NITROGEN MANAGEMENT

Field-Scale Variability in Optimal Nitrogen Fertilizer Rate for Corn

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ABSTRACT

Applying only as much N fertilizer as is needed by a crop has economic and environmental benefits. Understanding variability in need for N fertilizer within individual fields is necessary to guide approaches to meeting crop needs while minimizing N inputs and losses. Our objective was to characterize the spatial variability of corn (*Zea mays* L.) N need in production corn fields. Eight experiments were conducted in three major soil areas (Mississippi Delta alluvial, deep loess, claypan) over 3 yr. Treatments were field-length strips of discrete N rates from 0 to 280 kg N ha^{-1}. Yield data were partitioned into 20-m increments, and a quadratic-plateau function was used to describe yield response to N rate for each 20-m section. Economically optimal N fertilizer rate (EONR) was very different between fields and was also highly variable within fields. Median EONR for individual fields ranged from 63 to 208 kg N ha^{-1}, indicating a need to manage N fertilizer differently for different fields. In seven of the eight fields, a uniform N application at the median EONR would cause more than half of the field to be over- or underfertilized by at least 34 kg N ha^{-1}. Coarse patterns of spatial variability in EONR were observed in some fields, but fine and complex patterns were also observed in most fields. This suggests that the use of a few appropriate management zones per field might produce some benefits but that N management systems using spatially dense information have potential for greater benefits. Our results suggest that further attempts to develop systems for predicting and addressing spatially variable N needs are justified in these production environments.

Many crops respond dramatically to applications of N fertilizer. Use of N fertilizer has dramatically increased world production of food and fiber. Smil (2001) estimates that 40% of the current human population would not be alive if the Haber–Bosch process for industrial fixation of N had not been invented.

The Haber–Bosch process has also substantially altered the global cycle of biologically reactive N (Vitousek et al., 2002). The amount of biologically reactive N delivered from the land to coastal waters has increased dramatically over the past century (Turner and Rabalais, 1991) and has been a primary causal factor in oxygen depletion of coastal waters (Rabalais, 2002). Most anthropogenic N in the USA and many other parts of the world originates as fertilizer. Movement of fertilizer N to surface water is primarily by subsurface flow of nitrate (Schilling, 2002; Steinheimer et al., 1998), particularly when N fertilizer has been applied at rates exceeding crop needs (Burwell et al., 1976).

Small-plot research has shown that experiments in different production corn fields can differ substantially in their need for N fertilizer (Bundy and Andraski, 1995; Schmitt and Randall, 1994). Need for N fertilizer may also vary widely over large fields (Malzer et al., 1996; Mamo et al., 2003) though very little research has been published addressing this issue. Attempts to predict the amount of N fertilizer needed have met with limited success in humid regions (Kitchen and Goulding, 2001). The dominant practice for agricultural producers is to apply the same rate of N fertilizer over whole fields and even whole farms. In fields with spatially variable N needs, this practice leads to frequent mismatches between N fertilizer rate and crop N need. Overapplication is more frequent since producers have an economic incentive to err more frequently in that direction: The cost of unneeded N fertilizer in areas of overapplication is less than the cost of lost yield potential in areas of underapplication.

The relatively small amount of data that is available suggests that there may be enough within-field spatial variability in EONR to justify variable-rate applications of N and to justify the development of accurate and cost-effective systems for predicting how much N to apply in different parts of a field. However, these are expensive undertakings—a more complete understanding of within-field variability in EONR is needed before the benefits will clearly outweigh the costs. The degree of variability in EONR as well as its spatial scale are important determinants of which management approaches might be successful. Our objective was to characterize the degree and spatial scale of variability of N fertilizer need in midwestern corn fields.

MATERIALS AND METHODS

Experiments were conducted in three major soil areas (Mississippi Delta alluvial, deep loess, and claypan) from 2000 to 2002. Experimental fields were chosen where the row direction appeared to cross the greatest variability in soil type and landscape. The 2002 experiment in the claypan soil region was abandoned due to low and highly variable corn population, leaving a total of eight experiments. New fields were used each year. All fields had been cropped to soybean [*Glycine max* (L.) Merr.] the year before the study year. Corn was planted by cooperating producers using their equipment. Planting date, hybrid, planting population, and tillage practices were selected by

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Abbreviations: EONR, economically optimal nitrogen fertilizer rate.

Table 1. Characteristics of experimental corn fields.

Year	Soil region	Soil great group predominant (secondary)	Elevation difference	Planting date	Seeding rate	Hybrid	Tillage	Mean yield at EONR†
			m		seeds ha^{-1}			Mg ha^{-1}
2000	Claypan	Albaqualfs (Epiaqualfs)	2.7	13 April	52 000	Dekalb 626B+Y	chisel and disc	10.3
2000	Deep loess	Argiudolls	6.9	5 April	66 700	Pioneer 33A14(Bt)	no-till	11.6
2000	Mississippi Delta	Fluvaquents (Epiaquerts)	1.0	10 April	64 200	Asgrow RX770RR	chisel and disc	11.7
2001	Claypan	Albaqualfs (Epiaqualfs)	4.6	3 May	70 400	Bo-Jac 5557	chisel and disc	8.1
2001	Deep loess	Argiudolls	5.3	21 April	71 600	Pioneer 33P72	no-till	13.5
2001	Mississippi Delta	Haplaquolls (Hapludalfs)	1.9	19 April	64 200	Dekalb 697	no-till	12.4
2002	Deep loess	Hapludalfs (Argialbolls)	7.2	21 May‡	70 400	Pioneer 32P75-N008	no-till	7.4
2002	Mississippi Delta	Epiaquolls (Udipsamments)	1.6	12 April	64 200	Dekalb 668	no-till	10.2

† EONR, economically optimal nitrogen fertilizer rate.

‡ This experiment was replanted on 21 May due to poor stand. Heavy rain within 24 h of the initial planting was the main reason for stand problems.

cooperating producers but were representative of practices used for corn production in these soil regions (Table 1). The fields in the Mississippi Delta alluvial soil area were irrigated using center-pivot irrigation systems. Rainfall amounts and distribution were generally favorable for corn production in 2000 and 2001 while moderate drought stress occurred at the nonirrigated experiment in July 2002.

Treatments were field-length strips of discrete N rates from 0 to 280 kg N ha^{-1} in 56 kg ha^{-1} increments. Ammonium nitrate was sidedressed between corn rows at approximately the V6 growth stage (Ritchie et al., 1993) using a Gandy pneumatic metering applicator with drop tubes. Fertilizer was not incorporated. At the Mississippi Delta location in 2002, some N rates were misapplied: The 56 kg N ha^{-1} treatment received 123 kg N ha^{-1} in Replications 1 and 2, the 224 kg N ha^{-1} treatment received 270 kg N ha^{-1} in Replications 3 and 4, and the 280 kg N ha^{-1} treatment received 335 kg N ha^{-1} in Replications 3 and 4. Plots were six rows wide (4.5 m) and ranged in length from 400 to 1000 m. The experimental design was a randomized complete block with four replications, except for the deep loess site in 2000 where only three replications were used. Corn grain was harvested from the center four rows of each plot using a combine instrumented with an AgLeader AL2000 grain yield monitor, grain moisture sensor, experimental corn population sensor (Sudduth et al., 2000), and real-time kinematic global positioning system receiver. Data were collected at 1-s intervals at typical harvest speeds of 1.7 to 2.0 m s^{-1}. Corn grain yield was corrected to a standard moisture of 150 g kg^{-1}. Positions associated with yield data were corrected for the time lag between picking of ears and grain reaching the yield sensor. To improve block yield estimates, individual data points were removed where yield data were unreliable. Points were rejected due to any one or a combination of the following factors: significant positional errors, abrupt changes in operating speed, and instantaneous yield values outside reasonable bounds, as described by Drummond and Sudduth (2005).

Plot-level yield response to N was evaluated by fitting four different response functions (linear, quadratic, linear-plateau, and quadratic-plateau) to the data. An F test to evaluate lack of fit was performed for each model (Neter et al., 1990, p. 131–140, 245–246.) using $\alpha = 0.05$. Residuals for each model were examined visually.

Yield data were analyzed primarily at a spatial scale considerably smaller than whole plots to address the spatial variability issue that was the main objective of this research. Yield data were divided into cells 20 m long (in the direction of the corn rows) and 40 m wide containing all six N rate treatments (plus three other treatments not related to the objectives of this paper). There were between 56 and 126 of these yield response cells per experiment. The 20-m length was chosen as the minimum length that would provide a robust yield estimate, based on our previous unpublished data and the work of others (Lark et al., 1997). At normal harvesting speeds, between 10 and 12 yield data points were collected in 20 m.

Nitrogen rate treatments were not randomized within each 20-m yield response cell. It would have been desirable to do this to maximize the distance between a given N rate in one cell and the same rate in the next cell, thus minimizing the probability that spatially correlated soil properties would cause similar "random error" effects in that N rate treatment from one 20-m cell to the next. However, randomizing N rate treatments for every 20-m response cell would also have serious drawbacks. If the N applicator and the combine were run continuously down strips thus randomized, large errors would be introduced due to the inability of the equipment to spatially resolve large changes in N rate or yield over short distances (although some applicators may be able to change rates more quickly than ours could). Yield measurement errors could perhaps be mostly eliminated by starting and stopping a combine equipped with a weighing grain bin (as opposed to a yield monitor) every 20 m, but this strategy would greatly increase the time required for N application and harvest, thereby reducing the amount of information generated. Leaving a buffer zone of unused yield data between N rate treatments is another possible approach but results in a substantial loss of spatial resolution. We selected our design because we felt that it optimized the quantity, quality, and spatial resolution of the information that could be produced.

When spatial factors affecting yield or N availability are randomly oriented, a strip design like ours increases the probability of spatially correlated errors by a relatively small amount. However, in cropping systems, management can sometimes induce variability in strips in the direction of cropping—for example, uneven N applications or uneven distribution of N-immobilizing residue behind a combine. A strip-plot design is susceptible to errors from these sources. In our experiments, residue distribution from the previous soybean crop would have little effect since soybean residue neither immobilizes nor mineralizes much N (Green and Blackmer, 1995). Any uneven N applications would have been at least 2 yr previous to our experiments, minimizing their effects. We simply call to the attention of the reader that there is some potential for this type of phenomenon, which would introduce some error into our observations.

In fields where harvest population significantly influenced yield ($p \leq 0.05$), yield for each 20-m yield cell was corrected for population effects. Population corrections were used in all experiments except the deep loess soil region experiments in 2001 and 2002. The default population correction used a simple linear function to adjust yield to predicted yield at the mean population for the experiment. Due to the risk that low N rates would lead to small plants that would not trigger the mechanical population counter that we used, we tested the influence of N rate on our population data. At the Mississippi Delta location in 2000, low N rates were associated with slightly lower populations, so two separate population corrections were used: one for the two lowest N rates and another for the four highest N rates. Similarly, population effect at low N rates may be different than at high N rates because the yield potential of each plant is reduced by N deficiency. At all locations with significant population effects on yield, we tested whether there were significantly different slopes for low-N (two lowest N rates) and high-N groups. Based on this criterion, two separate functions for correcting yields for population effects were used at the deep loess 2000 and Mississippi Delta 2001 experimental locations.

Initially, a quadratic-plateau function was fitted to describe corn yield response to N rate for each 20-m cell. Six data points, one for each N rate, were used to estimate this function. Proc NLIN in SAS statistical software was used to fit the quadratic-plateau function to the data.

The quadratic-plateau function was chosen based both on the literature and on model testing for our data (see Results and Discussion). Cerrato and Blackmer (1990) compared five functions for modeling corn yield response to N and concluded that the quadratic-plateau function best described corn yield response to N. Other functions tested gave equivalent R^2 values, but gave nonrandom patterns in the residuals, indicating lack of model fit. Over many years of conducting N response studies in a variety of crops, we have typically observed that the first increment of N gives a bigger yield response than the second increment, and so on, creating a curved shape in the responsive part of the curve. This is also typical of other nutrients and represents a general biological model for plant response to nutrients (Black, 1993, Chapter 1). We have also typically observed that, with corn, there is no yield penalty for over-application of N and that a plateau occurs at high N rates. There are other possible response functions that also incorporate these two features (for example, the hyperbolic tangent function, Olness et al., 1998), but the quadratic-plateau function has been widely applied and appears to describe corn yield response to N well over a broad range of environments.

Each of the 611 response functions was plotted along with the six data points that it described and visually inspected for fit. In cases where it appeared possible that a quadratic-plateau function was appropriate, but the initial NLIN procedure may not have found the best function, the NLIN procedure was run again with different starting parameters. In a few cases, this resulted in improved fit of the quadratic-plateau function.

We did not test to see whether other functions would have described yield response to N better for individual 20-m cells. We felt that, with only six data points, when other functions fit the data better, it would have more likely been due to random experimental error than to a truly different relationship between yield and N rate. There were three cases where we described yield response to N using a model other than the quadratic-plateau function:

1. When the linear (*b*) coefficient of the best-fitting quadratic-plateau model was negative (i.e., yield decreased with the first increment of N fertilizer), yield was modeled as unresponsive to N (i.e., a flat line).
2. When the quadratic (*c*) coefficient of the best-fitting quadratic-plateau model was positive (i.e., the response curve became steeper at higher N rates), yield was modeled as a simple linear function (unless $p > 0.10$ for the simple linear function, in which case yield was modeled as unresponsive).
3. When PROC NLIN in SAS failed to converge, a simple linear function was tried. Yield was modeled as a simple linear function unless $p > 0.10$, in which case yield was modeled as unresponsive to N.

These three cases accounted for only 40 of the 611 yield response cells. Economically optimal N rate was calculated for each 20-m yield response cell from the yield response function for that cell using a corn price of \$0.08 kg^{-1} and a N fertilizer price of \$0.55 kg^{-1}. For quadratic-plateau yield response functions, $\text{EONR} = [(\$0.55/\$0.08) - b]/2c$, where b and c are the linear and quadratic coefficients of the response function, respectively (and where $b > 0$ and $c < 0$). Although optimal N rates would be slightly different if different prices were used, optimal N rate is relatively insensitive to shifts in prices (Baethgen et al., 1989). The EONR was constrained to never be higher than our highest N fertilizer rate, 280 kg N ha^{-1}.

Yield-based N rate recommendations were calculated as 0.021 kg N (kg grain yield)$^{-1}$ minus a 35 kg N ha^{-1} N credit for the previous soybean crop.

Semivariograms for EONR were fitted to the data using a restricted maximum likelihood method as described by Schabenberger and Pierce (2002, p. 594). Such methods have been shown to give more robust estimates of the sill than other methods (Zimmerman and Zimmerman, 1991). Calculations were done using PROC MIXED in SAS. A spherical model was used for all experimental locations.

RESULTS AND DISCUSSION

Average yield at EONR for these eight fields was 10.6 Mg ha^{-1} (Table 1), indicating that, in general, growing conditions and production practices were good in these experiments. Average yield response to N (as determined from quadratic-plateau functions) was 5.1 Mg ha^{-1}, indicating that yields were generally very responsive to the addition of N fertilizer. Yield response to N was more than 5 Mg ha^{-1} at all experimental locations except for the claypan soil region experiment in 2001 and the deep loess soil region experiment in 2002 (Fig. 1), which were the only two locations where yield potential did not exceed 10 Mg ha^{-1}.

The quadratic-plateau function provided the best description of whole-plot corn yield response to N fertilizer (Fig. 1), as has also been the case in past studies (Cerrato and Blackmer, 1990). Average R^2 value over the eight experimental locations was 0.63, 0.80, 0.81, and 0.82 for the linear, quadratic, linear-plateau, and quadratic-plateau models, respectively. While differences in R^2 between the quadratic, linear-plateau, and quadratic-plateau models were small, lack-of-fit tests and distribution of residuals also provided evidence that the quadratic-plateau model provided the best description of the data. Lack-of-fit tests with $\alpha = 0.05$ rejected the linear model at seven locations, the quadratic model at three locations, the linear-plateau model at three locations, and the quadratic-plateau model at zero locations. Residuals for linear and quadratic models were observed to follow a trend at many of the experimental locations, providing additional evidence that these models did not describe the data well. When the residuals for the linear-plateau model were plotted as a function of distance from the model's break point (this is the point of transition from the linear model to the plateau), we found that they appeared to be evenly distributed around zero except in the vicinity just above break point.

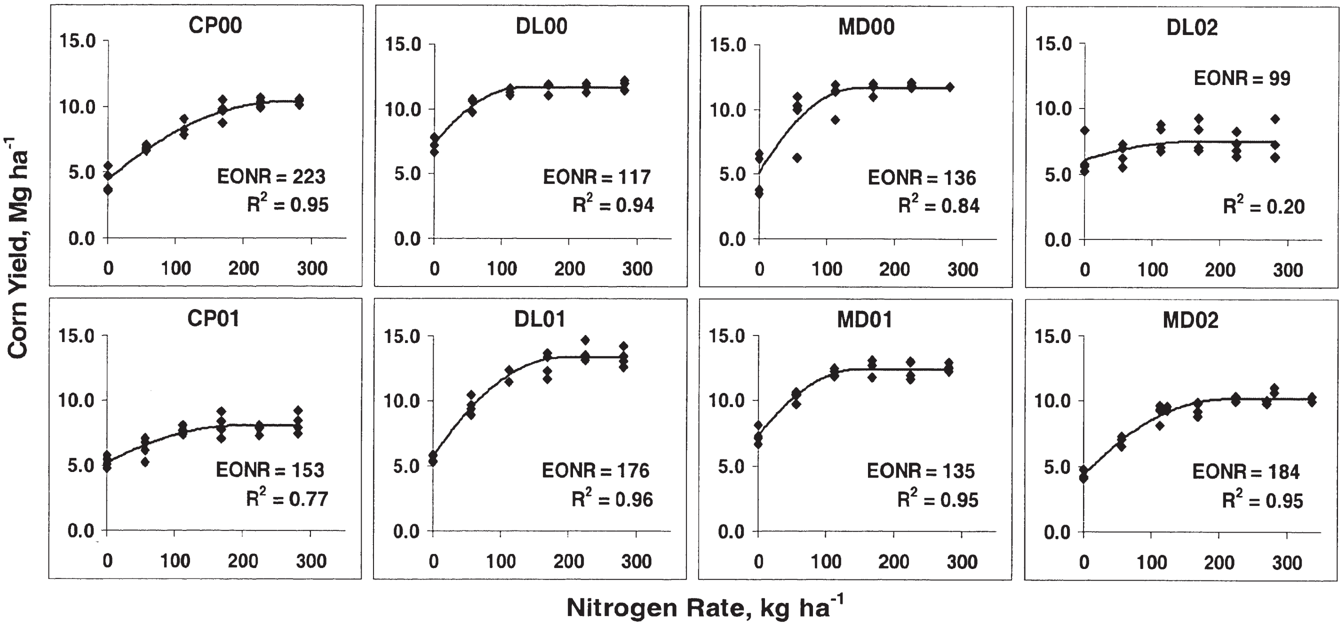

Fig. 1. Quadratic-plateau response functions describing yield response to N fertilizer for the eight experimental locations. Location abbreviations are CP = claypan soil region, DL = deep loess soil region, MD = Mississippi Delta soil region, 00 = 2000, 01 = 2001, and 02 = 2002. EONR = economically optimal N rate determined from the best-fitting quadratic-plateau response function for the whole field.

For the 23 plots with N rate from 6 to 41 kg N ha^{-1} above the break point of the model, 17 had negative residuals, and the linear-plateau function was on average 0.44 Mg ha^{-1} above the actual data. The linear-plateau and quadratic-plateau functions are very similar and diverge mainly in the vicinity of the break point of the linear-plateau function where it appears that the linear-plateau function does not describe the data well. Residuals for the quadratic-plateau model appeared to be randomly distributed around zero over all N rates.

Yield changes were generally moderate ($<$2 Mg ha^{-1}) from one 20-m yield cell to the next within a strip plot. The main exception to this observation was in the unfertilized treatment strips and occasionally the 56 kg N ha^{-1} treatment where larger changes were sometimes seen. These usually appeared to indicate large differences in soil N availability over short distances as they were not seen in the adjacent high N rate strips.

Out of 611 yield response cells, yield response to N was described using a quadratic-plateau function in 571 cells, a linear function in 15 cells, and a nonresponsive (flat) function in 25 cells by following our procedures for model choice. An independent confirmation that this was approximately the correct number of nonresponsive cells was provided by simple linear regression of yield against N rate for each of the 611 cells, resulting in 600 cells with slope $>$ 0 and 11 cells with slope $<$ 0. Given the overwhelming majority of positive slopes and the minimal evidence for negative corn yield response to N in the literature, we assumed that the 11 cells with slope $<$ 0 were all in fact nonresponsive; none of the 11 had slope significantly different than zero with α = 0.10. An equal number of cases would be expected where the slope was positive, but yield was in fact nonresponsive, producing an estimate of 22 yield cells with no true yield response to N.

Average coefficient of determination (R^2) for the 586 responsive cells was 0.87, and median coefficient of determination was 0.95. The cumulative distribution function for coefficient of determination is shown in Fig. 2. Approximately two-thirds of all yield response functions had coefficient of determination $\geq$ 0.90. Coefficient of determination was related to the size of the yield response to N (Fig. 3). Coefficients of determination less than 0.5 were seen only in yield response cells where yield response to N was less than 4 Mg ha^{-1}. This probably reflects similar levels of yield variability due to nontreatment (error) factors across all N response levels so that as N response decreases, the proportion of the total yield variability explained by N rate treatments decreases.

An example yield response function is shown in Fig. 4.

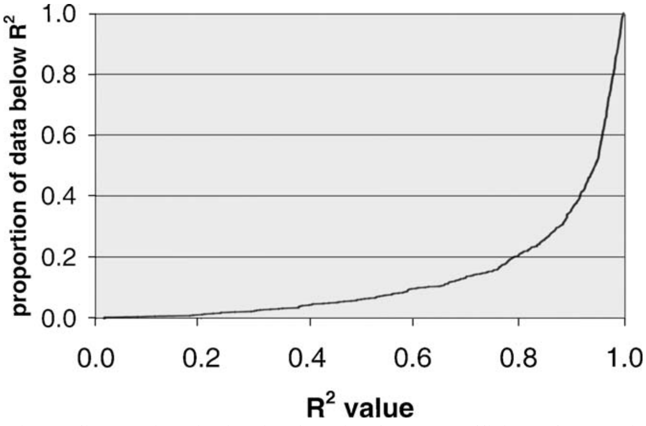

Fig. 2. Cumulative distribution function for the coefficient of determination for yield response models in the 586 yield response cells modeled as responsive to N (25 cells were modeled as nonresponsive). Approximately two-thirds of the models fit the yield data with R^2 of 0.90 or higher.

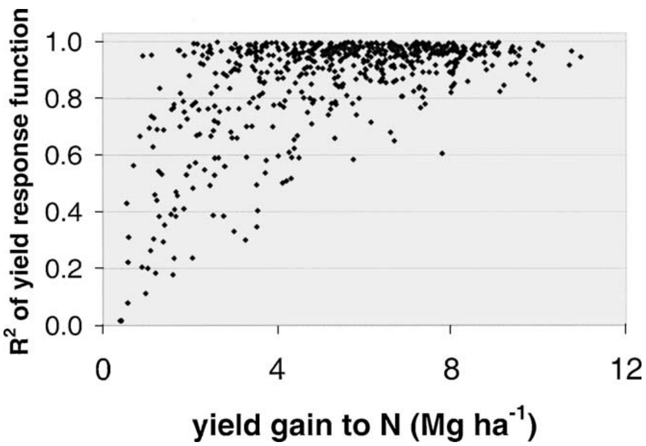

Fig. 3. Coefficient of determination for yield response models was related to the size of the yield response. When yield response was small, we observed more response functions with low coefficient of determination.

Yield response to N was 6.2 Mg ha^{-1} in this cell, which was slightly higher than the average yield response to N. Yield response functions were extremely variable, and it is not possible to show all 611 of them. The response function shown in Fig. 4 was chosen arbitrarily, by virtue of having the exact median coefficient of determination among all N-responsive cells.

Economically optimal N rate varied widely both among and within fields in this study. Median EONR ranged from 63 to 208 kg N ha^{-1} among fields (Fig. 5), indicating a need for different N fertilization strategies in different fields. This conclusion is in agreement with previous small-plot research (Bundy and Andraski, 1995; Schmitt and Randall, 1994; Scharf, 2001). Traditional yield-goal–based N rate recommendations overfertilized >75% of five experimental fields but underfertilized the claypan soil region experiment in 2000, indicating both low soil N supply and low fertilizer N efficiency at this experimental location. Median EONR varied substantially both within years and within soil regions, indicating that neither of these factors was a dominant factor determining EONR. Neither was median EONR significantly related ($p = 0.34$ by regression) to yield level (i.e., mean yield at the optimal N rate). Median EONR (Fig. 5) was slightly below field-average EONR (Fig. 1).

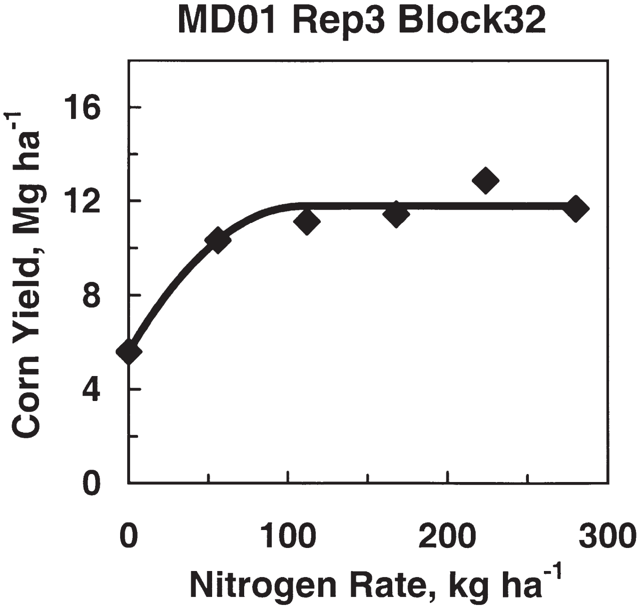

Fig. 4. Yield data and the fitted response function for a 20-m yield response cell at the Mississippi Delta location in 2001. Yield was modeled using a quadratic-plateau response function for this cell and for 571 of the 611 cells. This cell was chosen arbitrarily as an example based on having the median R^2 for the 586 responsive cells.

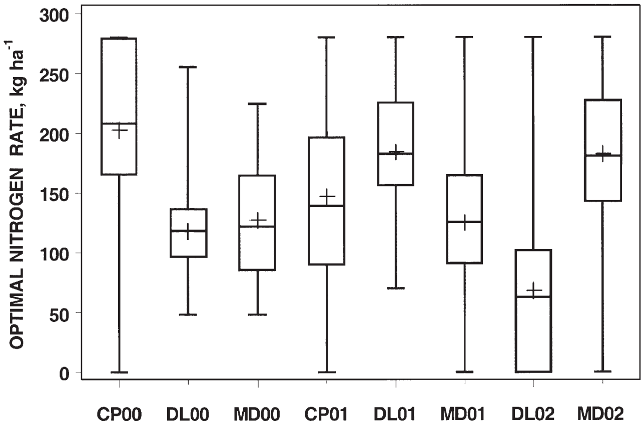

Fig. 5. Box-and-whiskers diagram of economically optimal N rate (EONR) distributions for the eight experimental fields. The upper and lower limits of each box signify the 25th and 75th percentiles for EONR, the horizontal line in the center of the box indicates the median, the "+" in each box indicates the mean, and the "whiskers" or arms represent the full range of EONR observed at an experimental location. The EONR ranged from 0 to 280 kg N ha^{-1} (the highest N rate used) for five of the eight locations. The span from the 25th to the 75th percentile was ≥69 kg N ha^{-1} at all locations except the deep loess location in 2000. Any uniform rate would miss the optimal N rate by a large margin for much of the field area. In the location abbreviations on the *x* axis, CP = claypan soil region, DL = deep loess soil region, MD = Mississippi Delta soil region, 00 = 2000, 01 = 2001, and 02 = 2002.

Within-field variability in EONR was also high. Average standard deviation of EONR was 58 kg N ha^{-1}. Five of the eight fields had EONR values that spanned the entire range of experimental N rates—0 to 280 kg N ha^{-1} (Fig. 5). The span from the 25th to 75th percentiles of EONR was ≥69 kg N ha^{-1} for seven of the eight experimental locations (Fig. 5). This implies that, even if the median EONR had been known for these seven fields, uniform application of the median EONRs would have resulted in half of each field (the quarter below the 25th percentile plus the quarter above the 75th percentile) receiving a N rate at least 34 kg N ha^{-1} different from the local EONR. Similarly, for these seven fields, uniform application of the median EONRs would have resulted in one-fifth of each field (below the 10th percentile and above the 90th percentile) receiving a N rate at least 65 kg N ha^{-1} different from the local EONR. This level of variability in EONR suggests that variable-rate N fertilizer applications for corn could be beneficial if EONR could be predicted with reasonable accuracy at various points across the field.

Our results agree with field-scale experiments conducted in Minnesota (Malzer et al., 1996; Mamo et al., 2003), Illinois (Harrington et al., 1997), and the United

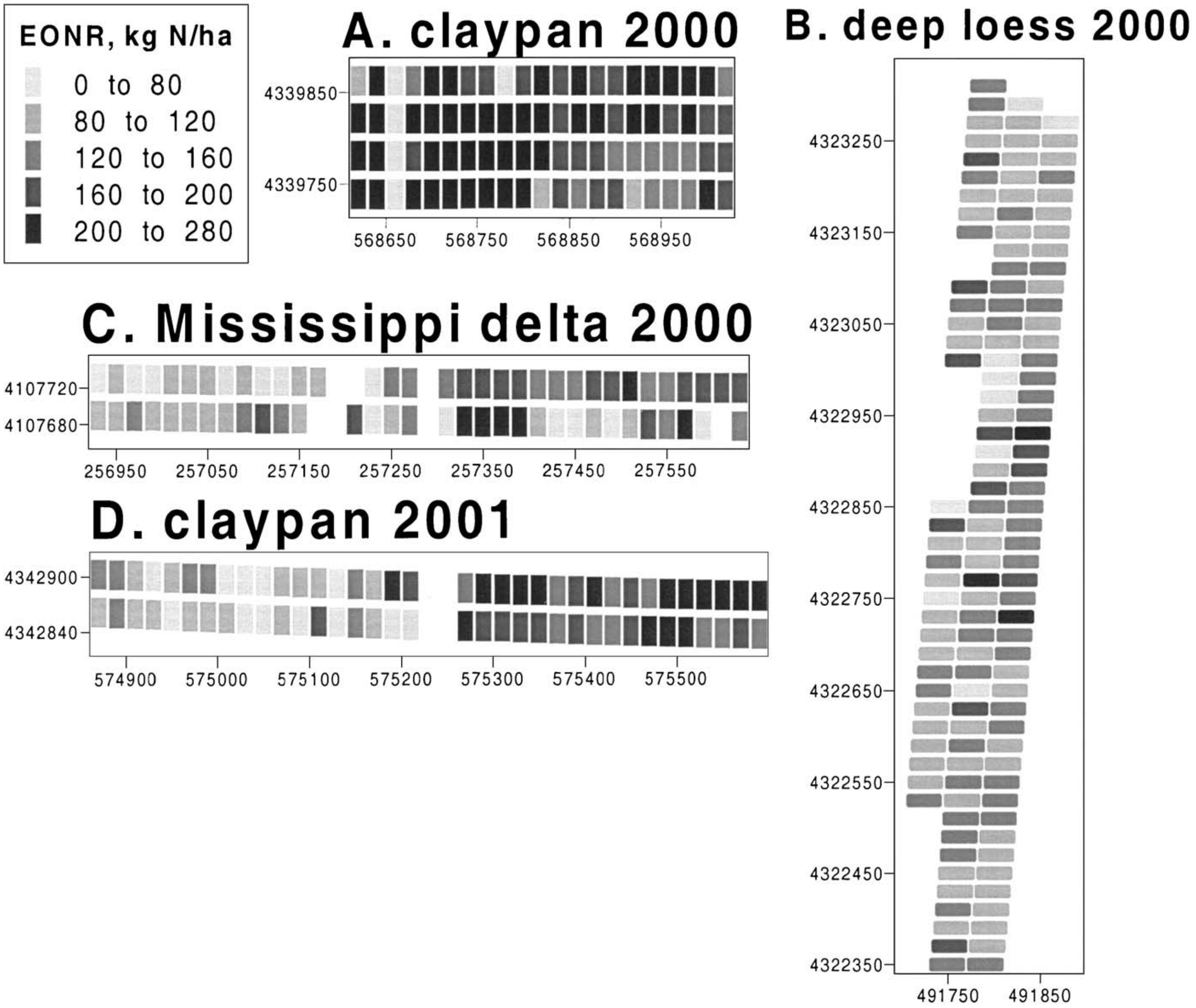

Fig. 6. Class maps of economically optimal N rate (EONR) for four experimental fields. Each gray rectangle represents an area in the field about 20 by 40 m, which contained six N rate treatments ranging from 0 to 280 kg N ha^{-1}. A quadratic-plateau function (see text for exceptions) was fitted to describe yield response to N rate in each 20- by 40-m area, and then this function was used to calculate EONR. The EONR for each area in the field is indicated by shade of gray, with darker shade signifying higher EONR. Missing rectangles in B are due to an irregular field boundary; in C, they are due to a drainage channel (west of center), a pivot road and rep break (center), and stand loss (near the southeast corner); and in D, they are due to the break between replications. Average yield at optimal N rate was 10.3, 11.6, 11.7, and 8.1 Mg ha^{-1} for the experiments shown in A, B, C, and D, respectively. Numbers on the boxes circumscribing the experimental areas are UTM coordinates in meters. Scale is identical for all fields in Fig. 6 and 8, and up is directly north in each of these figures.

Kingdom (Lark and Wheeler, 2003), which detected a similarly wide range in optimal N rate within individual corn or wheat (*Triticum aestivum* L.) fields. Experiments with small-plot observations at several points across a field have sometimes found low to moderate variability in optimal N rate (Schmidt et al., 2002; Bundy, 2002), but the number of observations per field was much lower in those studies. Taken all together, the available evidence suggests that wide variation in EONR is relatively common, that there is a need to understand how often it occurs in different systems, and that there is a need to develop strategies for managing fields with variable EONR.

The patterns of spatial variability in EONR that we observed were quite different from field to field, and we will discuss them in chronological order and then as a group. In the 2000 claypan soil region experiment, EONR values were generally high, with the lowest values in the southeast quarter and in a low-yielding streak across the west end of the field (Fig. 6A). The close proximity of very high and very low EONR values at this streak results in a high nugget in the semivariogram (Fig. 7). Although a high nugget value would tend to imply that N management would need to be at a spatial scale finer than 20 m to accurately reflect and respond to EONR variability, the economic consequences of managing at a coarser scale and overfertilizing the low-EONR streak may be minimal in this case.

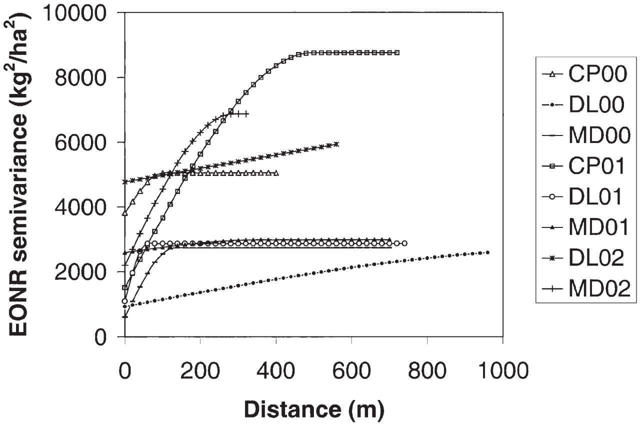

Fig. 7. Fitted semivariograms for economically optimal N rate (EONR) at the eight experimental locations. A restricted maximum-likelihood procedure was used to fit semivariogram spherical model parameters to the observed EONR data for each location. The length of each semivariogram is limited to the experimental length. In the location abbreviations in the legend, CP = claypan soil region, DL = deep loess soil region, MD = Mississippi Delta soil region, 00 = 2000, 01 = 2001, and 02 = 2002.

The calculated 95% confidence intervals for spherical-model semivariogram parameters were relatively wide in most cases. Thus, the models shown in Fig. 7 should not be considered to be highly precise. However, they are helpful in understanding differences in spatial structure between fields and how that might influence the suitability of variable-rate N management (relative to a uniform rate), or of different approaches to variable-rate N management.

The 2000 deep loess soil region experiment had less variability in EONR than any other location (Fig. 5), and only weak spatial patterns in EONR were observed (Fig. 6B). The fitted semivariogram indicates low variability at short distances and only a very gradual increase as distance increases (Fig. 7). Thus, although potential benefits due to variable application of N appear to be smaller at this location than any of our other locations, a fairly large proportion of the total potential benefit could be obtained with large management zones. Semivariance for EONR at a distance of 300 m is 40% lower than maximum semivariance (lower than at any other location), and managing at this scale would produce 60% of the reduction in semivariance that would be produced by managing at a 20-m scale (Fig. 7).

The 2000 Mississippi Delta and 2001 claypan soil region experiments were similar in their patterns of EONR (Fig. 6C and 6D). In each field, much of the variability in EONR could be captured simply by dividing the fields into east and west halves. Semivariance for EONR increases sharply as distance increases in the fitted semivariograms (Fig. 7). Among the eight fields that we studied, these two fields had the greatest relative structural variability (=partial sill/sill) (Schabenberger and Pierce, 2002, p. 581), followed by the Mississippi Delta 2002 field. This indicates a high level of spatial structure in the EONR values and high potential for variable-rate N management to increase N use efficiency and profitability. In both experiments, there appears to be potential for success even with a small number of relatively large and contiguous management zones, but especially in the claypan region 2001 experiment where the range was nearly 500 m (Fig. 7). Using 4-ha (200 by 200 m) management zones in this field would allow management of nearly half of the manageable variability (i.e., partial sill) in EONR that we observed. The semivariogram for the Mississippi Delta 2000 experiment suggests that management scale would have to be more on the order of 50 m to produce the same proportional improvement over field-scale management; however, the main disadvantage of simply managing the field as two halves would lie only in overfertilization of about one-fourth of the eastern half, which the producer was already doing using his current management practices.

Variability and spatial dependence of EONR were also similar for the deep loess (Fig. 8A) and Mississippi Delta (Fig. 8B) soil region experiments in 2001. Although the median EONR was higher for the deep loess experiment, the distributions (Fig. 5) and fitted semivariograms (Fig. 7) for EONR are quite similar for these two fields. Only at very short distances are the semivariograms substantially different—the nugget is much lower for the deep loess soil region experiment. However, the clear implication for both fields is that relatively fine-scale N management (30 m or less) would be required to address very much of the variability in EONR. Management tools such as spectral radiometers (Bausch and Duke, 1996) or remote sensing (Blackmer et al., 1996) may offer the greatest potential to manage N on a scale this fine. The suitability of using a small number of management zones for N is questionable in fields like these.

For both 2002 experiments, distribution of EONR was fairly wide, but the deep loess experiment had the lowest median EONR of all eight experiments while the Mississippi Delta experiment had the second-highest median EONR (Fig. 5). Yields were low in the deep loess experiment, partly due to slightly late replanting (see Table 1) coupled with drought in July. There was minimal increase in semivariance of EONR with distance in the deep loess experiment (Fig. 7), indicating that a zone-based approach to N management would have been unlikely to perform well in this field. The high nugget value (Fig. 7) indicates high variability at short distances. At several locations in this field, adjacent 20-m cells had very different values for EONR (Fig. 8C). However, the cells with high EONR values had shallow response slopes, and the yield response to N was not great. Thus, the behavior between adjacent cells was not as different as it might seem, and potential benefits to variable N in this field may not be as great as the relatively high semivariance (sill) suggests.

In contrast, semivariance of EONR tripled with distance in the Mississippi Delta experiment in 2002, with a range of about 280 m (Fig. 7). This indicates good potential for variable-rate N to be beneficial. It also indicates that zones could be moderate in size (perhaps 1 ha) and still produce substantial benefits. The highest EONR values were observed in fairly large blocks (approximately 80 by 80 m) in the northeast and southeast corners (Fig. 8D).

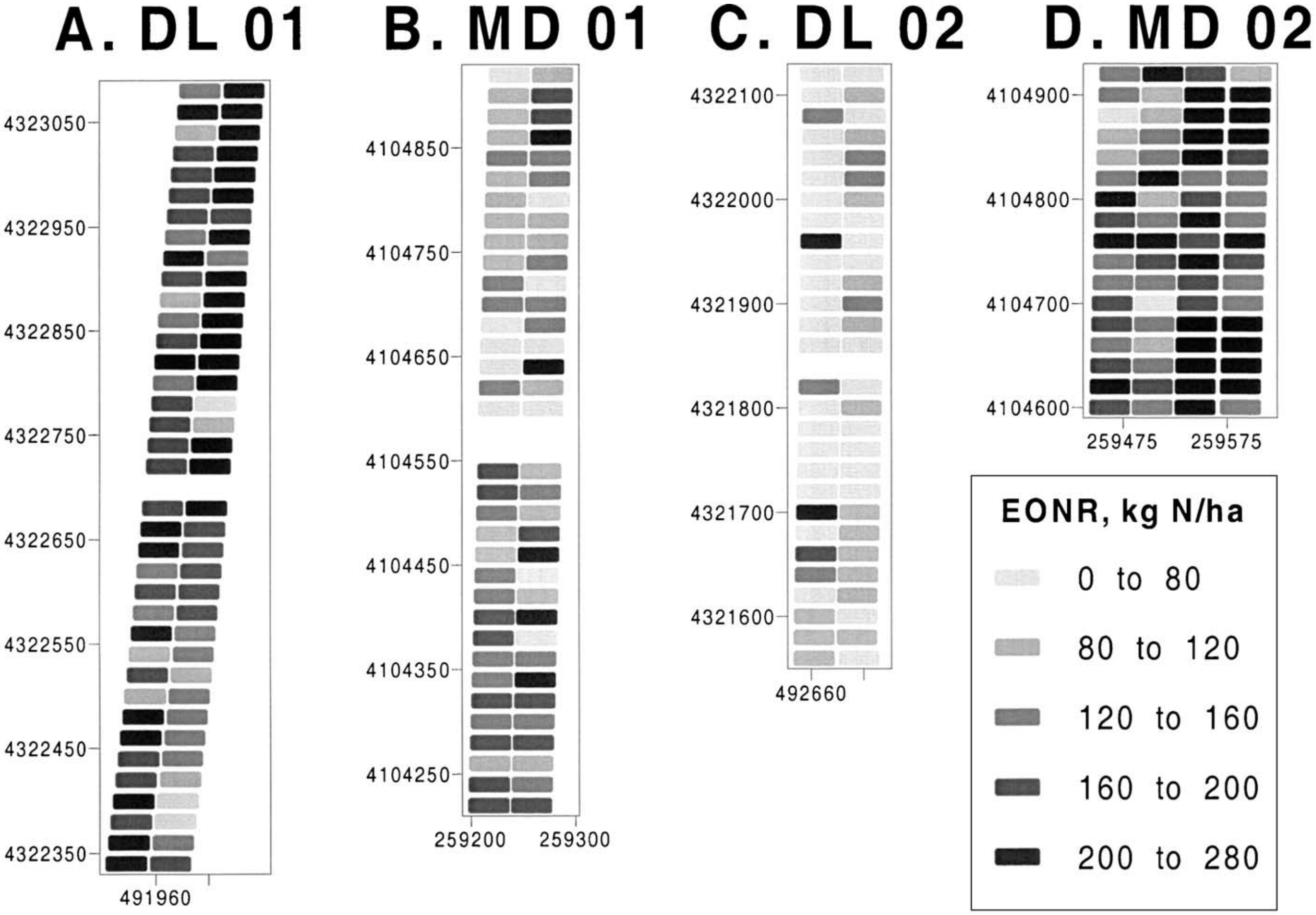

Fig. 8. Class maps of economically optimal N rate (EONR) for four experimental fields. Each gray rectangle represents an area in the field about 20 by 40 m, which contained six N rate treatments ranging from 0 to 280 kg N ha^{-1}. A quadratic-plateau function (see text for exceptions) was fitted to describe yield response to N rate in each 20- by 40-m area, and then this function was used to calculate EONR. The EONR for each area in the field is indicated by shade of gray, with darker shade signifying higher EONR. Missing rectangles in A, B, and C are due to the break between replications. Average yield at optimal N rate was 13.5, 12.4, 7.4, and 10.2 Mg ha^{-1} for the experiments shown in A, B, C, and D, respectively. Numbers on the boxes circumscribing the experimental areas are UTM coordinates in meters, and up is directly north. Scale is identical for all fields in Fig. 6 and 8. Location abbreviations: DL = deep loess soil area, MD = Mississippi Delta soil area, 01 = 2001, and 02 = 2002.

There are two main elements in a semivariogram that give some indication as to whether variable-rate N application might be beneficial and at what scale. The higher the sill (the semivariance where the function reaches a plateau), the more variability in EONR and potential profit from correct variable-rate N application. By this criterion, the semivariograms indicate that variable-rate N would have been most promising at the claypan 2001, Mississippi Delta 2002, deep loess 2002, and claypan 2000 experimental fields. Semivariograms also indicate scale of variability and thus the appropriate scale of management. If we look at how much of the total semivariance for EONR is eliminated at a scale of 100 m in Fig. 7, only the claypan 2001, Mississippi Delta 2002, and deep loess 2000 experimental fields appear to have good potential to produce benefits through management at this scale, which corresponds to 1-ha management units. At a scale of 50 m, semivariance for EONR is substantially reduced in the Mississippi Delta 2000 experimental field. Semivariograms for the remaining fields suggest that N management would need to be at a scale of 25 m or less to produce appreciable benefits.

Neither year nor soil region appeared to have a consistent influence on N response patterns. None of the years or soil regions stood out as being different from the others in terms of their distributions of EONR (Fig. 5), their semivariograms describing the spatial dependence of EONR (Fig. 7), or their observable patterns of EONR in the field (Fig. 6 and 8). Although both soil properties and weather years are known to influence spatial patterns of N mineralization, N losses, and N use efficiency, it appears that the interactions among soils, weather, and management history were complex enough for these fields that no simple generalizations can be made. Determination of optimum N fertilizer rates and management scales may need to be diagnosed on a field-by-field basis.

An important but neglected area in the body of EONR research is the degree of uncertainty associated with EONR estimates. We are not aware of any papers addressing this issue though many papers have been published on estimating and predicting EONR. It is possible to combine uncertainty estimates in quadratic-plateau model terms to calculate a confidence interval, but this procedure seems awkward and likely to have low statistical power. Development of procedures designed specifically to estimate confidence intervals for EONR would be desirable. We have not attempted to estimate confidence intervals for EONR in this paper but encourage readers to keep in mind that there are errors associated with our estimates of EONR. These errors are due to both measurement errors (e.g., limits of yield monitor accuracy) and spatial variation of non-treatment factors (e.g., hydrology, aspect, soil compaction) that influence yield.

SUMMARY

In eight field-scale experiments, we observed a wide range of values for EONR for corn in each field. Median EONR values were quite different from field to field, and much of each field had EONR values quite different than the median. Spatial structure of EONR indicated that relatively coarse management zones (≥1 ha) might be appropriate for four of the eight fields (claypan 2001, Mississippi Delta 2002, Mississippi Delta 2000, and deep loess 2000) while finer-scale management would probably be necessary in the other four fields. These observations suggest that:

1. There continues to be a need to distinguish between fields in terms of their overall need for N.
2. The average level of within-field variability in EONR is high enough that variable-rate N applications have potential to produce economic and environmental benefits.

Spatial patterns of variability in EONR have implications for what types of variable-rate N management can be successful. We observed considerable diversity between fields in the patterns of spatial variability in EONR, implying that different fields would best be managed with different tools, approaches, and scales of variable-rate N applications. Thus, in addition to the challenge of creating these different tools, we are also faced with the challenge of predicting which tool or scale is most appropriate for a particular field. Some fields might be optimally managed with only a few well-chosen zones while others might require N management systems using spatially dense information to reach their full potential.

Our results suggest that further attempts to develop systems for predicting spatially variable N needs are justified in these production environments.

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