iowa Cooperative Soil Survey. 2000. http://icss.agron.iastate.edu (verified 3 April 2001). Ames, IA.

Little, T.M. and F. J. Hills. 1978. Agricultural experimentation design and analysis. John Wiley & Sons, Inc. New York, NY.

Soil Survey Staff. 1998. Keys to soil taxonomy, 8th ed. USDA-SCS. U.S.Gov. Print. Office, Washington, DC.

Yang, N. C. 2000. Modeling crop response to nitrogen. PhD. dissertation. Iowa State University, Ames.

Table 1. Site number, location, area, soil association, soil map symbol (SMS), soil map unit (SMU), and percentage area covered by SMU for the 16 sites in this study.

| Site | County | Area | Association | SMS | SMU | Area by SMU |
|---|---|---|---|---|---|---|
| | | ha | | | | % |
| 1 | Blackhawk | 5.4 | Marshan-Sawmill-Bremer; | 426 | Aredale | 28 |
| | | | Dinsdale-Klinger-Maxfield; | 11 | Colo-Ely Complex | 24 |
| | | | Kenyon-Clyde-Floyd | 83 | Kenyon | 45 |
| 2 | Blackhawk | 6.2 | Tama-Muscatine-Garwin | 118 | Garwin | 15 |
| | | | | 119 | Muscatine | 62 |
| | | | | 120 | Tama | 14 |
| 3 | Buchanan | 3.4 | Kenyon-Clyde-Floyd | 171 | Bassett | 10 |
| | | | | 391 | Clyde-Floyd Complex | 42 |
| | | | | 83 | Kenyon | 47 |
| 4 | Hamilton | 6.1 | Canisteo-Clarion-Nicollet | 507 | Canisteo | 40 |
| | | | | 138 | Clarion | 32 |
| | | | | 107 | Webster | 13 |
| 5 | Linn | 4.8 | Kenyon-Dinsdale | 377 | Dinsdale | 48 |
| | | | | 381 | Klinger-Maxfield Complex | 40 |
| 6 | Boone | 6.4 | Canisteo-Clarion-Nicollet | 507 | Canisteo | 30 |
| | | | | 138 | Clarion | 44 |
| | | | | 55 | Nicollet | 19 |
| 7 | Boone | 5.9 | Canisteo-Clarion-Nicollet | 507 | Canisteo | 12 |
| | | | | 138 | Clarion | 55 |
| | | | | 55 | Nicollet | 11 |
| | | | | 107 | Webster | 12 |
| 8 | Greene | 4.0 | Canisteo-Webster-Nicollet | 507 | Canisteo | 78 |
| | | | | 138 | Clarion | 13 |
| 9 | Boone | 6.7 | Canisteo-Clarion-Nicollet | 507 | Canisteo | 15 |
| | | | | 138 | Clarion | 52 |
| | | | | 55 | Nicollet | 13 |
| | | | | 107 | Webster | 16 |
| 10 | Boone | 4.1 | Canisteo-Clarion-Nicollet | 507 | Canisteo | 43 |
| | | | | 55 | Nicollet | 36 |
| | | | | 6 | Okoboji | 12 |
| 11 | Greene | 4.2 | Clarion-Nicollet-Webster | 138 | Clarion | 50 |
| | | | | 55 | Nicollet | 13 |
| | | | | 107 | Webster | 30 |

Table 1. (continued)

| Site | County | Area | Association | SMS | SMU | Area by SMU |
|---|---|---|---|---|---|---|
| | | ha | | | | % |
| 12 | Buchanan | 5.8 | Kenyon-Clyde-Floyd | 391 | Clyde-Floyd Complex | 38 |
| | | | | 83 | Kenyon | 57 |
| 13 | Hamilton | 3.9 | Canisteo-Clarion-Nicollet | 507 | Canisteo | 65 |
| | | | | 138 | Clarion | 17 |
| | | | | 55 | Nicollet | 15 |
| 14 | Boone | 4.0 | Brownton-Ottosen-Bode | 52 | Bode | 16 |
| | | | | 1507 | Brownton | 15 |
| | | | | 138 | Clarion | 23 |
| | | | | 388 | Kossuth | 20 |
| | | | | 288 | Ottosen | 23 |
| 15 | Kossuth | 5.1 | Spicer-Fieldon-Coland | 28 | Dickman | 10 |
| | | | | 335 | Harcot | 18 |
| | | | | 1595 | Harpster | 16 |
| | | | | 330 | Kingston | 12 |
| | | | | 6 | Okoboji | 10 |
| | | | | 1032 | Spicer | 16 |
| 16 | Boone | 10.6 | Canisteo-Clarion-Nicollet | 507 | Canisteo | 40 |
| | | | | 138 | Clarion | 37 |
| | | | | 55 | Nicollet | 16 |

Table 2. Soil map unit (SMU), soil map symbols (SMS), and corresponding classifications of soils found at 16 sites (Iowa Cooperative Soil Survey, Ames, IA).

| SMU | SMS | Classification |
|---|---|---|
| Aredale | 426 | Fine-loamy, mixed, superactive, mesic Typic Hapludolls |
| Bassett | 171 | Fine-loamy, mixed, superactive, mesic Oxyaquic Hapludalfs |
| Bode | 52 | Fine-loamy, mixed, mesic Typic Hapludolls |
| Brownton | 1507 | Fine, smectitic, calcareous, mesic Vertic Epiaquolls |
| Canisteo | 507 | Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls |
| Clarion | 138 | Fine-loamy, mixed, superactive, mesic Typic Hapludolls |
| Clyde | 84 | Fine-loamy, mixed, superactive, mesic Typic Endoaquolls |
| Colo | 133 | Fine-silty, mixed, superactive, mesic Cumulic Endoaquolls |
| Dickman | 28 | Sandy, mixed, mesic Typic Hapludolls |
| Dinsdale | 377 | Fine-silty, mixed, mesic Typic Argiudolls |
| Ely | 428 | Fine-silty, mixed, superactive, mesic Aquic Cumulic Hapludolls |
| Floyd | 198 | Fine-loamy, mixed, superactive, mesic Aquic Hapludolls |
| Garwin | 118 | Fine-silty, mixed, superactive, mesic Typic Endoaquolls |
| Harcot | 335 | Fine-loamy over sandy or sandy-skeletal, mesic Typic Calciaquolls |
| Harpster | 1595 | Fine-silty, mixed, superactive, mesic Typic Calciaquolls |
| Kenyon | 83 | Fine-loamy, mixed, mesic Typic Hapludolls |
| Kingston | 330 | Fine-silty, mixed, superactive, mesic Aquic Hapludolls |
| Klinger | 184 | Fine-silty, mixed, mesic Aquic Hapludolls |
| Kossuth | 388 | Fine-loamy, mixed, mesic Typic Endoaquolls |
| Maxfield | 382 | Fine-silty, mixed, superactive, mesic Typic Endoaquolls |
| Muscatine | 119 | Fine-silty, mixed, mesic Aquic Hapludolls |
| Nicollet | 55 | Fine-loamy, mixed, superactive, mesic Aquic Hapludolls |
| Okoboji | 6 | Fine, smectitic, mesic Cumulic Vertic Endoaquolls |
| Ottosen | 288 | Fine-loamy, mixed, superactive, mesic Aquic Hapludolls |
| Spicer | 1032 | Fine-silty, mixed, calcareous, mesic Typic Endoaquolls |
| Tama | 120 | Fine-silty, mixed, superactive, mesic Typic Argiudolls |
| Webster | 107 | Fine-loamy, mixed, superactive, mesic Typic Endoaquolls |

Table 3. Mean yields and LSD values for three rates of N fertilizer at 16 sites in Iowa.

| | Yield | | | |
|---|---|---|---|---|
| Site | Rate 1 | Rate 2 | Rate 3 | $LSD_{0.05}$ |
| | Mg $ha^{-1}$ | | | |
| 1 | 6.2 | 9.1 | 10.4 | 0.15 |
| 2 | 7.0 | 9.8 | 11.1 | 0.13 |
| 3 | 7.3 | 9.8 | 10.6 | 0.19 |
| 4 | 7.4 | 9.8 | 10.3 | 0.20 |
| 5 | 8.5 | 10.8 | 11.2 | 0.15 |
| 6 | 7.9 | 9.8 | 10.4 | 0.13 |
| 7 | 9.1 | 10.3 | 10.6 | 0.16 |
| 8 | 7.9 | 9.1 | 9.5 | 0.16 |
| 9 | 6.5 | 8.2 | 8.3 | 0.30 |
| 10 | 9.7 | 10.5 | 10.8 | 0.30 |
| 11 | 7.9 | 8.8 | 9.0 | 0.22 |
| 12 | 8.4 | 9.1 | 9.2 | 0.13 |
| 13 | 10.8 | 11.1 | 11.4 | 0.21 |
| 14 | 7.1 | 7.7 | 7.8 | 0.13 |
| 15 | 10.8 | 11.2 | 11.3 | 0.15 |
| 16 | 8.5 | 8.7 | 8.7 | 0.07 |
| Mean | 8.2 | 9.6 | 10.0 | 0.17 |

Table 4. Parameters describing the probability density functions (PDF) for three rates of N at 16 sites in Iowa (see Fig. 1).

| Site | R1 | | | | R2 | | | |
|---|---|---|---|---|---|---|---|---|
| | n | SD | Skew.† | Kurt.‡ | n | SD | Skew. | Kurt. |
| | | Mg ha$^{-1}$ | | | | Mg ha$^{-1}$ | | |
| 1 | 633 | 1.8 | 0.0 | -0.5 | 630 | 1.2 | 0.2 | 2.5 |
| 2 | 728 | 1.3 | -1.4 | 5.2 | 710 | 1.4 | -1.4 | 3.2 |
| 3 | 401 | 1.1 | -1.1 | 5.4 | 398 | 1.5 | -1.3 | 11.6 |
| 4 | 703 | 2.0 | -1.1 | 1.8 | 702 | 1.9 | -2.2 | 7.2 |
| 5 | 554 | 1.6 | -1.2 | 1.8 | 558 | 1.1 | -2.8 | 16.4 |
| 6 | 757 | 1.3 | -1.3 | 4.1 | 753 | 1.3 | -1.6 | 10.9 |
| 7 | 633 | 1.6 | -1.2 | 3.8 | 632 | 1.5 | -2.1 | 8.9 |
| 8 | 535 | 1.3 | -1.2 | 2.5 | 535 | 1.5 | -1.5 | 3.1 |
| 9 | 88 | 1.4 | -0.7 | 0.2 | 265 | 1.2 | -0.8 | 3.7 |
| 10 | 487 | 2.3 | -2.4 | 6.8 | 488 | 2.5 | -2.6 | 8.2 |
| 11 | 499 | 1.8 | -1.9 | 5.7 | 497 | 1.8 | -1.4 | 3.2 |
| 12 | 662 | 1.3 | -1.4 | 11.4 | 658 | 1.1 | -3.1 | 15.3 |
| 13 | 461 | 1.6 | -3.1 | 17.3 | 463 | 1.6 | -2.2 | 16.3 |
| 14 | 400 | 0.9 | -0.4 | 1.7 | 388 | 1.0 | 0.0 | 2.2 |
| 15 | 579 | 1.5 | -2.7 | 14.7 | 579 | 1.4 | -3.6 | 18.8 |
| 16 | 1247 | 0.9 | -2.3 | 10.9 | 1252 | 0.8 | -2.0 | 9.5 |

†Skewness

‡Kurtosis

Table 4. (continued)

| Site | R3 | | | |
|---|---|---|---|---|
| | n | SD | Skew. | Kurt. |
| | | Mg ha$^{-1}$ | | |
| 1 | 629 | 0.9 | -1.3 | 3.1 |
| 2 | 719 | 1.2 | -2.7 | 9.6 |
| 3 | 401 | 1.5 | -2.7 | 16.8 |
| 4 | 704 | 1.8 | -2.1 | 7.0 |
| 5 | 554 | 1.0 | -2.5 | 13.1 |
| 6 | 752 | 1.3 | -2.4 | 12.9 |
| 7 | 630 | 1.4 | -2.7 | 13.0 |
| 8 | 535 | 1.3 | -0.9 | 1.2 |
| 9 | 265 | 1.5 | -1.7 | 4.5 |
| 10 | 488 | 2.5 | -2.9 | 9.1 |
| 11 | 500 | 1.8 | -1.7 | 4.9 |
| 12 | 657 | 1.2 | -2.4 | 11.7 |
| 13 | 461 | 1.6 | -2.9 | 17.5 |
| 14 | 384 | 0.8 | -0.7 | 2.9 |
| 15 | 576 | 1.1 | -3.2 | 19.0 |
| 16 | 1250 | 0.8 | -1.5 | 8.2 |

Table 5. Mean yield response to three N-fertilizer treatments for 16 sites in Iowa.

| Site | Yield Response $R_2$-$R_1$ | $R_3$-$R_2$ |
|---|---|---|
| | —— Mg ha$^{-1}$ —— | |
| 1 | 2.9 | 1.3 |
| 2 | 2.8 | 1.3 |
| 3 | 2.4 | 0.9 |
| 4 | 2.5 | 0.5 |
| 5 | 2.3 | 0.3 |
| 6 | 1.9 | 0.6 |
| 7 | 1.2 | 0.2 |
| 8 | 1.1 | 0.4 |
| 9 | 1.6 | 0.1 |
| 10 | 0.7 | 0.3 |
| 11 | 0.9 | 0.1 |
| 12 | 0.7 | 0.1 |
| 13 | 0.4 | 0.3 |
| 14 | 0.6 | 0.0 |
| 15 | 0.4 | 0.0 |
| 16 | 0.2 | 0.0 |
| Mean | 1.4 | 0.4 |

Table 6. Parameters describing the probability density function (PDF) for two levels of yield response at 16 sites in Iowa (see Fig. 2).

| Site | $Y_{R2}$-$Y_{R1}$ | | | | $Y_{R3}$-$Y_{R2}$ | | | |
|---|---|---|---|---|---|---|---|---|
| | n | SD | Skew.† | Kurt.‡ | n | SD | Skew. | Kurt. |
| | | Mg ha$^{-1}$ | | | | Mg ha$^{-1}$ | | |
| 1 | 628 | 1.3 | 0.1 | 0.3 | 625 | 1.1 | -0.5 | 2.8 |
| 2 | 707 | 1.0 | 0.0 | 2.4 | 697 | 1.3 | 1.0 | 4.5 |
| 3 | 397 | 1.2 | -2.0 | 17.7 | 395 | 1.7 | -1.2 | 24.6 |
| 4 | 691 | 1.5 | 0.6 | 5.6 | 695 | 1.2 | 0.0 | 6.0 |
| 5 | 551 | 1.4 | 0.8 | 2.3 | 553 | 0.9 | -0.4 | 9.8 |
| 6 | 750 | 1.4 | 0.5 | 4.4 | 748 | 1.4 | -0.3 | 1.4 |
| 7 | 628 | 1.2 | -0.6 | 2.6 | 624 | 1.1 | -0.8 | 11.6 |
| 8 | 535 | 1.3 | -0.6 | 2.4 | 535 | 1.4 | 0.8 | 2.9 |
| 9 | 263 | 1.8 | 0.1 | 1.3 | 265 | 1.7 | -0.7 | 3.6 |
| 10 | 487 | 1.2 | 1.8 | 25.1 | 488 | 1.1 | -1.1 | 9.9 |
| 11 | 497 | 1.5 | 2.5 | 14.0 | 497 | 0.9 | 0.1 | 3.3 |
| 12 | 650 | 1.1 | -1.1 | 11.2 | 648 | 1.0 | 0.1 | 8.4 |
| 13 | 459 | 1.5 | 0.4 | 11.3 | 459 | 1.7 | -1.1 | 11.3 |
| 14 | 388 | 1.3 | -0.2 | 1.9 | 384 | 1.3 | -0.1 | 2.4 |
| 15 | 577 | 1.7 | -1.4 | 21.5 | 575 | 1.4 | 0.5 | 16.1 |
| 16 | 1243 | 0.8 | 1.2 | 6.8 | 1250 | 0.7 | 0.2 | 7.7 |

†Skewness

‡Kurtosis

Table 7. Yield response to N-fertilizer treatments for major soil map unit (percent area) at 16 sites in Iowa

| Site | Yield Response $R_2$-$R_1$ | $R_3$-$R_2$ |
|---|---|---|
| | Mg $ha^{-1}$ | |
| 1 | 2.8 | 1.7 |
| 2 | 2.8 | 1.0 |
| 3 | 2.2 | 1.1 |
| 4 | 2.7 | 0.5 |
| 5 | 2.4 | 0.3 |
| 6 | 2.1 | 0.5 |
| 7 | 1.3 | 0.3 |
| 8 | 1.1 | 0.5 |
| 9 | 1.6 | 0.1 |
| 10 | 0.7 | 0.3 |
| 11 | 0.7 | 0.2 |
| 12 | 0.7 | 0.2 |
| 13 | 0.4 | 0.4 |
| 14 | 0.4 | 0.0 |
| 15 | 0.6 | -0.1 |
| 16 | 0.1 | 0.1 |
| Mean | 1.4 | 0.4 |

Table 8. Parameters describing the probability density function (PDF) for two levels of yield response on the major soil map unit (percentage area) at 16 sites in Iowa.

| Site | $Y_{R2}$-$Y_{R1}$ | | | | $Y_{R3}$-$Y_{R2}$ | | | |
|---|---|---|---|---|---|---|---|---|
| | n | SD | Skew.† | Kurt.‡ | n | SD | Skew. | Kurt. |
| | | Mg ha$^{-1}$ | | | | Mg ha$^{-1}$ | | |
| 1 | 286 | 1.1 | 0.4 | 0.0 | 293 | 0.9 | -0.4 | 0.7 |
| 2 | 452 | 0.8 | -0.1 | 1.9 | 446 | 1.0 | -0.4 | 0.8 |
| 3 | 183 | 1.4 | -3.1 | 16.4 | 188 | 1.7 | 2.2 | 11.8 |
| 4 | 268 | 1.7 | 1.0 | 6.6 | 268 | 1.1 | 0.0 | 2.0 |
| 5 | 278 | 1.3 | 1.3 | 3.8 | 280 | 0.7 | 0.4 | 0.7 |
| 6 | 337 | 1.4 | 0.9 | 3.9 | 331 | 1.4 | -0.4 | 1.1 |
| 7 | 341 | 1.3 | -0.7 | 2.7 | 342 | 1.2 | -0.1 | 8.2 |
| 8 | 310 | 1.3 | -0.2 | 1.0 | 321 | 1.5 | 0.8 | 2.4 |
| 9 | 141 | 1.8 | -0.4 | 1.8 | 152 | 1.6 | 0.4 | 2.4 |
| 10 | 206 | 1.5 | 3.2 | 29.7 | 206 | 1.2 | -1.6 | 11.7 |
| 11 | 200 | 1.2 | 0.1 | 0.6 | 206 | 0.9 | 0.1 | 4.3 |
| 12 | 389 | 0.9 | -1.7 | 18.1 | 382 | 0.7 | -0.1 | 11.7 |
| 13 | 295 | 1.4 | 1.9 | 9.5 | 301 | 1.6 | -1.6 | 12.7 |
| 14 | 99 | 1.1 | -0.3 | 0.6 | 97 | 0.9 | 1.1 | 1.6 |
| 15 | 87 | 2.0 | 1.8 | 8.3 | 103 | 2.1 | 0.2 | 10.1 |
| 16 | 486 | 0.7 | 1.0 | 5.6 | 515 | 0.7 | 0.5 | 2.9 |

†Skewness

‡Kurtosis

Table 9. Yield response to N-fertilizer treatments for each of the soil map units representing more than 10% of the area at each of the 16 sites studied. LSD values are presented at two levels, $\alpha$ = 0.05 and 0.20. Yield attained at the highest rate of N for each soil map unit is shown.

| Site | SMU | $Yield_{R3}$ | $R_3$-$R_2$ | $LSD_{0.05}$ | $LSD_{0.2}$ | $R_2$-$R_1$ | $LSD_{0.05}$ | $LSD_{0.2}$ |
|---|---|---|---|---|---|---|---|---|
| | | Mg $ha^{-1}$ | | | | | | |
| 1 | Aredale | 10.5 | 1.2 | | | 3.6 | | |
| | Colo-Ely Comp. | 10.6 | 0.6 | 0.2 | 0.1 | 2.4 | 0.2 | 0.2 |
| | Kenyon | 10.2 | 1.7 | | | 2.8 | | |
| 2 | Garwin | 11.2 | 2.3 | | | 2.7 | | |
| | Muscatine | 11.0 | 1.0 | 0.3 | 0.2 | 2.8 | 0.2 | 0.2 |
| | Tama | 11.6 | 1.7 | | | 2.9 | | |
| 3 | Bassett | 10.8 | 0.6 | | | 2.5 | | |
| | Clyde-Floyd Comp. | 10.8 | 0.6 | 0.5 | 0.3 | 2.6 | 0.4 | 0.3 |
| | Kenyon | 10.3 | 1.1 | | | 2.2 | | |
| 4 | Canisteo | 10.9 | 0.5 | | | 2.7 | | |
| | Clarion | 10.2 | 0.4 | 0.3 | 0.2 | 2.5 | 0.3 | 0.2 |
| | Webster | 9.2 | 0.7 | | | 2.2 | | |
| 5 | Dinsdale | 11.1 | 0.3 | 0.2 | 0.1 | 2.4 | 0.3 | 0.2 |
| | Klinger-Maxfield Comp. | 11.1 | 0.3 | | | 2.1 | | |
| 6 | Canisteo | 10.5 | 0.8 | | | 1.9 | | |
| | Clarion | 10.2 | 0.5 | 0.3 | 0.2 | 2.1 | 0.3 | 0.2 |
| | Nicollet | 10.6 | 0.7 | | | 1.6 | | |
| 7 | Canisteo | 10.8 | 0.3 | | | 1.1 | | |
| | Clarion | 10.3 | 0.3 | 0.3 | 0.2 | 1.3 | 0.4 | .23. |
| | Nicollet | 11.2 | 0.3 | | | 1.2 | | |
| | Webster | 10.6 | 0.1 | | | 1.3 | | |
| 8 | Canisteo | 9.3 | 0.5 | 0.3 | 0.2 | 1.1 | 0.3 | 0.2 |
| | Clarion | 10.0 | 0.4 | | | 1.4 | | |
| 9 | Canisteo | 8.1 | 0.5 | | | 1.9 | | |
| | Clarion | 8.2 | 0.1 | 0.7 | 0.5 | 1.7 | 0.7 | 0.5 |
| | Nicollet | 8.2 | 0.1 | | | 1.2 | | |
| | Webster | 9.2 | 0.5 | | | 1.5 | | |

Table 9. (continued)

| Site | SMU | $Yield_{R3}$ | $R_3$-$R_2$ | $LSD_{0.05}$ | $LSD_{0.2}$ | $R_2$-$R_1$ | $LSD_{0.05}$ | $LSD_{0.2}$ |
|---|---|---|---|---|---|---|---|---|
| | | Mg ha$^{-1}$ | | | | | | |
| 10 | Canisteo | 10.2 | 0.3 | 0.3 | 0.2 | 0.7 | 0.3 | 0.2 |
| | Nicollet | 11.7 | 0.4 | | | 0.8 | | |
| | Okoboji | 9.3 | 0.4 | | | 0.3 | | |
| 11 | Clarion | 9.0 | 0.2 | 0.2 | 0.2 | 0.7 | 0.5 | 0.3 |
| | Nicollet | 9.5 | 0.2 | | | 0.8 | | |
| | Webster | 9.2 | 0.0 | | | 1.1 | | |
| 12 | Clyde-Floyd Comp. | 9.0 | 0.1 | 0.2 | 0.1 | 0.6 | 0.2 | 0.1 |
| | Kenyon | 9.3 | 0.2 | | | 0.7 | | |
| 13 | Canisteo | 11.8 | 0.4 | 0.5 | 0.3 | 0.4 | 0.4 | 0.3 |
| | Clarion | 10.9 | 0.0 | | | 0.2 | | |
| | Nicollet | 10.3 | 0.0 | | | 0.5 | | |
| 14 | Bode | 7.6 | -0.3 | 0.5 | 0.3 | 0.8 | 0.4 | 0.3 |
| | Brownton | 8.1 | 0.7 | | | 0.2 | | |
| | Clarion | 7.6 | 0.0 | | | 0.4 | | |
| | Kossuth | 7.9 | 0.0 | | | 0.6 | | |
| | Ottosen | 7.7 | -0.1 | | | 0.9 | | |
| 15 | Dickman | 11.2 | -0.1 | 0.4 | 0.3 | 0.2 | 0.5 | 0.3 |
| | Harcot | 11.0 | -0.1 | | | 0.6 | | |
| | Harpster | 11.4 | 0.1 | | | 0.4 | | |
| | Kingston | 11.3 | -0.1 | | | 0.5 | | |
| | Okoboji | 11.1 | 0.1 | | | 0.0 | | |
| | Spicer | 11.3 | 0.1 | | | 0.2 | | |
| 16 | Canisteo | 8.6 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | Clarion | 8.7 | 0.0 | | | 0.3 | | |
| | Nicollet | 8.8 | 0.1 | | | 0.2 | | |

Fig. 1. Probability density functions of yield for three rates of nitrogen across the entire field at each of 16 sites in Iowa.

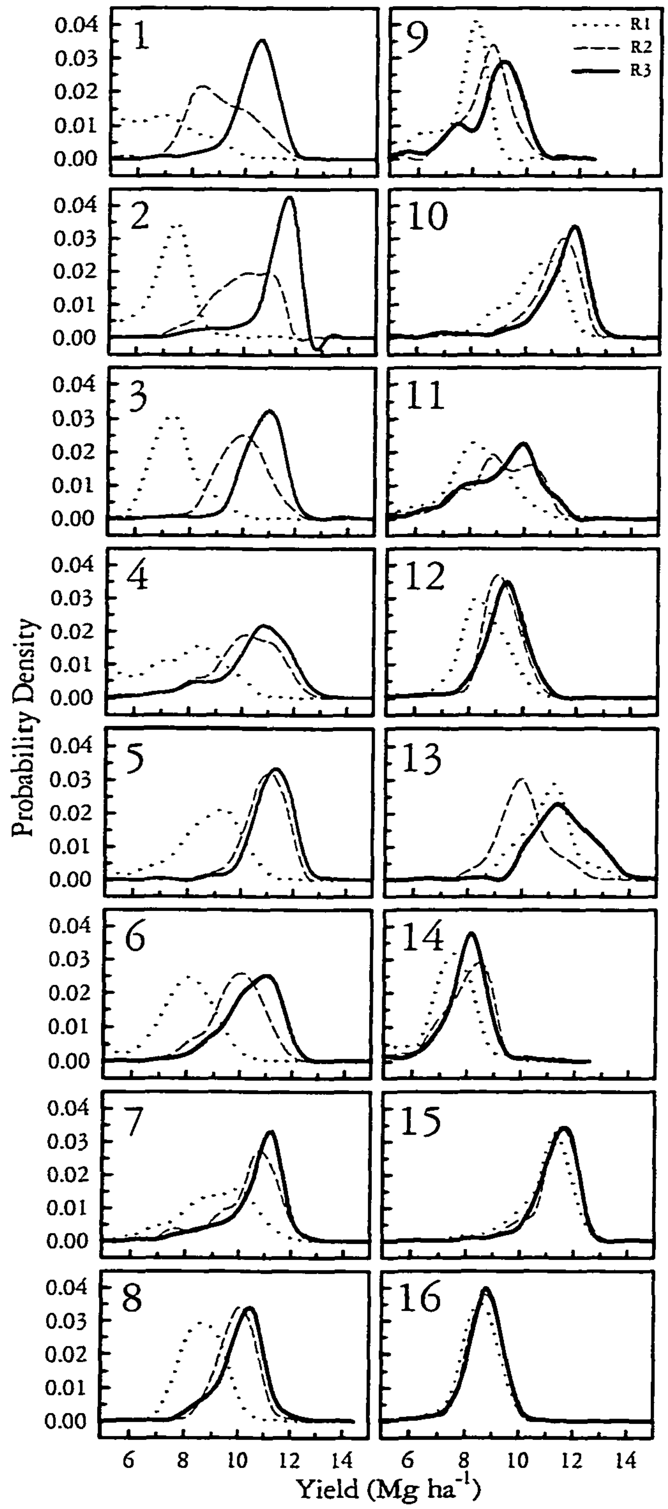


Fig. 2. Probability density functions of yield response for two increments of N-fertilizer at 16 sites in Iowa. $R_2$-$R_1$ is the yield response from R1 to R2 and $R_3$-$R_2$ is the yield response from R2 to R3.

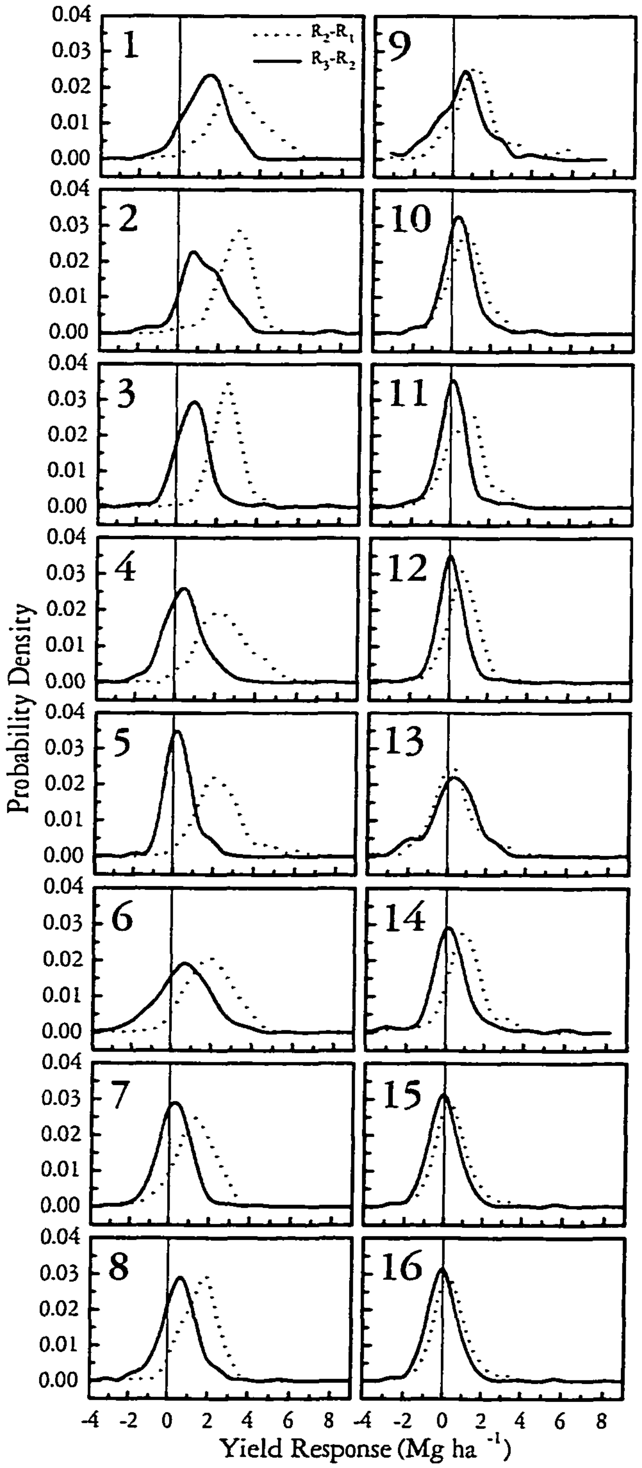
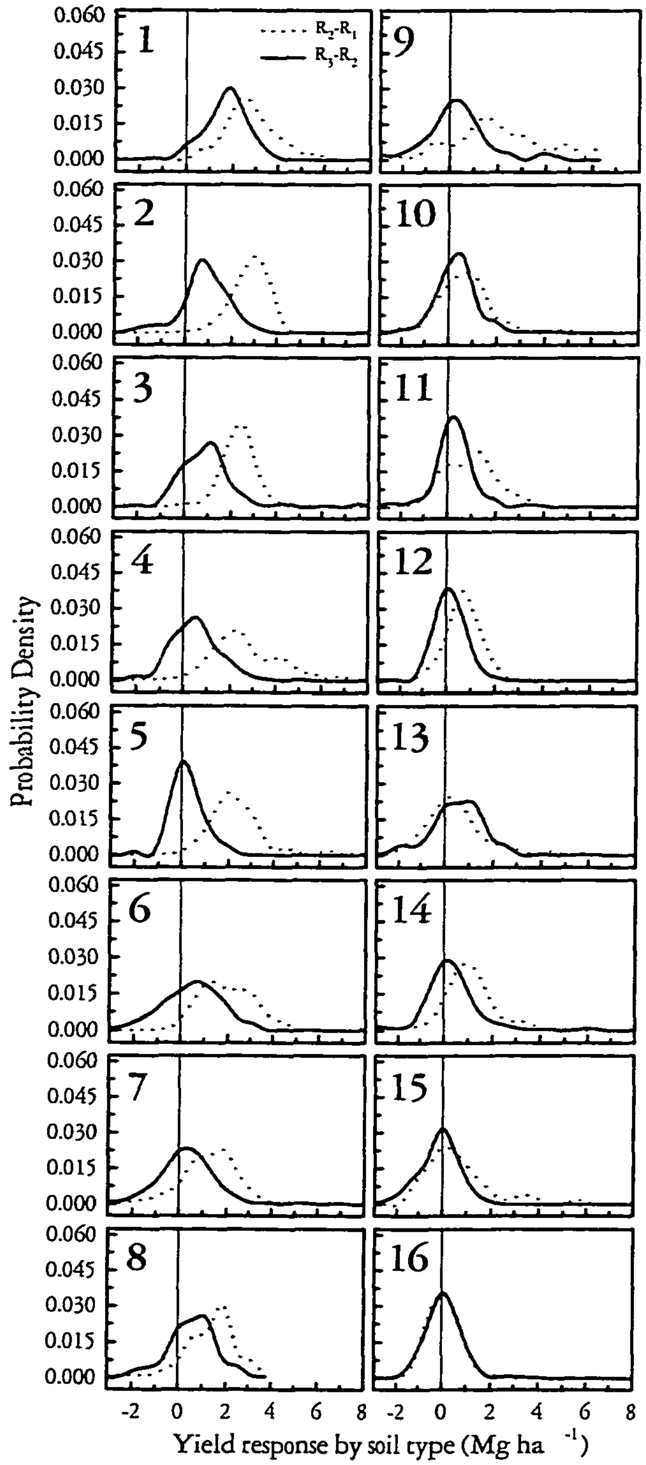


Fig. 3. Probability density functions of yield response within the major soil map unit (percentage area) to two increments of N-fertilizer at 16 sites in Iowa. $R_2$-$R_1$ is the yield response from R1 to R2 and $R_3$-$R_2$ is the yield response from R2 to R3.



# Chapter III: Remote Sensing of Corn and Soybean Fields to Define Nitrogen Management Units

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## Abstract

The advent of variable-rate application technologies has created a need for methods of dividing fields into N management units, or areas similar enough to receive the same rate of N. In this paper, we explore the potential of using remote sensing of soybean canopies to divide cornfields into N-management units. Studies were conducted on a single 32-ha field that was planted to corn in 1999. Various N treatments were applied in replicated strips, and complex spatial patterns in crop response to these treatments were observed but could not be explained by considering soil survey map units. Aerial photographs of the soybean canopy the next year showed remarkably similar spatial patterns in stress associated with small areas of calcareous soils. Evidence suggested that the spatial patterns observed during corn production were caused by greater losses of fertilizer N from the calcareous soils than the non-calcareous soils. The results show that remote sensing of crop canopies has great value for mapping small areas of soil that are significantly different than the surrounding soil.

## Introduction

The advent of fertilizer applicators that can adjust rates of fertilization while moving across fields has generated need for developing maps of N-fertilizer needs within cornfields. Ellsworth et al. (2001) recently described a method of dividing fields into two or more N-management units, or areas of soil that should receive a common rate of fertilization. The method involved applying various fertilizer treatments in relatively narrow strips that cross fields known to be heterogeneous, harvesting each strip using combines equipped with yield monitors and global positioning system (GPS) receivers, and calculating yield response to treatments. A geographic information system (GIS) was used to isolate and study populations of observed yield responses within and among soil survey map units to assess degree of similarity of responses observed. Ellsworth and Blackmer (2001) demonstrated how this method could be used to evaluate alternative methods of N fertilization.

Ellsworth et al (2001) focused on using published soil survey map units for defining management units because these maps are readily available and widely used in production agriculture. Although soil survey maps clearly provide important information needed to divide fields into appropriate management units, other tools can provide additional useful information. Recent studies, for example, suggest that fields can be divided by using soil test values (Coelho et al. 1998), electrical conductivity (Kitchen et al., 2000; Kitchen et al., 1999), topography (Kravchenko and Bullock, 2000; Franzen et al., 1998; Nolan et al., 1998), farmer defined management zones (Fleming et al., 1998), yield maps (Stafford et al., 1998), several related soil factors (Fridgen et al., 2000), or spatial patterns in crop response to fertilizers. The relative merits of each method have not been established, but they undoubtedly will depend on some balance between the importance of the exact characteristic measured and practicality of making enough observations to adequately characterize the relevant spatial patterns within fields.

Remote sensing can be used to characterize spatial patterns of N response in cornfields where various rates of N are applied in strips (Blackmer and White, 1998). Spatial patterns are revealed because N-deficient corn shows higher reflectance of visible light (i.e., less greenness) than does corn with adequate N. Optimal and above-optimal supplies of N, however, result in similar amounts of reflected light in this portion of the spectrum. Contrasting amounts of light reflected from adjacent strips having different rates of N, therefore, provide a relatively simple way to study spatial patterns in N deficiencies and can be used to identify spatial patterns in N response. The key advantage of remote sensing is that much higher degrees of spatial resolution can be attained than with yield monitors or any other method of point sampling.

Recent studies (Blackmer et al., 2000) indicate that losses of N applied as anhydrous ammonia in the fall tend to increase with increasing soil pH and that additions of N-Serve tend to reduce the effect of pH on these losses. These observations suggest that soil pH deserves attention when dividing cornfields into N-management units. Other recent studies (Rogosvka and Blackmer, unpublished) indicate that areas of high-pH soils can be identified by remote sensing of soybean canopies. The specific characteristic detected in the soybean crop was patches of chlorosis, which are normally associated with high-pH soils and soils having free calcium carbonate (Mengel and Kirkby, 1987). These observations suggest that remote sensing of soybean canopies may provide an efficient way to identify high-pH areas and thereby help define potential N-management units for corn. Ability to characterize spatial patterns influenced by free calcium carbonate could be especially valuable in Iowa because calcareous areas often occur in small, irregular-shaped areas that are imperfectly mapped within fields.

The objectives of this paper are to demonstrate the use of remote sensing of soybean and corn canopies to define N management units in cornfields and discuss the potential benefits of using this technique. The studies were conducted at a site where areas of calcareous soils were not correctly identified on soil survey maps. This error in mapping was not detected during intensive studies of N response in corn, it was serendipitously discovered in aerial photographs of the soybean canopy within the same field the next year.

## Materials and Methods

This 32-ha site is located about 1.2 km north of Ogden, IA in Boone County. The site is situated on the Des Moines Lobe, the most recently glaciated area in central and north central Iowa. This landscape feature is of the Wisconsinan Glacial Stage (12,000-14,000 ybp) and is characterized by fresh glacial drift, no loess cover and poor surface drainage. The soils are in the Canisteo-Clarion-Nicollet association. This area receives about 840 mm of precipitation a year, 73% from April to September. The mean annual temperature is 10°C. The site has been under no-till practices for the past 15 years in a corn-soybean rotation.

Soil types found within the study site are [area, classification (Soil Survey Staff, 1998)]: Canisteo (12%, Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), Clarion (55%, Fine-loamy, mixed, superactive, mesic Typic Hapludolls), Coland (3%, Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls), Harps (1%, Fine-loamy, mixed, superactive, mesic Typic

Calciaquolls), Nicollet (11%, Fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Okoboji (1%, Fine, smectitic, mesic Cumulic Vertic Endoaquolls), Terril (4%, Fine-loamy, mixed, superactive, mesic Cumulic Hapludolls), and Webster (12%, Fine-loamy, mixed, superactive, mesic Typic Endoaquolls).

On 24 November 1998, 140 kg N $ha^{-1}$ were applied in a stratified design with an applicator that could simultaneously apply N, P, K and N-Serve [nitrapyrin, 2-chloro-6-(trichloromethyl) pyridine, Dow AgroSciences, Indianapolis, IN]. In the first application pass across the field (in addition to the P and K), 140 kg N $ha^{-1}$ in the form of anhydrous ammonia was applied with 2.3 L N-Serve $ha^{-1}$. In the next pass 140 kg N $ha^{-1}$ was applied without N-Serve. The next two application passes did not receive fall-N. The pattern was repeated for six replications. Each applicator pass was marked with flags at both ends and locations were recorded with a GPS.

Pioneer hybrid 35N05 (Pioneer Hi-Bred International, Inc., Des Moines, IA) was planted at a population of 79,000 plant $ha^{-1}$ in early May. After planting, the field was divided into 6-row strips going the length of the field and numbered consecutively across the field. On June 6, urea ammonium nitrate, (UAN, 32% N) was injected at rates of 56, 112, and 168 kg N $ha^{-1}$ to the strips that did not receive N in the fall.

The field was harvested using a conventional combine mounted with a Yield Monitor 2000 (Ag Leader Technology, Inc., Ames, IA) and AG132 GPS receiver (Trimble Navigation Limited, Sunnyvale, CA). Data points were recorded at one second intervals. Average speed while harvesting each strip was 5.3 km $hr^{-1}$. Yield data was imported into ArcView GIS (v. 3.2, ESRI, Redlands, CA) for post processing and analysis.

For analysis, the experimental areas in each trial were divided into a grid formed by strips (treatments and combine swaths) and 6.1 m tiers that were perpendicular to the treatment strips and numbered consecutively from one end of the field to the other. The area of each grid cell was approximately 28 $m^2$. Yield values for each cell in the grid were calculated (each cell contained an average of two yield points) and qualitative properties such as soil map unit were assigned to each cell. Yield responses were calculated by subtracting the yield in one cell from yields in the appropriate adjacent cell. Cells were treated as individual experimental units.

An aerial image of the corn canopy at this site was taken on 26 August 1999 by a commercial aerial image provider. The photo was scanned and georeferenced to control points which were 60 x 120 cm plywood targets painted white and placed in the field at the corners of the study area.

An aerial image of the soybean canopy was acquired in late August of 2000 using a high quality SLR camera with an auto focus wide-angle zoom lens on 200-speed color slide film at an altitude of 1000 m above ground level. The slide was scanned and georeferenced using existing landmarks to the corn canopy image taken in 1999. Since the camera was not stabilized in the plane and the image was slightly oblique, rubber sheeting was used to bring the 2000 image into close alignment to the 1999 image.

The field was divided into N-management units using three methods to classify calcareous soils. The first method (Map A) used the published soil survey. Only those soils designated calcareous according to the Keys to Soil Taxonomy were used for this analysis (Soil Survey Staff, 1998). Figure 1A shows the digitized soil survey map overlaid on an image of the corn canopy in late August 1999.

For the second method (Map B), areas of the field that appeared to be highly responsive to N treatments based on corn canopy reflectance (Fig. 1B) were selected by enclosing the area in a polygon within the ArcView software. In the corn canopy image, areas marked by streaks of high reflectance (i.e., light green or yellow color) required the highest rates of N to maximize yields. The lowest rates of N essentially maximized yields in those areas that showed no streaks due to N treatment.

Figure 1D shows spatial patterns in color of the soybean canopy within the same field in August of 2000. Yellow or brown portions of the field indicate chlorosis that is usually associated with high pH soils and presence of free $CaCO_3$. Chlorotic areas were tested for carbonates by walking through the field and checking for effervescence when dilute HCl was applied at various depths. Areas that tested positive for carbonates are marked in Figures 1C and 1D. A similar check on the areas mapped as calcareous by the published soil survey revealed no effervescence.

Selecting areas based on a range of pixel values was not possible with the corn canopy photo because treatment effects confounded canopy color; nor was it possible with the soybean canopy photo because of inadequate light when the photographs were taken, thus, each area was arbitrarily selected.

SAS (v. 8.1, SAS Institute, Cary, NC) was used to calculate the means and probability density functions of yield and yield response. Probability density functions (PDF) were calculated using the PROC UNIVARIATE procedure. The PDF was selected over a standard frequency distribution because yield and yield response are continuous variables. Sigma Plot (v. 5.0, SPSS Inc., Chicago, IL) was used to present data in graph form.

## Results

### Responses to UAN

Data presented in Table 1 shows that increasing rate on UAN from 56 to 112 kg N $ha^{-1}$ resulted in significant yield increases in both the calcareous and non-calcareous soils. The analysis of all maps agreed that this increase in rate was profitable on the calcareous and non-calcareous soils because it takes 0.28 Mg of grain to pay for the fertilizer applied. Analysis of Maps B and C showed that yield responses differed among calcareous and non-calcareous soils but analysis of Map A showed no significant differences. The disagreement can be explained because Map A incorrectly indicated locations of calcareous soils. This disagreement was not of practical importance, however, because analysis of all maps would have indicated the correct decision to apply this increment of fertilizer to both the calcareous and non-calcareous soils.

Analysis showed that increasing the rate of UAN from 112 to 168 kg N $ha^{-1}$ on the non-calcareous soils resulted in significant yield increases when Map A was analyzed but not when Maps B and C were analyzed. On the calcareous soils, the yield increases were not significant when Map A was analyzed but were significant when Maps B and C were analyzed. The calcareous and non-calcareous soils differed in magnitude of yield response when Maps B and C were analyzed but not when Map A was analyzed.

The error associated with Map A was important because it would have resulted in an incorrect decision concerning where this increment should have been applied. As indicated by analysis of Maps B and C this increment was profitable only on the calcareous soils. Indeed, analysis showed that one dollar invested in fertilizer on these soils returned $2.32 to $2.64 in additional grain. A dollar spent on fertilizers on the non-calcareous soils would return $0.36 to $0.54. Use of Map A, therefore, would have resulted in a substantial loss in profit on calcareous soils.

Figure 2 shows distributions of yield responses observed within calcareous and non-calcareous portions of the field that received various rates of UAN solution applied in the spring. The distribution of yield responses resulting from increasing rates of fertilization from 56 to 112 kg N $ha^{-1}$ resulted in apparent bimodal distributions in the areas mapped as calcareous and non-calcareous. The calcareous area, however, showed a much greater percentage of the area having large responses to this increment. These bimodal distributions can be explained by recognizing that Map A incorrectly indicated locations of calcareous soils.

Although it can be questioned whether these distributions in Fig. 2 are truly bimodal, it should be noted that increasing rates of fertilization produced nearly normal distributions. The higher rates of fertilization decreased variability in yield responses, so fewer observations were needed to produce relatively smooth curves. This observation demonstrates that, as should be expected, the maps of variability in yield response to a given increment of N should be expected to vary with the level of N already present in the soil.

Figure 3 shows the distribution of yields observed within calcareous and non-calcareous portions of the field that received various rates of UAN applied in the spring. Map A shows nearly normal distributions of yields. As should be expected, a slight skewness to the left is observed on the non-calcareous soils because lower yielding calcareous soils were incorrectly included in the non-calcareous areas.

Maps B and C showed nearly normal distributions of yields (Fig. 3) for the non-calcareous soils. For the calcareous soils, however, there was marked dispersion of the yields especially at the higher rates of fertilization. It seems that high variability in losses resulted in sufficient dispersion of yields that the numbers of observations were not adequate to produce smooth curves.

**Responses to N-Serve**

Analysis of all maps showed that yield responses to N-Serve were statistically significant and profitable on non-calcareous soil (Table 4). Responses to N-Serve on the calcareous soil were neither statistically significant nor profitable when Map A was analyzed. However, the responses to N-Serve on the calcareous soil were both significant and profitable when Maps B and C were analyzed. The errors associated with analysis of Map A were of great practical importance because it would have resulted in not applying N-Serve where use of N-Serve would have been most profitable. It is noteworthy that Maps B and C indicated that $1.00 spent on N-Serve returned $7.81 to $11.00 in additional grain on the calcareous soil on this site.

The distribution of yield responses to N-Serve over the whole field appeared near normal (Fig. 4). The distribution centered to the right of zero, which indicates a net positive response to N-Serve. The standard deviation for this population is about twice the mean standard deviation for yield responses to 56 kg N $ha^{-1}$ that Ellsworth et al. (2001) observed across 16 sites. Greater variability in response to N-Serve should be expected because this nitrification inhibitor prevented losses of fall-applied N that were much larger on calcareous portions of the field than on non-calcareous portions of the field.

Figure 5 shows distribution of yield responses observed within calcareous and non-calcareous portions of the field that received anhydrous ammonia applied in the fall with and without N-Serve. Maps B and C showed an apparent bimodal distribution of yield responses on the non-calcareous areas. This bimodal distribution should be expected because our method of identifying calcareous areas always included some non-calcareous areas. Indeed visual analysis of Fig. 1 suggests that as much as a third of the area identified as calcareous may have been non-calcareous or weakly calcareous. Under such conditions clear bimodal distributions should be expected for the area called calcareous by Maps B and C even though they do not show up in the non-calcareous area by Map A. With Map A, the truly calcareous areas would show up in the PDF as skewness to the right on the area mapped as non-calcareous.

Figure 6 shows the distributions of yields observed within calcareous and non-calcareous portions of the field that received anhydrous ammonia applied in the fall with and without N-Serve. Map A indicated that N-Serve had relatively small effects on yields in the calcareous and non-calcareous portions of the fields. The distribution in the non-calcareous soil showed more skewness to the left. This skewness can be explained by recognizing that this method incorrectly identifies the calcareous and non-calcareous soils.

Maps B and C showed relatively small effects of N-Serve and nearly normal distributions of yields on the non-calcareous soils. On the calcareous soils, however, yields without N-Serve clearly were not normally distributed. Extremely high variability in losses of fertilizer N resulted in extremely high dispersion of the observations, so the numbers of observations were not adequate to produce a near normal curve.

The lack of near normality in distribution of yields without N-Serve cannot be attributed solely to the small area of calcareous soils because approximately the same number of samples produced nearly normal distribution for the same sized area in Map A. The distribution of yields with N-Serve in the calcareous soils showed much less dispersion because the N-Serve reduced variability and losses of the fall applied N. An important point illustrated is the number of observations necessary to produce smooth curves increases with dispersion of data.

## Discussion

Remote sensing of soybean canopies shows areas of high-pH soils as indicated by a pH-sensitive crop. Advantages of this approach include that it directly addresses the soil characteristic of importance and that it identifies high-pH areas with a high degree of spatial resolution. It becomes apparent that this high degree of spatial resolution was attained at relatively little cost if one considers the cost of collecting and analyzing soil samples in a grid pattern fine enough to characterize these patterns with a comparable degree of resolution.

It is likely that remote sensing of the corn canopies to detect spatial patterns in crop response to N-Serve or fertilizer N would have provided a basis for characterizing spatial patterns in response to N if only two treatments were compared in alternating strips. This approach, however, would not reveal soil pH as the primary soil characteristic responsible for the spatial patterns in response observed. In this study, for example, we had no explanation for the complex spatial patterns in response observed until we saw an image of the soybean canopy.

The results of this study show that remote sensing of soybean canopies solved another important dilemma. The first part of the dilemma is that spatial patterns in corn response to N are poorly defined when several treatments are compared and only a few of these treatments show responses to N. The analysis presented in this paper focus on treatment comparisons where important differences were observed. Some nonresponsive treatments included in the study are not discussed here, and discussion of these treatments would not solve the problem. As illustrated in Fig. 7, the treatment comparisons discussed cover only a small percentage of the field. Aerial images of corn canopies must have poor spatial resolution under such conditions because treatments that do not result in deficiencies do not reveal spatial patterns.

The second part of the dilemma is that comparisons that involve only two treatments provide much less information than do comparisons of several treatments. Comparison of fall-applied anhydrous ammonia with and without N Serve, for example, showed that use of N-Serve was profitable for farmers, and it was most profitable on calcareous soils. This comparison, however, overlooks the finding that spring-applied UAN at a rate of 112 kg N $ha^{-1}$ was more profitable than fall-applied anhydrous ammonia with N-Serve (Ellsworth et al., 2001). The spring-applied N also seemed to result in less loss of N to the environment. Comparison of both treatments, therefore, indicates that use of N-Serve with fall-applied N could be considered profitable only in situations where the spring applications of N were not possible.

The conclusions concerning the relative profitability of alternative treatments obviously depend on relevant prices for materials and application. It is interesting to note, however, that a lower price of fertilizer would have resulted in the conclusion that the second increment was profitable when Map A is analyzed. Application of the 56 kg increment of N to the whole field would have resulted in substantial losses of profit because over application of N would have occurred over 83% the field that was not calcareous. Ironically, the higher cost of N used in the analyses in Table 1 actually reduced the importance of the errors included in Map A.

The results of this study demonstrate that the greatest value of remote sensing of crop canopies may be to detect and map relatively small areas of soil that have important differences in soil characteristics from the surrounding soil. Small areas of different soil types are not indicated on soil survey maps, and soil survey maps should not be expected to reflect all factors that may influence plant growth. Even where these areas are judged too small to manage differently, it is important to identify small areas that are different. Avoiding these areas makes it possible to study the surrounding areas with greater precision. Studying these areas provides an opportunity for learning about the effects of specific soil characteristics under situations where all other factors are held constant. Once these factors are identified, they can be studied without the aid of remote sensing by locating fields that have larger areas of the soil characteristics of interest.

Use of soybean canopies to map areas of high-pH soil should be considered only an example of how remote sensing of fields can be used to identify small areas of soil that differ substantially from the surrounding soil. We have observed that images taken at different times under different conditions seem to reveal many soil characteristics other than high pH. It seems likely that further studies will show that periodic remote sensing of the same fields over a period of a few years may provide a cost-effective way to obtain very detailed maps showing spatial patterns in many important factors that influence plant growth within fields.

## REFERENCES

Blackmer, A.M. and S.E. White. 1998. Using precision farming technologies to improve management of soil and fertiliser nitrogen. Aust. J. Agric. Res., 49:555-564.

Blackmer, A.M., P.M. Kyveryga, and R. Isla. 2000. Recovery of fall-applied anhydrous ammonia nitrogen as affected by soil properties. p. 293. In Agronomy abstracts. ASA, Madison, WI.

Brady, N.C. and R.R. Weil. 1999. The nature and properties of soils, 12th ed. Prentice Hall, Inc. Upper Saddle River, NJ.

Ellsworth, J.W. and A.M. Blackmer. 2001. Remote sensing of corn and soybean fields to define nitrogen management units. In preparation. (contained in this dissertation)

Ellsworth, J.W., A.M. Blackmer, and J. Zhang. 2001. Characterizing corn yield response to nitrogen fertilization within soil map units. In preparation. (contained in this dissertation)

Fleming, K.L., D.G. Westfall, D.W. Wiens, L.E. Rothe, J.E. Cipra, and D.F. Heerman. 1998. Evaluating farmer developed management zone maps for precision farming. p. 335-343. *In* P.C. Robert et al. (ed.) Proc. of the 4$^{th}$ International Conference on Precision Agriculture. St. Paul, MN. 19-22 July. ASA, CSSA, and SSSA, Madison, WI.

Franzen, D.W., L.J. Cihacek, V.L. Hofman, and L.J. Swenson. 1998. Topography-based sampling compared with grid sampling in the northern Great Plains. J. Prod. Agric. 11:364-370.

Fridgen, J.J., C.W. Fraisse, N.R. Kitchen, K.A. Sudduth, and S.T. Drummond. 2000. Delineation and analysis of site-specific management zones. Vol II p. 402-411. *In* Proc. of the 2nd Intern. Conf. on Geospatial Information in Agric. and Forestry, Lake Buena Vista, FA. 10-12 Jan. 2000. ERIM Intern., Inc. Ann Arbor, MI.

Kitchen, N.R., K.A. Sudduth, and S.T. Drummand. 1999. Soil electrical conductivity as a crop productivity measure for claypan soils. J. Prod. Agric. 12:607-617.

Kitchen, N.R., K.A. Sudduth, and S.T. Drummond. 2000. Characterizing soil physical and chemical properties influencing crop yield using soil electrical conductivity. Vol II p. 122-131. *In* Proc. of the 2nd Intern. Conf. on Geospatial Information in Agric. and Forestry, Lake Buena Vista, FA. 10-12 Jan. 2000. ERIM Intern., Inc. Ann Arbor, MI.

Kravchenko, A.N. and D.G Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83.

Mengel, K., and E.A. Kirkby. 1987. Principles of plant nutrition, 4th ed. International Potash Institute, Bern, Switzerland.

Nolan, S.C., T.W. Goddard, D.C. Penney, and F.M. Green. 1998. Yield response to nitrogen within landscape classes. p. 479-485. *In* P.C. Robert et al. (ed.) Proc. of the 4th International Conference on Precision Agriculture. St. Paul, MN. 19-22 July. ASA, CSSA, and SSSA, Madison, WI.

Soil Survey Staff. 1998. Keys to soil taxonomy, 8th ed. USDA-NRCS. U.S. Gov. Print Office, Washington, DC.

Stafford, J.V., R.M. Lark, and H.C. Bolam. 1998. Using yield maps to regionalize fields into potential management units. P. 225-237. *In* P.C. Robert et al. (ed.) Proc. of the 4th International Conference on Precision Agriculture. St. Paul, MN. 19-22 July. ASA, CSSA, and SSSA, Madison, WI.

Table 1. Yield response to spring-applied UAN for Maps A-C on calcareous and non-calcareous soils.

| Change in rate of UAN | Field map analyzed | Response to UAN† | | LSD |
|---|---|---|---|---|
| | | Calcareous soils | Non calcareous soils | |
| kg N ha$^{-1}$ | | Mg N ha$^{-1}$ | | |
| 56 to 112 | A | 1.12 (10.2) | 1.23 (10.3) | 0.28 |
| | B | 1.48 (9.2) | 1.14 (10.6) | 0.21 |
| | C | 1.80 (9.3) | 1.11 (10.5) | 0.24 |
| 112 to 168 | A | 0.27 (10.6) | 0.23 (10.6) | 0.28 |
| | B | 0.74 (9.9) | 0.10 (10.7) | 0.21 |
| | C | 0.65 (9.9) | 0.15 (10.7) | 0.23 |

†Yield levels at higher N rate are indicated in parentheses.

Table 2. Parameters describing the probability density functions of yield response to spring-applied UAN for the whole field and the calcareous and non-calcareous soils for Maps A-C.

| Population of responses | $Y_{112-56}$ | | | | | | $Y_{168-112}$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n | MAD | Q1 | Median | Q3 | %>0† | n | MAD | Q1 | Median | Q3 | %>0 |
| | | Mg $ha^{-1}$ | | | | | | Mg $ha^{-1}$ | | | | |
| Whole field | 627 | 0.69 | 0.63 | 1.32 | 1.94 | 87 | 624 | 0.56 | -0.31 | 0.25 | 0.82 | 58 |
| Map A | | | | | | | | | | | | |
| Calcareous | 76 | 0.50 | 0.75 | 1.35 | 1.76 | 86 | 73 | 0.44 | -0.06 | 0.38 | 0.82 | 70 |
| Non-calcareous | 551 | 0.69 | 0.56 | 1.25 | 2.00 | 87 | 551 | 0.56 | -0.31 | 0.19 | 0.82 | 57 |
| Map B | | | | | | | | | | | | |
| Calcareous | 146 | 0.63 | 0.94 | 1.63 | 2.26 | 90 | 136 | 0.66 | 0.00 | 0.66 | 1.29 | 75 |
| Non-calcareous | 481 | 0.63 | 0.50 | 1.19 | 1.82 | 86 | 488 | 0.53 | -0.38 | 0.16 | 0.69 | 55 |
| Map C | | | | | | | | | | | | |
| Calcareous | 101 | 0.75 | 1.13 | 1.88 | 2.57 | 93 | 106 | 0.56 | 0.00 | 0.69 | 1.19 | 75 |
| Non-calcareous | 526 | 0.63 | 0.50 | 1.19 | 1.82 | 86 | 518 | 0.50 | -0.38 | 0.79 | 0.69 | 55 |

†Percentage of observation greater than 0.

Table 3. Parameters describing the probability density functions for yields at three rates of UAN for the whole field and for calcareous and non-calcareous soils in Maps A-C.

| Population of yields | 56 kg N ha$^{-1}$ | | | | 112 kg N ha$^{-1}$ | | | | 168 kg N ha$^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n | SD | Skew.† | Kurt.‡ | n | SD | Skew. | Kurt. | n | SD | Skew. | Kurt. |
| | | Mg ha$^{-1}$ | | | | Mg ha$^{-1}$ | | | | Mg ha$^{-1}$ | | |
| Whole field | 633 | 1.6 | -1.2 | 3.8 | 632 | 1.5 | -2.1 | 8.9 | 630 | 1.4 | -2.8 | 13.1 |
| Map A | | | | | | | | | | | | |
| Calcareous | 77 | 1.1 | -1.8 | 6.8 | 76 | 1.5 | -2.5 | 6.5 | 73 | 1.8 | -3.5 | 14.8 |
| Non-calcareous | 556 | 1.6 | -1.2 | 3.5 | 556 | 1.4 | -2.0 | 9.4 | 558 | 1.6 | -2.5 | 11.6 |
| Map B | | | | | | | | | | | | |
| Calcareous | 148 | 1.6 | -0.9 | 2.8 | 140 | 1.9 | -1.8 | 5.4 | 135 | 1.8 | -2.4 | 9.4 |
| Non-calcareous | 485 | 1.4 | -1.4 | 6.3 | 492 | 1.1 | -1.6 | 7.7 | 495 | 1.2 | -2.7 | 13.5 |
| Map C | | | | | | | | | | | | |
| Calcareous | 104 | 1.5 | 0.1 | 0.2 | 107 | 1.5 | -0.6 | 0.4 | 101 | 1.4 | -1.1 | 3.2 |
| Non-calcareous | 529 | 1.4 | -1.7 | 7.6 | 525 | 1.4 | -2.7 | 14.6 | 529 | 1.3 | -3.3 | 17.4 |

†Skewness

‡Kurtosis

Table 4. Yield response to N-Serve for calcareous and non-calcareous soils in each of the three maps.

| Field map analyzed | Response to N-Serve† | | LSD |
|---|---|---|---|
| | Calcareous soils | Non-calcareous soils | |
| | Mg N $ha^{-1}$ | | |
| A | 0.18 (9.2) | 1.19 (10.4) | 0.44 |
| B | 2.42 (10.0) | 0.65 (10.2) | 0.40 |
| C | 1.72 (9.8) | 0.89 (10.3) | 0.48 |

†Yield levels with N-Serve are indicated in parentheses.

Table 5. Parameters to describe the probability density function for yield response to N-Serve on calcareous and non-calcareous soil in Maps A-C.

| Population of responses | n | SD | Skewness | Kurtosis |
|---|---|---|---|---|
| | | Mg ha$^{-1}$ | | |
| Whole field | 625 | 2.16 | 0.45 | 1.77 |
| Map A | | | | |
| Calcareous | 112 | 2.05 | -1.09 | 3.46 |
| Non-calcareous | 513 | 2.15 | 0.76 | 1.07 |
| Map B | | | | |
| Calcareous | 127 | 2.65 | 0.08 | -0.65 |
| Non-calcareous | 498 | 1.86 | 0.13 | 3.37 |
| Map C | | | | |
| Calcareous | 91 | 2.64 | 0.55 | -0.26 |
| Non-calcareous | 534 | 2.05 | 0.31 | 2.27 |

Table 6. Parameters to describe the probability density function of yields for treatments that did and did not receive N-Serve on calcareous and non-calcareous soils.

| Population of Yields | +N-Serve | | | | -N-Serve | | | |
|---|---|---|---|---|---|---|---|---|
| | n | SD | Skew.† | Kurt.‡ | n | SD | Skew. | Kurt. |
| | | Mg ha$^{-1}$ | | | | Mg ha$^{-1}$ | | |
| Whole field | 635 | 1.6 | -1.9 | 5.7 | 631 | 2.2 | -1.2 | 1.2 |
| Map A | | | | | | | | |
| Calcareous | 114 | 1.8 | -2.2 | 6.1 | 93 | 1.4 | -0.8 | 2.1 |
| Non-calcareous | 521 | 1.5 | -1.8 | 5.4 | 538 | 2.3 | -1.2 | 1.0 |
| Map B | | | | | | | | |
| Calcareous | 133 | 1.7 | -1.7 | 5.0 | 180 | 2.6 | -0.5 | -0.7 |
| Non-calcareous | 502 | 1.6 | -1.9 | 6.0 | 451 | 1.7 | -1.2 | 2.5 |
| Map C | | | | | | | | |
| Calcareous | 94 | 1.7 | -0.8 | 0.7 | 107 | 2.8 | -0.2 | -1.0 |
| Non-calcareous | 541 | 1.6 | -2.1 | 7.1 | 524 | 1.8 | -1.3 | 2.4 |

†Skewness
‡Kurtosis

Fig. 1. Aerial photographs of the crop canopies at the site studied. Management zones formed by soil map units (1A, Map A), by spatial patterns of N deficiencies in corn (1B, Map B), and by color of soybean plants (August 2000, 1C) which are imposed on an aerial photograph of the corn canopy (1D, Map C).

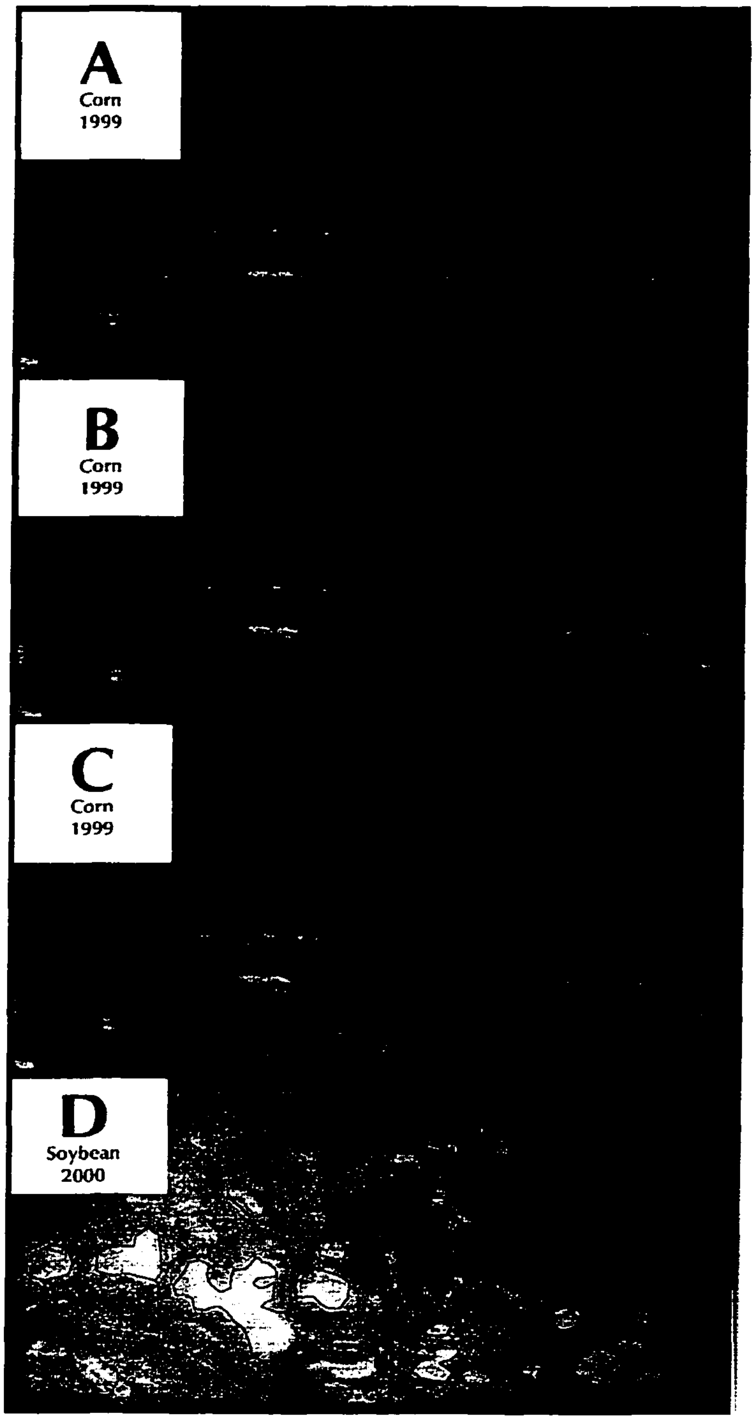


Fig. 2. Frequency distribution of yield responses observed within calcareous and non-calcareous portions of the field that received various rates of UAN solution applied in the spring.

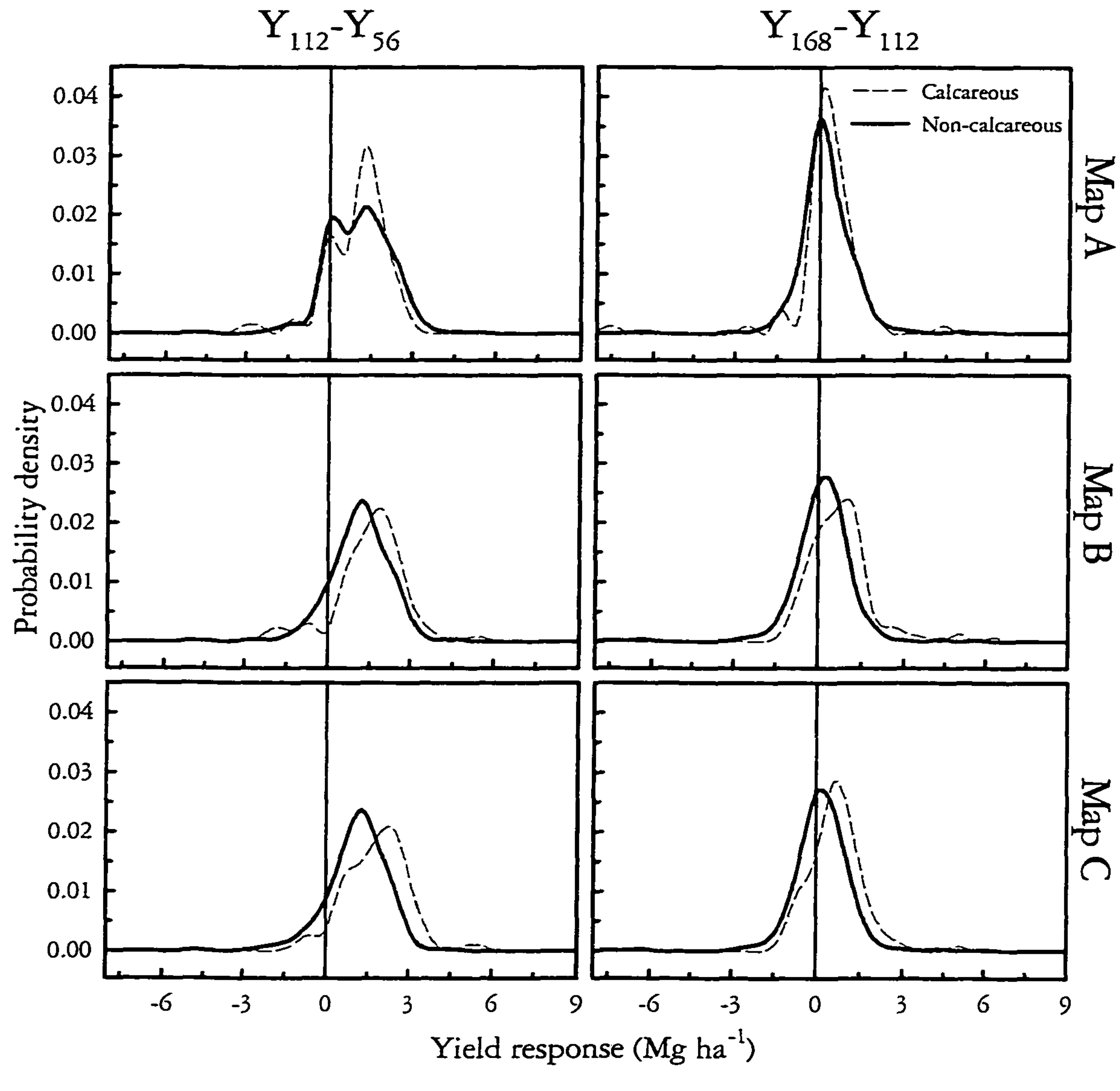


Fig. 3. Frequency distribution of yields observed within calcareous and non-calcareous portions of the field that received various rates of UAN solution applied in the spring.

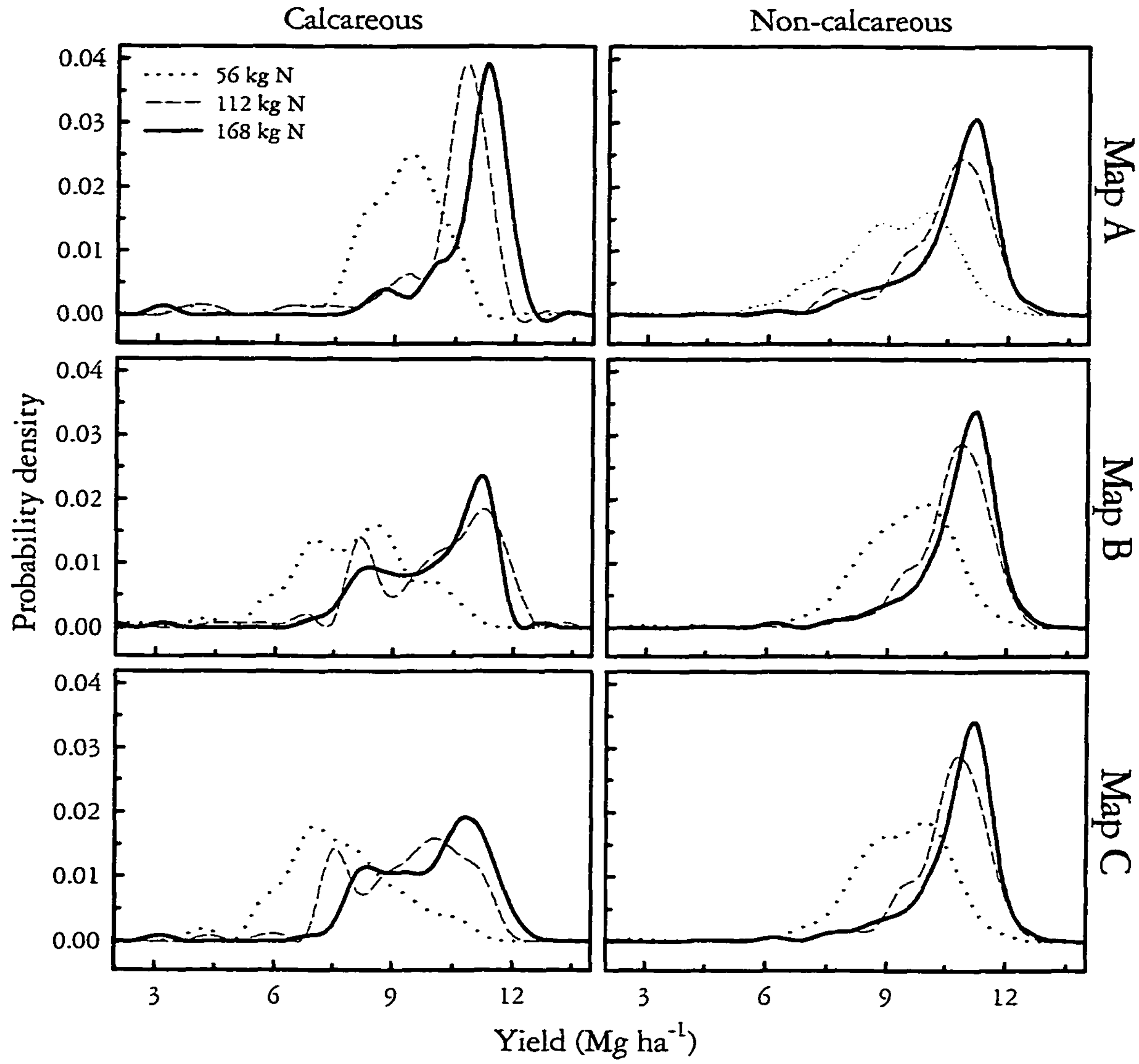


Fig. 4. Frequency distribution of yield responses to N-Serve applied with anhydrous ammonia applied in the fall.

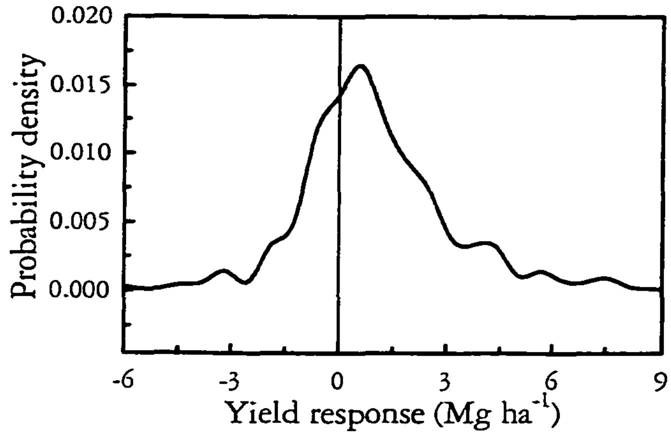


Fig. 5. Frequency distribution of yield response to N-Serve observed within calcareous and non-calcareous portions of the field.

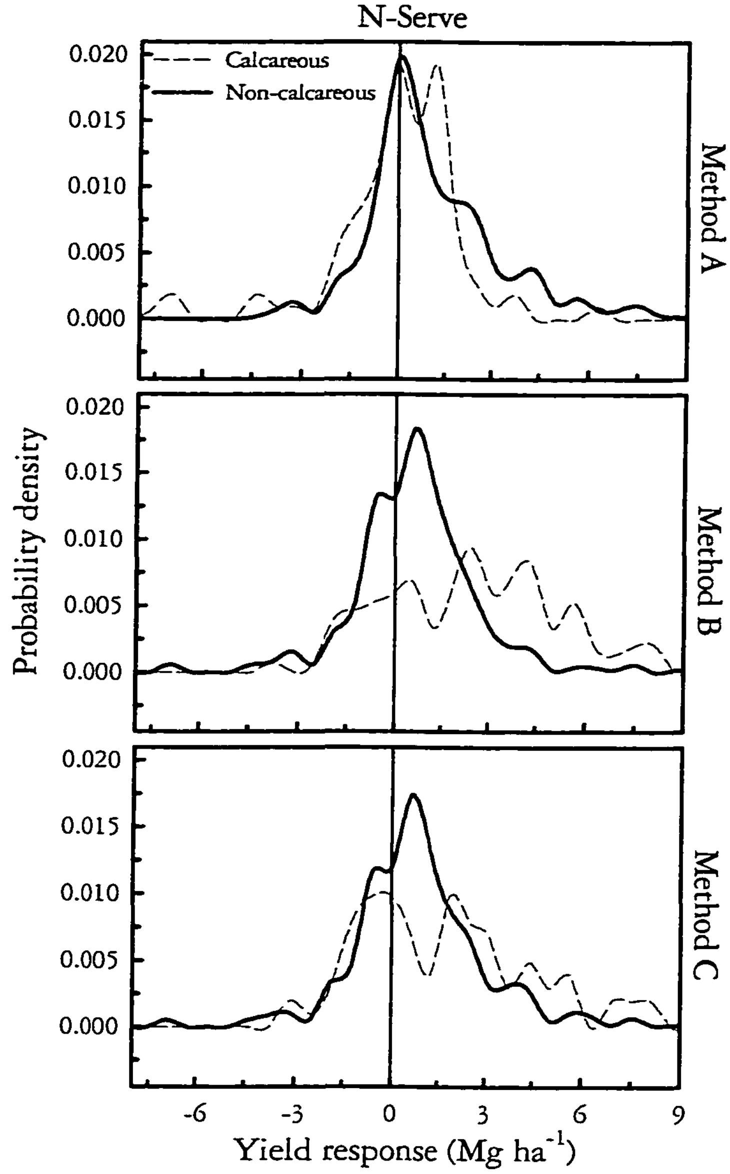


Fig. 6. Frequency distribution of yields observed within calcareous and non-calcareous portions of the field that received anhydrous ammonia applied in the fall with and without N-Serve.

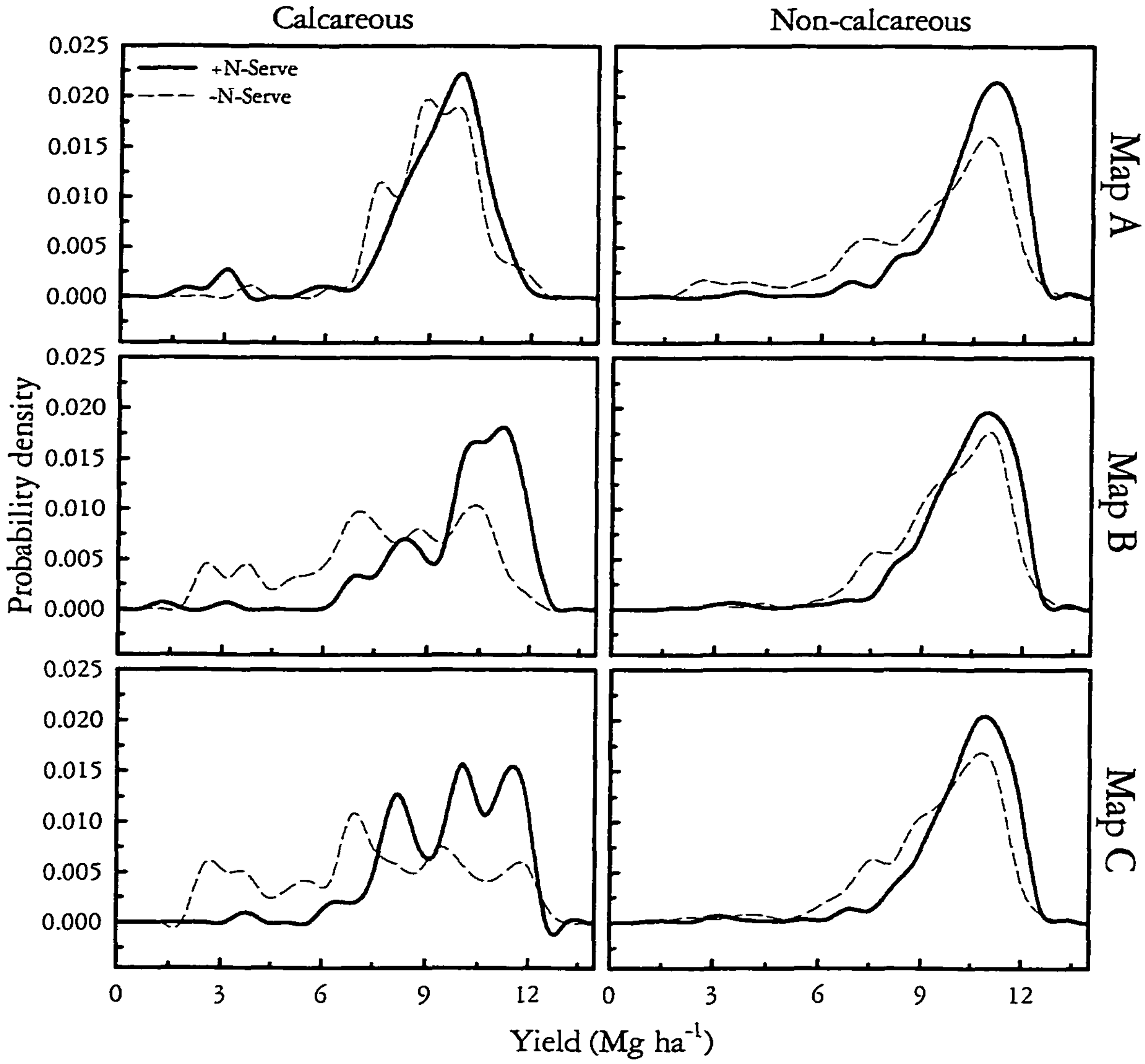
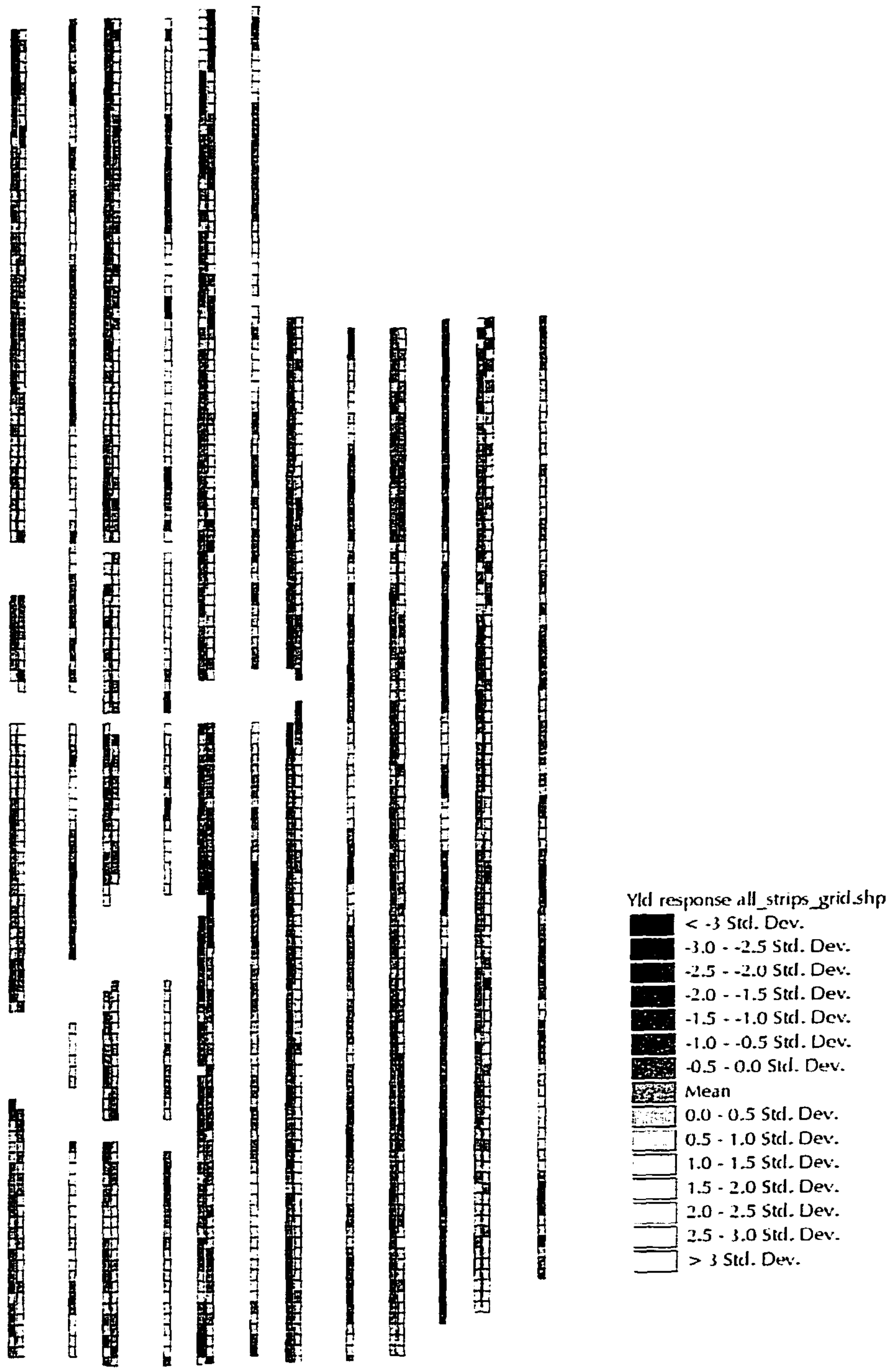


Fig. 7. Yield response map of the field studied. Yellow cells had a larger positive response to the treatment and green cells had a smaller response.



# Chapter IV: Comparing Nitrogen Management Practices Within Management Units

A paper prepared for submission to the Soil Science Society of America Journal
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## Abstract

Nitrogen (N) fertilizer recommendations for corn usually focus on rates of application with less attention to form of N applied, time of application, or placement of the fertilizer. This approach is necessary due to lack of methods for identifying optimal combinations of rates, forms, placements and timing. Studies were conducted to explore the potential of using yield-monitoring technologies in strip-plot trials for selecting the best method of fertilization for areas of soil that will be managed as a single unit. Seven different fertilization methods were compared in three 25-ha fields, each of which contained calcareous and non-calcareous soils. Analyses revealed significant effects of treatments on yields within each of 12 potential N-management units considered, but many treatments resulted in similar yields. Significant differences seemed to be caused by differential losses of fertilizer N before plants grew significantly. The problem of selecting the best of several methods of fertilization was reduced by considering differences in amounts of N applied to obtain equal profits and costs of fertilization. The results indicate that the new technologies have great potential for selecting the most economical and environmentally sound among several methods of fertilization. One of the greatest advantages of the new method is that farmers can compare practices of interest to them and see the results on their fields.

## INTRODUCTION

Modern methods of estimating N fertilizer needs are based on studies in which several rates of fertilizer are applied and crop responses are analyzed to determine an optimal rate of fertilization (Black, 1993; Colwell, 1994). Optimal rates of fertilization usually are considered to be those that maximize profits for producers under conditions specified or assumed. One assumption necessary for all estimates of optimal rates is that a slightly different method of fertilization would not produce greater profits. This assumption deserves attention because optimal rates of fertilization should be expected to vary with form of nutrient applied as well as with placement and time of application.

There have been many discussions of how plant growth or yields are influenced by the effects of form of N (Huffman, 1989), time of fertilization (Jokela and Randall, 1989), placement of fertilizers (Randall et al., 1985), and additives such as nitrification inhibitors (Christensen and Huffman, 1992; Cerrato and Blackmer, 1990; Maddux et al., 1985). However, we have found no discussions of experimental techniques for selecting the best combination of form of N (including additives), rate of application, time of application, and placement of fertilizer. It must be recognized that any method of fertilization is inadequately described unless fertilizer materials, additives, rates, times, and placement of these materials are specified.

The task of identifying the best fertilization method may seem impossible due to an almost infinite number of possibilities. In addition, the best method of fertilization for a specific crop should be expected to vary with soil characteristics, weather and interactions of these factors. Because farmers must select a method of fertilization each year, there needs to be a clearly established experimental method of identifying the best methods of fertilization. In practice, the overall task can be simplified by focusing on selecting the best among practices currently available and of interest to farmers. The task can be further simplified by recognizing that individual farmers deal with a limited range of soil types in a specific region and, therefore, a relatively restricted range of weather conditions.

It seems likely that the advent of yield monitors on combines can further simplify the task of selecting the best fertilization practices. Recent studies (Blackmer and White, 1998; Ellsworth et al., 2001) have demonstrated that these new technologies can be used to characterize spatial patterns in yield response to fertilizer in fields where various fertilizer treatments are applied in strips that coincide with combine swaths. Ellsworth and Blackmer (2001) recently showed how this method could be used to evaluate methods for dividing fields into N-management units based on observed yield responses to fertilizer N. Their studies presented clear evidence that yield responses to N within a management unit often vary with method of N fertilization. However, more work is needed to explore the potential of this new technique for selecting the best method of fertilization.

The overall objective of this paper is to explore the potential benefits of using yield-monitoring technologies in strip-plot trials for selecting the best method of fertilization for areas of soil that will be managed as a single unit (i.e., N-management units). The work reported is based on the assumption that the problem of dividing large areas of soils into appropriate management units is part of the overall task of selecting the best method of fertilization. The specific objective of this paper, therefore, is to demonstrate how the new technologies can be used to simultaneously divide fields into management units and select the best from several alternative methods of fertilization for these management units.

## Materials and Methods

The study was initiated in 1998 at three sites in Boone and Greene counties in Iowa. The soil associations, soil map symbol (SMS), soil map unit (SMU) and percent area covered by the SMU at each site is given in Table 1. Table 2 gives the corresponding soil classification for each SMU given in Table 1.

On 24 and 25 November 1998, fall treatments were applied in a stratified design with an applicator that could simultaneously apply N, P, K and N-Serve [nitrapyrin, 2-chloro-6-(trichloromethyl) pyridine, Dow AgroSciences, Indianapolis, IN] at all three sites. In the first application pass across the field (in addition to the P and K), 140 kg N $ha^{-1}$ in the form of anhydrous ammonia was applied with 2.3 L N-Serve $ha^{-1}$. In the next pass 140 kg N $ha^{-1}$ was applied without N-Serve. The next two application passes did not receive fall-N. The pattern was repeated for a total of six replications. Each applicator pass was marked with flags at both ends and locations were recorded using the Global Positioning System (GPS).

Corn was planted in early May at all three sites. After planting, the fields were divided into 6-row strips going the length of the field and numbered consecutively across the field. In early June, urea ammonium nitrate (UAN), 32% N was applied at rates of 56, 112, and 168 kg N $ha^{-1}$ to the strips that did not receive fall N. In mid to late July, one of the two 6-row strips that received anhydrous ammonia in the fall was fertilized with an additional 84 kg N $ha^{-1}$ as UAN by dribbling it on the soil surface. A summary of all treatments is given in Table 3.

The fields were harvested using conventional combines mounted with Yield Monitor 2000's (Ag Leader Technology, Inc., Ames, IA) and AG132 GPS receivers (Trimble Navigation Limited, Sunnyvale, CA). Data points were recorded at ONE SECOND intervals. Average speed while harvesting each strip was 5.3 km $hr^{-1}$. Yield data was imported into ArcView GIS (v. 3.2, ESRI, Redlands, CA) for post processing and analysis.

For analysis, the experimental areas in each trial were divided into a grid formed by strips (treatments and combine swaths) and tiers that were 6.1 m wide and the width of the experimental area. These tiers were perpendicular to the treatment strips and were numbered consecutively from one end of the field to the other. Yield values for each cell in the grid were calculated (each cell contained an average of two yield points) and qualitative properties such as soil type were assigned to each cell. Yield responses were calculated by subtracting the yield in one cell from yields in the appropriate adjacent cell. Cells were treated as individual experimental units.

Potential N-management units are areas of soil that will receive a common rate of N fertilizer. The most basic N-management unit is all three fields grouped as one. The first logical division was making each site an individual N-management unit, as is commonly done. The three sites grouped together were also split into calcareous and non-calcareous soils base on current knowledge of the three sites. Finally, each site was divided into calcareous and non-calcareous soils. Table

4 illustrates the 12 potential managment units for this study.

SAS (v. 8.1, SAS Institute, Cary, NC) was used to calculate the means and LSD of yield and yield response. SigmaPlot (v. 5.0, SPSS, chicago, IL) was used to graph each of the figures.

## Results and Discussion

### Yield Analysis

Treatment means for grain yields within each of the 12 potential N-management unit are shown in Table 4. A key observation is that differences in yield due to treatment are relatively small. Within potential N-management units, the lowest yielding treatment ranged from 76 to 94% of the highest yielding treatment and averaged 88% of the highest yielding treatment. Small differences in yield due to treatment should be expected when comparing methods of fertilization that are of interest to farmers, because farmers have no interest in methods that result in low yields. Thus, finding small differences in yield should not be confused with lack of important differences among the treatments.

Figure 1 presents the treatment means for yields in a way that separate the effects of rate of N application from the effects of other components of fertilization method. The three rates of spring-applied UAN are essentially used as a standard for assessing the biologically effective quantities of N supplied by other methods. This approach has been used in evaluations of fertilizer materials (Black, 1993) and in assessments of effective quantities of N supplied by legumes (Blackmer, 2000). This method reveals that N applied as fall-applied anhydrous ammonia without N-Serve was only about 70% as effective as N applied as UAN if all sites are treated as a single management unit. The fall-applied N was much less effective than spring-applied UAN on the calcareous soils than on the non-calcareous soils. The addition of N-Serve made the fall-applied N nearly as effective as the spring-applied UAN and reduced the effects of calcium carbonate. This presentation of data reveals important differences that were not clearly revealed in Table 1.

Data presented in Fig. 1 provides strong evidence for substantial losses of fall-applied N from the rooting zone before plants grow because N-Serve is an additive intended to inhibit nitrification and thereby reduce losses of fertilizer N by leaching and denitrification. The results suggest that the losses were substantially greater on calcareous soils than on non-calcareous soils. Support for this conclusion is provided by Blackmer et al. (2000), who found low recoveries of fall-applied N when the surface 45-cm layer of soils in these fields were sampled at crop emergence in the spring. The soil testing also showed that recoveries of N substantially decreased with increase in soil pH and that N-Serve tended to minimize this effect.

The spring-applied UAN failed to produce the highest yields in two of the 12 management units considered (Jefferson whole field, and Jefferson non-calcareous soil). This finding is most likely explained by losses of UAN during a 7.0-cm rainfall event that occurred within 3 hours of application. Both the urea and nitrate were vulnerable to loss by leaching at this time because the urea could not have been hydrolyzed to ammonium. This problem seemed to be masked by greater losses of the fall-applied anhydrous ammonia on the calcareous soils at this site. Because substantial losses of fertilizer N can occur soon after application with any method of N fertilization, conclusions derived from Fig. 1 must recognize the amount of N that actually influenced plant growth may differ substantially from the amounts of N applied.

Conclusions derived from Table 1 or Fig. 1 must also recognize that the forms of N and locations of N in the soil that plants responded to are not necessarily indicated by descriptions of the fertilization method. Transformations and movements of fertilizer N applied by any given method are greatly influenced by soil characteristics and weather conditions. For this reason, comparisons of *any* two or more methods of fertilization are as valid as are comparisons of placements, forms of N or rates of N while other components of fertilization method are held constant.

Analysis of variance revealed that fertilization method had statistically significant effects on yields attained. Ability to attain statistical significance was due in part to the high degree of experimental precision of the methods used, LSD values ranged from 0.13 to 0.80 and averaged 3.1% of the highest yield mean within the management units considered. Poor experimental precision has been recognized as a serious problem in field studies to assess crop responses to fertilizer (Terman, 1960, 1961; Blackmer, 1986; Colwell, 1994). Terman (1960, 1961), for example, concluded that a three-fold difference in fertilizer effectiveness produced yield effects large enough to be statistically significant at 95% probability level in only about 10% of the numerous studies he reviewed.

It should be noted that the choice of fertilization methods compared must be considered part of the reason statistically significant differences were attained in this study. Studies comparing alternative forms, placement, or timing of fertilization can be invalidated if N is applied at rates that are too high. This is because timing, form, and placement of fertilizers influences the level of yields attainable with adequate N. On the other hand, this problem cannot be resolved by conducting studies with N rates that are significantly below optimal. Thus, effective comparisons of fertilization methods must be conducted under conditions where yield responses are often too small to detect. This problem can be reduced by considering the costs of fertilization; because, when differences are noted, farmers have greater interest in fertilization practices that maximize profits than those that maximize yields.

**Profit Analysis**

Table 2 shows mean yields of grain remaining after costs (in Mg $ha^{-1}$) of the fertilizer treatments were subtracted. Such an analysis shows that treatment 2 (112 kg N $ha^{-1}$ applied as UAN in the spring) resulted in the greatest profit in most of the management units considered. The only exceptions were the Jefferson whole field and Jefferson non-calcareous soil, where heavy rainfall within hours of application seemed to result in significant losses of fertilizer N. Analysis of variance revealed that subtracting the costs of fertilization had essentially no effect on LSD values, but did change conclusions concerning which treatment means should be considered statistically similar or different.

Figure 2 presents the adjusted treatment means for yields in a way that separates the effects of rate of N application from the effects of other components of fertilization method. This figure uses the spring applied UAN as a standard to illustrate differences in amounts of N applied that must be applied to attain the same level of profit. For example, the results showed that when data from all sites are analyzed as a single management unit, 56 kg N $ha^{-1}$ of spring applied UAN would generate the same amount of profit as treatments 6 or 8 with 150 kg less N applied. This point is not illustrated in Table 1 and Fig. 1, but it should be considered very important in situations where losses of N to the environment carry costs that are important but difficult to detect.

The task of identifying the best among several fertilization methods gets easier if the costs of unnecessary fertilization are considered. These costs are the differences in amounts of N required when comparing methods that produce equal profits. When this approach is used, two methods of fertilization can be considered equal only when profits *and* amounts of N applied are essentially the same. This approach offers the advantage of identifying practices that help farmers simultaneously address economic and environmental concerns related to the use of fertilizer N during crop production.

Analyses based on mean yields adjusted for fertilizer and application costs and costs of unneeded N make it possible to identify the best combination of fertilization practices and management units. In this study, for example, we calculated the mean adjusted profits for each of 12 potential management units. One of these considers all of the area studied as a single management unit. This can be used as a reference when estimating the benefits of dividing the fields in two management units (i.e., calcareous and non-calcareous soils) or more N-management units. Any costs associated with forming separate management units can be evaluated relative to the benefits expected. Although not addressed in this study, the effects of variability in weather can be addressed by collecting similar types of data over several years and basing decisions on the means of adjusted yields over this period. The advantage of this approach becomes most evident if it is assumed that N-management units will be defined by a specified range of characteristics (e.g., soil map unit, pH, organic matter concentration, etc.) rather than by fences or natural boundaries to fields.

Analyses based on mean yields adjusted for profits and amounts of unneeded N often avoids the need for including extremely high or low rates of N application in experiments. Especially in situations where optimal rates of N are known with some degree of certainty, the costs of experimentation can be reduced by focusing on treatments having near optimal rates of N fertilization. The costs of experimentation can be negligible in studies where differences in profitability are too small to be determined by other methods and costs of applying the different treatments are small. Indeed, with the advent of variable rate application technologies, it is possible to envision experiments in which farmers compare two or more fertilization methods across large areas of land each year to detect small differences and obtain the information needed to continuously refine their N management practices with minimal experimental costs.

## References

Black, C.A. 1993. Soil fertility evaluation and control. Lewis Publishers, Boca Raton, FL.

Blackmer, A.M. 1986. Potential yield response of corn to treatments that conserve fertilizer nitrogen in soils. Agron. J. 78:571-575.

Blackmer, A.M. 2000. Bioavailability of nitrogen. p. D3-D18, *In* M.E. Sumner (ed.) Handbook of soil science. CRC Press LLC, Boca Raton, FL.

Blackmer, A.M. and S.E. White. 1998. Using precision farming technologies to improve management of soil and fertiliser nitrogen. Aust. J. Agric. Res., 49:555-564.

Blackmer, A.M., P.M. Kyveryga, and R. Isla. 2000. Recovery of fall-applied anhydrous ammonia nitrogen as affected by soil properties. p. 293. *In* Agronomy abstracts. ASA, Madison, WI.

Cerrato, M.E. and A.M. Blackmer. 1990. Effects of nitrapyrin on corn yields and recovery of ammonium-N at 18 site-years in Iowa. J. Prod. Agric. 3:513-521.

Christensen, R.H. and J.R. Huffman. 1992. Response of corn to preplant applications of nitrogen and to nitrogen plus nitrapyrin. J. Prod. Agric. 5:352-358.

Colwell, J.D. 1994. Estimating fertilize requirements: A quantitative approach. CAB International, Wallingford, Oxon, UK

Ellsworth, J.W. and A.M. Blackmer. 2001. Remote sensing of corn and soybean fields to define nitrogen management units. In preparation. (contained within this dissertation)

Ellsworth, J.W., A.M. Blackmer and J. Zhang. 2001. Characterizing corn yield response to nitrogen fertilization within soil map units. In preparation. (contained within this dissertation)

Huffman, J.R. 1989. Effects of enhanced ammonium nitrogen availability for corn. J. Agron. Educ. 18:93-97.

Jokela, W.E. and G.W. Randall. 1989. Corn yield residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81:720-726.

Maddux, L.D., D.E. Kissel, J.D. Ball, and R.J. Raney. 1985. Nitrification inhibition by nitrapyrin and volatile sulfur compounds. Soil Sci. Soc. Am. J. 49:239-242.

Randall, G.W., K.L. Wells, and J.J. Hanway. 1985. Modern techniques in fertilizer placement. P. 521-560. *In* O.P. Englestad (ed.) Fertilizer technology and use, 3rd Ed. Soil Sci. Soc. Am., Madison, WI.

Terman, G.L. 1960. Yield responses in experiments with phosphorus fertilizers in relation to: I. Meaningful differences among sources on acid soils of the Southeastern States. Soil Sci. Soc. Am. Proc. 24:356-360.

Terman, G.L. 1961. Yield responses in experiments with phosphorus fertilizers in relation to: II. Variability and differences among sources on soils of the Northern and Western States. Soil Sci. Soc. Am. Proc. 25:49-52.

Table 1. County name, soil map symbols (SMS), soil map units (SMU), percentage area for each SMU and soil association for the three sites in the study.

| Site | SMS | SMU | Area | Association |
|---|---|---|---|---|
| | | | % | |
| Boone (1) | 507 | Canisteo | 65% | Canisteo-Clarion-Nicollet |
| | 138 | Clarion | 17% | |
| | 55 | Nicollet | 15% | |
| | 6 | Okoboji | 3% | |
| Jefferson (2) | 138 | Clarion | 50% | Clarion-Nicollet-Webster |
| | 638 | Clarion-Storden Complex | 7% | |
| | 55 | Nicollet | 13% | |
| | 107 | Webster | 30% | |
| Ogden (3) | 507 | Canisteo | 12% | Canisteo-Clarion-Nicollet |
| | 138 | Clarion | 55% | |
| | 135 | Coland | 3% | |
| | 95 | Harps | 1% | |
| | 55 | Nicollet | 11% | |
| | 6 | Okoboji | 1% | |
| | 27 | Terril | 4% | |
| | 107 | Webster | 12% | |

Table 2. Soil map unit (SMU), soil map symbol (SMS), and soil classification at the three sites in this study.

| SMU | SMS | Classification |
|---|---|---|
| Canisteo | 507 | Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls |
| Clarion | 138 | Fine-loamy, mixed, superactive, mesic Typic Hapludolls |
| Coland | 135 | Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls |
| Harps | 95 | Fine-loamy, mixed, superactive, mesic Typic Calciaquolls |
| Nicollet | 55 | Fine-loamy, mixed, superactive, mesic Aquic Hapludolls |
| Okoboji | 6 | Fine, smectitic, mesic Cumulic Vertic Endoaquolls |
| Storden | 62 | Fine-loamy, mixed, superactive, mesic Typic Eutrudepts |
| Terril | 27 | Fine-loamy, mixed, superactive, mesic Cumulic Hapludolls |
| Webster | 107 | Fine-loamy, mixed, superactive, mesic Typic Endoaquolls |

Table 3. Treatments applied at the three sites in this study.

| Treatment number | Nitrogen form | Time and rate | | |
|---|---|---|---|---|
| | | Fall | Spring | Summer |
| | | | kg N ha$^{-1}$ | |
| 1 | Urea ammonium nitrate (UAN) | | 56 | |
| 2 | " | | 112 | |
| 3 | " | | 168 | |
| 5 | Anhydrous Ammonia (AA) + N-Serve | 140 | | |
| 6 | AA + N-Serve + UAN | 140 | | 84 |
| 7 | AA | 140 | | |
| 8 | AA + UAN | 140 | | 84 |

Table 4. Yields and LSD values for seven common treatments within 12 potential N-management units.

| Site | Treatment | Entire field | Calcareous | Non-calcareous |
|---|---|---|---|---|
| | | Mg $ha^{-1}$ | | |
| Boone (1) | 1 | 10.8 | 11.0 | 10.4 |
| | 2 | 11.1 | 11.3 | 10.8 |
| | 3 | 11.4 | 11.8 | 10.8 |
| | 5 | 11.4 | 11.6 | 11.0 |
| | 6 | 11.3 | 11.3 | 11.3 |
| | 7 | 10.8 | 10.8 | 10.9 |
| | 8 | 11.0 | 11.1 | 10.7 |
| | $LSD_{0.05}$ | 0.2 | 0.3 | 0.4 |
| | $LSD_{0.2}$ | 0.1 | 0.2 | 0.3 |
| | P > f | <0.01 | <0.01 | <0.01 |
| Jefferson (2) | 1 | 8.0 | 8.0 | 8.0 |
| | 2 | 8.7 | 9.5 | 8.7 |
| | 3 | 8.9 | 9.7 | 8.9 |
| | 5 | 9.0 | 7.9 | 9.1 |
| | 6 | 10.0 | 9.8 | 10.0 |
| | 7 | 8.9 | 7.5 | 9.0 |
| | 8 | 10.0 | 9.6 | 10.0 |
| | $LSD_{0.05}$ | 0.2 | 0.8 | 0.2 |
| | $LSD_{0.2}$ | 0.1 | 0.5 | 0.1 |
| | P > f | <0.01 | <0.01 | <0.01 |
| Ogden (3) | 1 | 9.1 | 7.7 | 9.3 |
| | 2 | 10.3 | 9.3 | 10.5 |
| | 3 | 10.6 | 9.9 | 10.7 |
| | 5 | 10.2 | 9.8 | 10.3 |
| | 6 | 10.1 | 8.8 | 10.4 |
| | 7 | 9.2 | 7.5 | 9.5 |
| | 8 | 9.9 | 8.7 | 10.2 |
| | $LSD_{0.05}$ | 0.2 | 0.5 | 0.2 |
| | $LSD_{0.2}$ | 0.1 | 0.3 | 0.1 |
| | P > f | <0.01 | <0.01 | <0.01 |
| All sites | 1 | 9.2 | 9.9 | 9.0 |
| | 2 | 10.0 | 10.7 | 9.8 |
| | 3 | 10.3 | 11.2 | 10.0 |
| | 5 | 10.2 | 10.9 | 9.9 |
| | 6 | 10.4 | 10.6 | 10.3 |
| | 7 | 9.6 | 9.7 | 9.5 |
| | 8 | 10.2 | 10.4 | 10.2 |
| | $LSD_{0.05}$ | 0.1 | 0.3 | 0.1 |
| | $LSD_{0.2}$ | 0.1 | 0.2 | 0.1 |
| | P > f | <0.01 | <0.01 | <0.01 |
| | Mean | 10.0 | 9.7 | 10.0 |

Table 5. Mean yields for seven treatments after the costs of fertilization (in Mg ha$^{-1}$) have been subtracted. Costs associated with fertilization are as follows: AA, \$0.33 kg N$^{-1}$; UAN, \$0.44 kg N$^{-1}$; application of AA, \$15.55 ha$^{-1}$; application of UAN, \$10.75 ha$^{-1}$; and N-Serve, \$7.90 L$^{-1}$.

| Site | Treatment | Entire field | Calcareous | Non-calcareous |
|---|---|---|---|---|
| | | | Mg ha$^{-1}$ | |
| Boone (1) | 1 | 10.4 | 10.6 | 10.0 |
| | 2 | 10.5 | 10.7 | 10.1 |
| | 3 | 10.5 | 10.8 | 9.8 |
| | 5 | 10.5 | 10.6 | 10.1 |
| | 6 | 9.9 | 9.9 | 9.8 |
| | 7 | 10.1 | 10.1 | 10.2 |
| | 8 | 9.8 | 9.9 | 9.5 |
| | $LSD_{0.05}$ | 0.2 | 0.3 | 0.4 |
| | $LSD_{0.2}$ | 0.1 | 0.2 | 0.3 |
| | P > f | <0.01 | <0.01 | <0.01 |
| Jefferson (2) | 1 | 7.6 | 7.6 | 7.6 |
| | 2 | 8.0 | 8.8 | 8.0 |
| | 3 | 8.0 | 8.8 | 7.9 |
| | 5 | 8.1 | 7.0 | 8.2 |
| | 6 | 8.5 | 8.3 | 8.5 |
| | 7 | 8.2 | 6.8 | 8.3 |
| | 8 | 8.7 | 8.3 | 8.8 |
| | $LSD_{0.05}$ | 0.2 | 0.8 | 0.2 |
| | $LSD_{0.2}$ | 0.1 | 0.5 | 0.1 |
| | P > f | <0.01 | <0.01 | <0.01 |
| Ogden (3) | 1 | 8.7 | 7.3 | 8.9 |
| | 2 | 9.6 | 8.6 | 9.8 |
| | 3 | 9.6 | 9.0 | 9.7 |
| | 5 | 9.3 | 8.9 | 9.3 |
| | 6 | 8.7 | 7.3 | 8.9 |
| | 7 | 8.5 | 6.8 | 8.8 |
| | 8 | 8.7 | 7.4 | 9.0 |
| | $LSD_{0.05}$ | 0.2 | 0.5 | 0.2 |
| | $LSD_{0.2}$ | 0.1 | 0.3 | 0.1 |
| | P > f | <0.01 | <0.01 | <0.01 |
| All sites | 1 | 8.8 | 9.5 | 8.6 |
| | 2 | 9.4 | 10.0 | 9.1 |
| | 3 | 9.3 | 10.2 | 9.0 |
| | 5 | 9.2 | 9.9 | 9.0 |
| | 6 | 9.0 | 9.2 | 8.9 |
| | 7 | 8.9 | 9.0 | 8.8 |
| | 8 | 9.0 | 9.1 | 9.0 |
| | $LSD_{0.05}$ | 0.1 | 0.3 | 0.1 |
| | $LSD_{0.2}$ | 0.1 | 0.2 | 0.1 |
| | P > f | <0.01 | <0.01 | <0.01 |
| | Mean | 9.1 | 8.7 | 9.1 |

Fig. 1. Mean yields for 12 potential N-management units. UAN is essentially used as a reference to compare the other treatments.

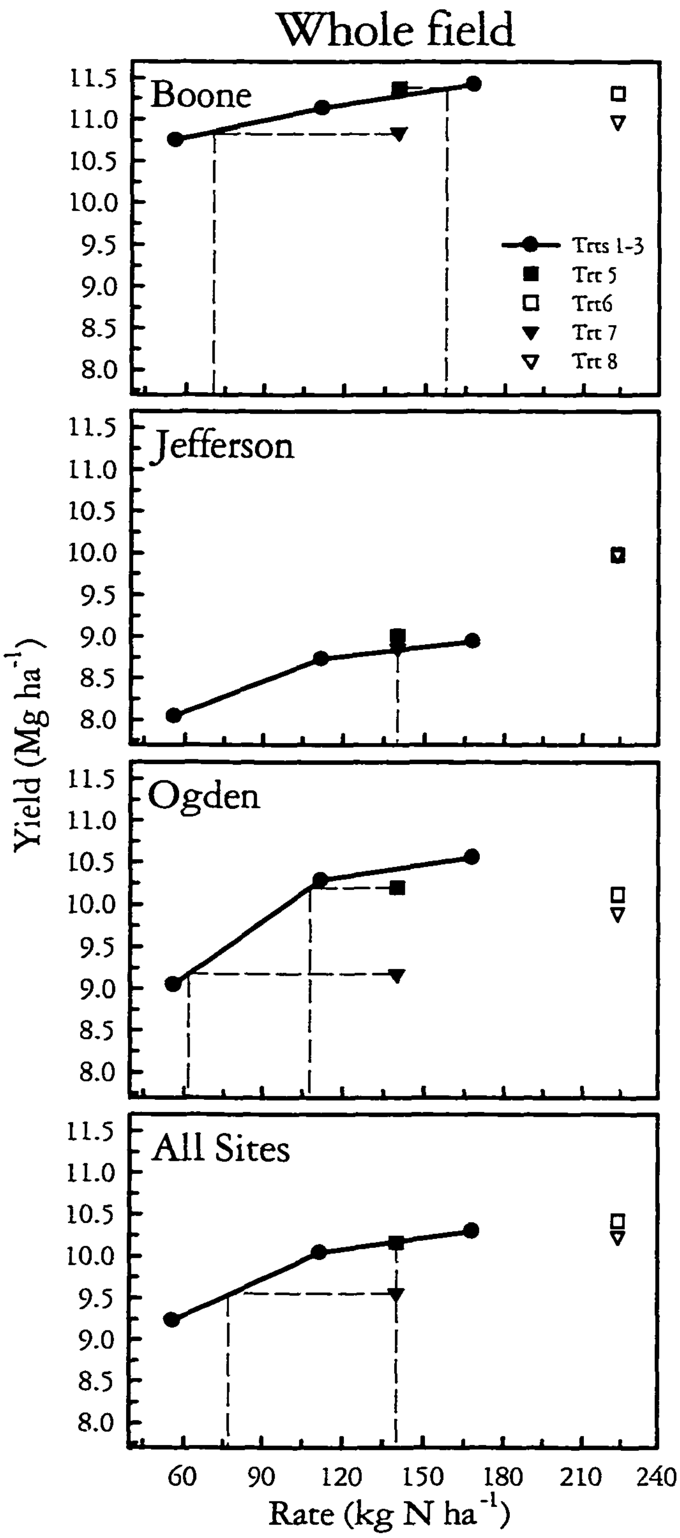


Fig 1. (continued)

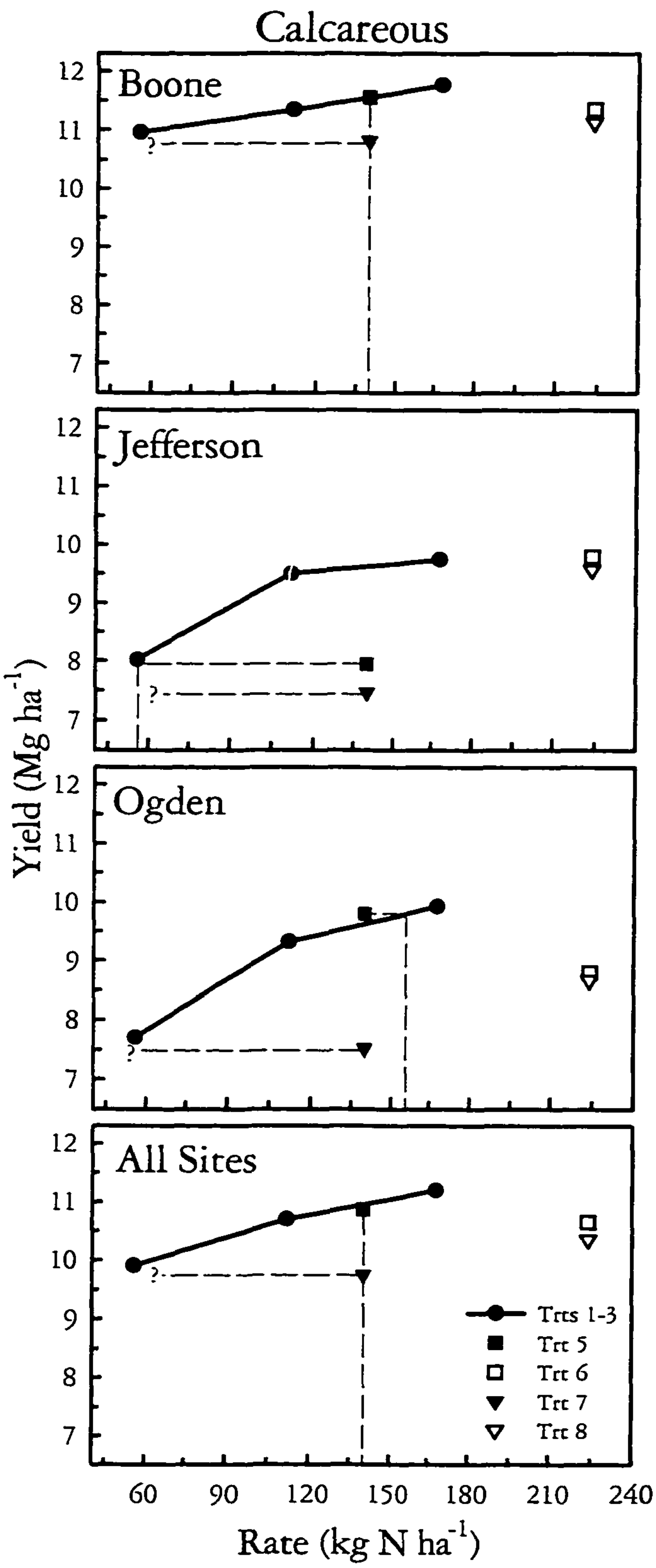


Fig 1. (continued)

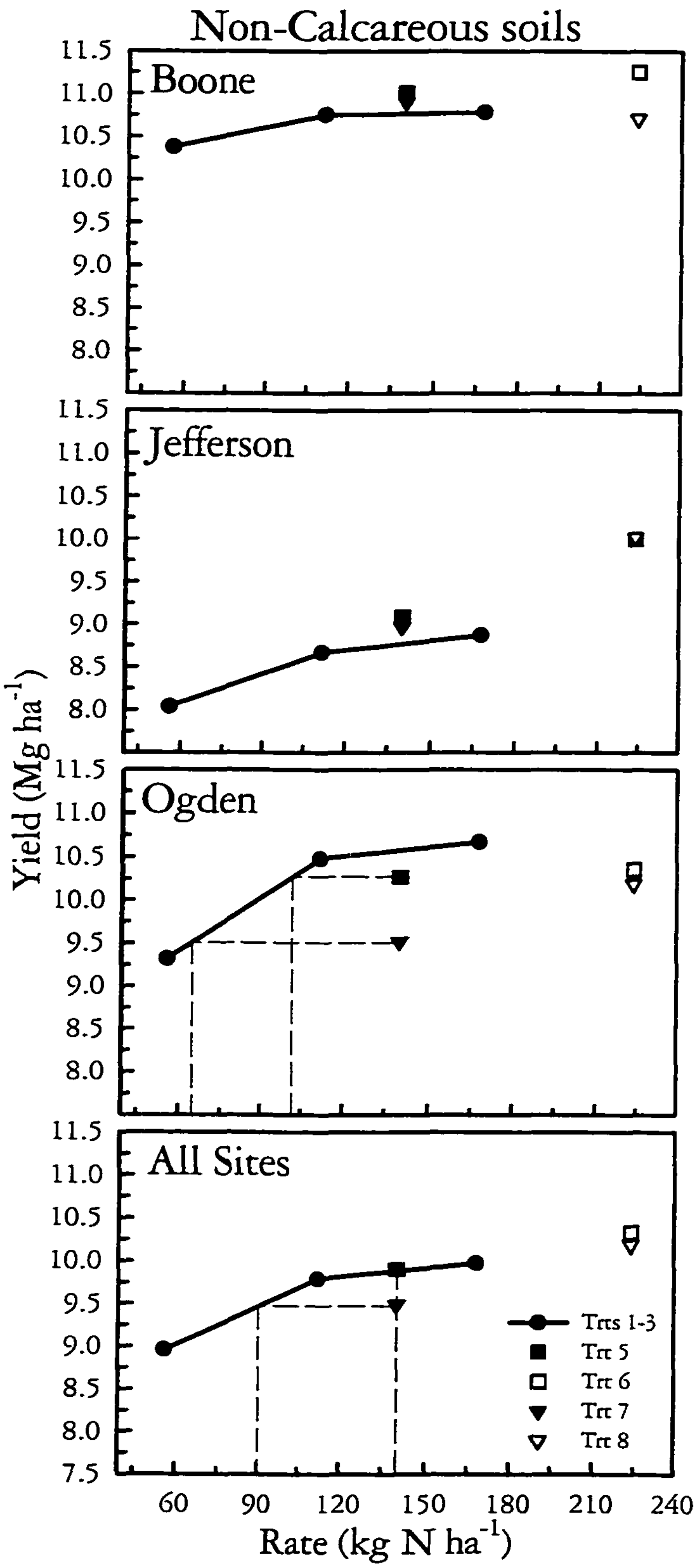


Fig. 2. Mean yields for 12 potential N-management units after the costs associated with fertilization have been subtracted (Mg $ha^{-1}$). UAN is essentially used as a reference to compare the other treatments.

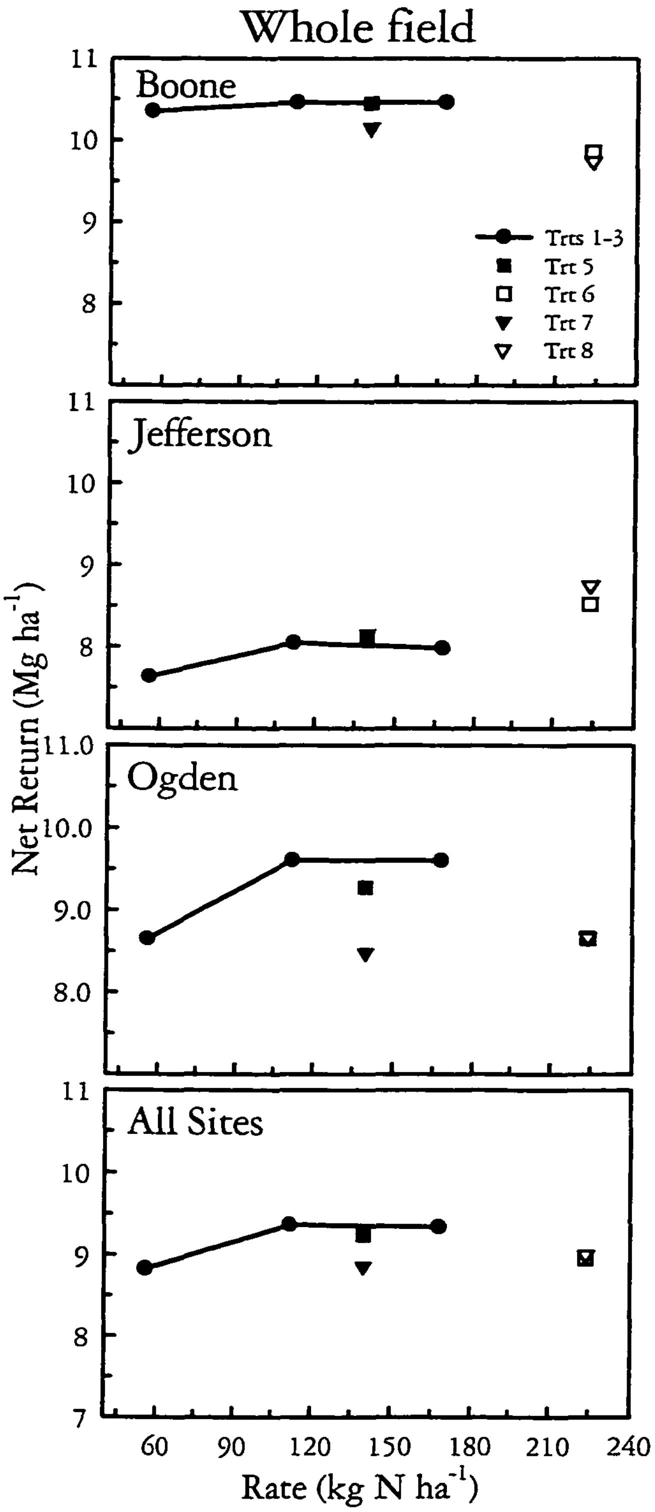


Fig 2. (continued)

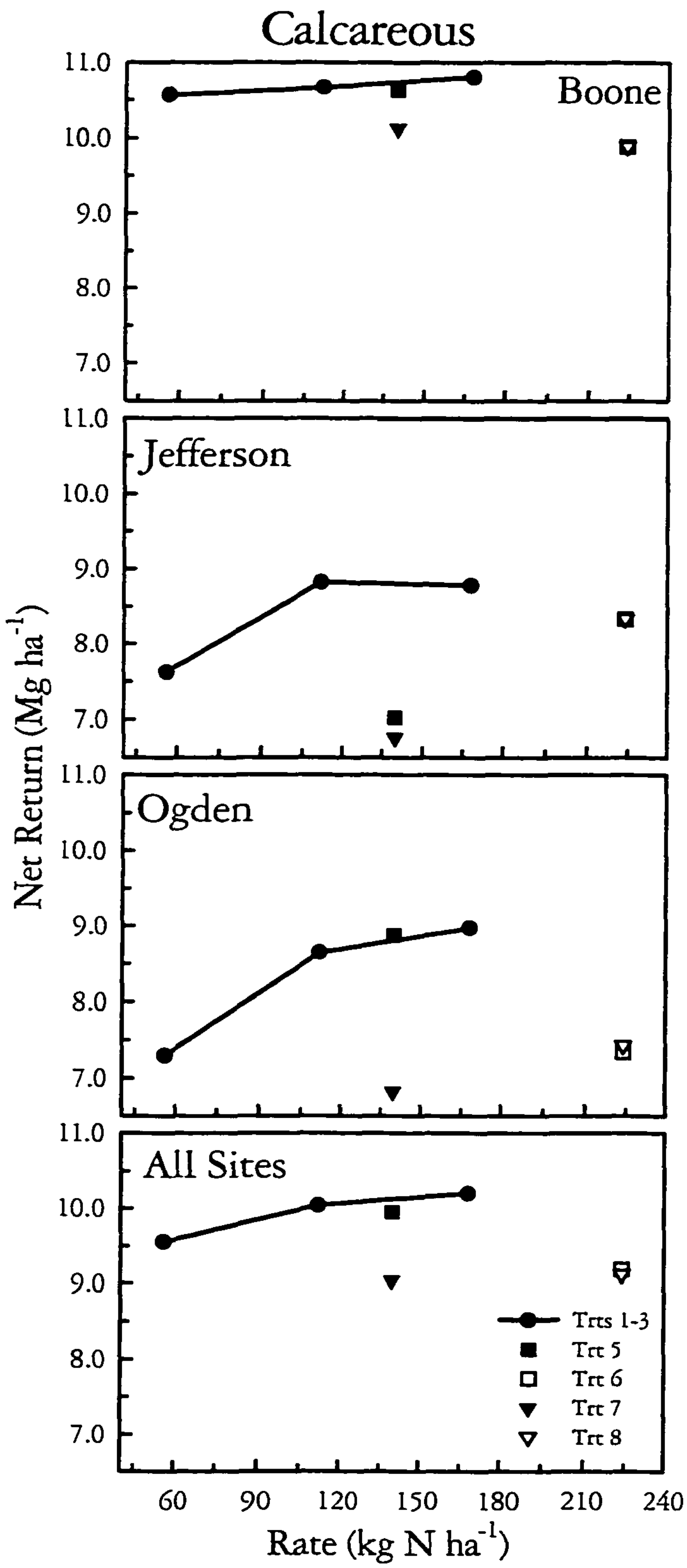
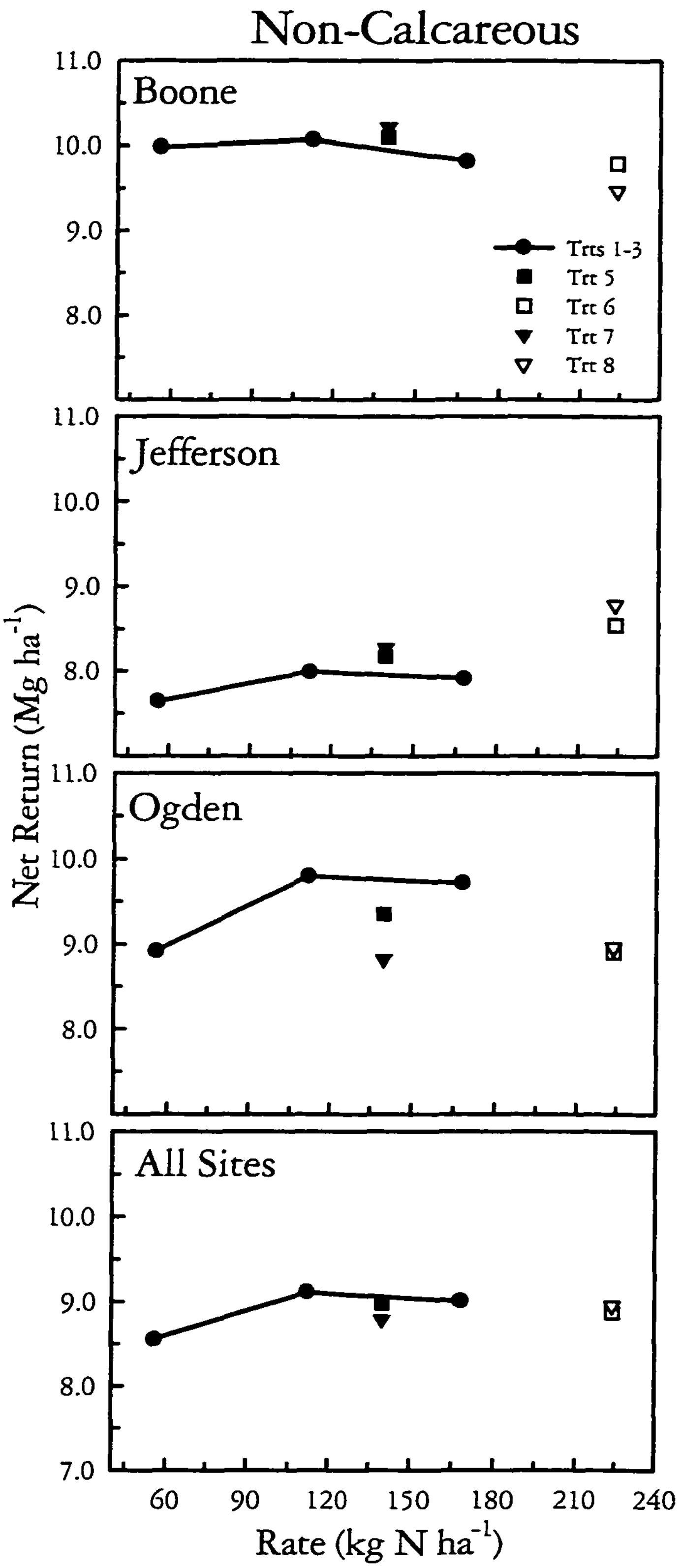


Fig. 2. (continued)



# Chapter V: General Conclusions

The use of Precision Agriculture technologies has made it possible to vary the rate of fertilizer across the soil landscape. This dissertation has explored methods by which such tools as yield monitors, remote sensing, global positioning system (GPS), and geographic information systems (GIS) can be used to characterize variability within and between soil map units, delineate and evaluate potential N-management units, and determine N-fertilizer methods that are most profitable and environmentally sound. This was done at rates that were all very near optimal in terms of N sufficiency for corn plants. Each of the methods explored is simple and inexpensive enough that growers will be able to implement them on their own farms to improve N-management methods.