Published online October 27, 2006

Spatially Variable Corn Yield is a Weak Predictor of Optimal Nitrogen Rate

Peter C. Scharf,* Newell R. Kitchen, Kenneth A. Sudduth, and J. Glenn Davis

ABSTRACT

Historically, a mass-balance approach (yield goal times a factor) has been the dominant method for making N fertilizer rate recommendations. Although several states have moved away from the mass-balance approach for N rate recommendations for corn (*Zea mays* L.), much of the effort that has gone into variable-rate N research has focused on combining spatial yield predictions with a mass-balance approach. Our objectives were to evaluate, at field scale, the relationship between spatially variable yield levels and economically optimal N fertilizer rates (EONR) and to evaluate the performance of yield-based N rate recommendations. 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 yield cell. The EONR varied much more widely than did plateau yield. Yield level explained on average only 15% of the variability in EONR. Averaged over the eight fields, variable application of mass-balance-based N rates based on actual yields would have increased yield by only 31 kg ha^{-1}, and profit by \$2 ha^{-1}, relative to uniform mass-balance N rates based on field average yields. In comparison, variable-rate application of EONR would have increased profit by an average of \$38 ha^{-1}. Of this, \$14 ha^{-1} could have been obtained by uniform application of the median optimal N rate for each field. We conclude that although we observed considerable spatial variability in optimal N rates, this was due mainly to variations in soil N supply and N uptake efficiency, rather than to variations in crop demand for N. Yield variability appears to be at best a small part of the information that must be used to make successful variable-rate N recommendations for corn.

Historically, a mass-balance approach (yield goal times a factor, minus credits) has been the dominant method for making N fertilizer rate recommendations. Stanford (1973) presented a classic discussion of the rationale for and mechanics of this approach. Only a few published reports evaluate this rationale using field data. Lory and Scharf (2003) combined results from a large number of N rate plot experiments with corn in humid regions of the USA, concluding that there was only a very weak relationship between yield goal and economically optimal N fertilizer rate in these experiments. Long-term experiments, in which the same N rate is applied to the same plot over a long period, are more difficult to interpret, but Vanotti and Bundy (1994) showed that the best long-term N rate treatment in a given year was not related to the yield level that year.

The dominant N fertilizer management system is still application of uniform rates over whole fields (and often whole farms) that approximate the well-established mass-balance rate recommendations. For some regions or some producers, rates may be noticeably above or below normal mass-balance rates, but application of the same rate to whole fields remains nearly universal. This contrasts with recent research that has shown that the amount of N needed often varies widely within individual corn fields (Davis et al., 1996; Blackmer and White, 1998; Mamo et al., 2003; Schmidt et al., 2002; Scharf et al., 2005). Observations of within-field variability in EONR suggest that efforts to develop accurate systems for variable N applications are justified.

Power et al. (2001) identified uniform N applications over variable landscapes as a major deficiency in current farming systems that creates opportunities for N loss to ground and surface waters. Variable-rate N application gives producers the potential to assess and respond to landscape variation in a way that maintains or increases crop productivity while reducing loss of N (Pan et al., 1997). This potential can be reached only if the system for deciding how much N to put where is accurate.

Although several states have moved away from mass-balance approaches for N rate recommendations for corn, much of the effort that has gone into variable-rate N research has focused on combining spatial yield predictions with a mass-balance approach (e.g., Godwin et al., 1999; Kitchen and Goulding, 2001; Ferguson et al., 2002; Murdock et al., 2002; Varsa et al., 2003; Khosla et al., 2002). A driving factor for using yield-based predictions for variable-rate N management is the ability to document within-field yield variability using combine yield monitoring systems (Pierce and Nowak, 1999). Yield-based applications have also been studied with reference to variable applications of P and K (Grove et al., 2000); however, with these relatively stable nutrients, the approach has focused on replacing the nutrients that were removed by past spatially variable yields. With N, management is much more short-term than with P and K, and the relevant yield variability is not in the past but in the future. This has created additional debate about how to best predict spatially variable yields to produce variable N rate recommendations. The credibility of using expected yield to generate a mass balance-type variable-N prescription rests on how well within-field yield variability is related to within-field EONR variability. This relationship has not been evaluated well.

Crop demand for N clearly increases when yield increases, and this is the basis for mass balance N rate

P.C. Scharf, Plant Sciences Division, Univ. of Missouri, Columbia, MO 65211; N.R. Kitchen and K.A. Sudduth, USDA-ARS, Cropping Systems and Water Quality Research Unit, Columbia, MO 65211; J.G. Davis, USDA-NRCS, Columbia, MO 65203. Contribution from the Missouri Agricultural Experiment Station and the USDA-ARS. Received 25 July 2005. *Corresponding author (scharfp@missouri.edu).

Published in Soil Sci. Soc. Am. J. 70:2154–2160 (2006).
Nutrient Management & Soil & Plant Analysis
doi:10.2136/sssaj2005.0244

Abbreviations: EONR, economically optimal N rate.

recommendations. However, the situation is complicated by the complex and rapidly shifting biochemistry of N in soil. In particular, N loss processes associated with wet soil conditions may be spatially variable and difficult to predict due to the highly heterogeneous movement of water through most soils and landscapes. Heterogeneity of water movement may also influence N mineralization rates through effects on soil temperature and oxygen availability. Such factors may lead to spatial variability in the ability of the soil to provide N to the crop.

With spatial variability occurring in both N supply from the soil (the net of mineralization, immobilization, fertilization, and losses) and N demand from the crop (yield and related N uptake and removal), it is unclear which of these two factors (or both) will have a pronounced impact on spatially variable EONR. Until this point is more clearly understood, it will be difficult to develop successful management systems for variable-rate application of N fertilizer.

Few studies have been conducted at the field scale documenting spatially variable EONR and comparing results with yields. With the current trend of using combine yield maps to develop site-specific N recommendations, field-scale variable-N management investigations are warranted. Recent field-scale research on three different soil types in Missouri demonstrated EONR to be highly variable both between and within fields (Scharf et al., 2005). As an extension of that research, our objective here was to evaluate within individual fields the relationship between spatially variable corn yield level and EONR. A second objective was to compare the performance (yield and profitability) of a yield-based variable N fertilizer recommendation with an EONR-based N recommendation, if we had been able to know yield level and EONR at the time N fertilizer was applied.

MATERIALS AND METHODS

Experiments were conducted in three major soil areas (Mississippi delta alluvial, deep loess, claypan) from 2000 to 2002. 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*) 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 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 non-irrigated experiment in July 2002.

Treatments were field-length strips of discrete N rates from 0 to 280 kg N ha^{-1} in 56-kg increments. Ammonium nitrate was sidedressed between corn rows using a Gandy metering applicator with drop tubes. Plots were six rows wide (4.5 m) and ranged in length from 400 to 1000 m. Experimental areas ranged from 5 to 12 ha in size. 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. Corn grain yield was corrected to a standard moisture of 150 g kg^{-1}.

Data were analyzed primarily at a spatial scale considerably smaller than replications. Yield data were preprocessed to remove erroneous data points and to account for the grain flow lag through the combine. They were then divided into sections 20 m long and containing all six N rate treatments, which we term “yield cells.” There were between 56 and 126 of these yield cells per experimental field. The 20 m length was chosen as the minimum length that we felt would give robust yield data. At normal harvesting speeds, between 10 and 12 yield data points were collected in 20 m.

In fields where harvest population (as measured by population sensors on the combine) significantly influenced yield ($p < 0.05$), but was independent of N rate, yield for each 20-m yield cell was corrected to the mean population for the field using a linear function.

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 both because it has historically been the best function for describing corn yield response to N (Cerrato and Blackmer, 1990) and because it gave the best description of our yield data among four functions tested (Scharf et al., 2005). When certain criteria were not met, yield response to N was modeled as either a linear or a nonresponsive function (Scharf et al., 2005). Economically optimal N rate (EONR) 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 price of \$0.55 kg^{-1}. 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). EONR was constrained to never be higher than our highest N fertilizer rate, 280 kg N ha^{-1}.

Table 1. Characteristics of experimental areas in corn fields.

Year	Soil region	Soil great group	Elevation difference in exp. area	Planting date	Seeding rate	Hybrid	Tillage	Mean yield at EONR (year of test)
		Predominant (secondary)	m		seed ha^{-1}			Mg ha^{-1}
2000	Claypan	Albaqualfs (Epiaqualfs)	2.7	13 April	52000	Dekalb 626B+Y	Chisel & Disc	10.3
2000	Deep loess	Argiudolls	6.9	5 April	66700	Pioneer 33A14(Bt)	No-till	11.6
2000	Mississippi delta	Fluvaquents (Epiaquerts)	1.0	10 April	64200	Asgrow RX770RR	Chisel & Disc	11.7
2001	Claypan	Albaqualfs (Epiaqualfs)	4.6	3 May	70400	Bo-Jac 5557	Chisel & Disc	8.1
2001	Deep loess	Argiudolls	5.3	21 April	71600	Pioneer 33P72	No-till	13.5
2001	Mississippi delta	Haplaquolls (Hapludalfs)	1.9	19 April	64200	Dekalb 697	No-till	12.4
2002	Deep loess	Hapludalfs (Argialbolls)	7.2	21 April	70400	Pioneer 32P75-N008	No-till	7.4
2002	Mississippi delta	Epiaquolls (Udipsamments)	1.6	12 April	64200	Dekalb 668	No-till	10.2

Simple linear regression was used to model the ability of yield at the EONR (i.e., just below the plateau yield) from each 20-m yield cell to predict EONR. 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. Yield and economic performance were evaluated for four situations (uniform yield-goal-based rate, variable yield-goal-based rate, uniform median EONR, and variable EONR) in each field by putting the N rate for each yield cell into the yield response function for that cell, then averaging yield and N rate over all the cells in a field. Economic calculations were based only on N fertilizer cost and corn grain yield (prices used are given above), with no cost attributed to variable-rate application of N or to creating spatially variable N rate recommendations.

Nitrogen rates for four scenarios were assigned to each cell based on:

1. The economic optimum as determined by the N response function for that cell;
2. The median EONR for the entire field;
3. Yield goal-based N rate for the individual cell with the yield goal determined as the expected yield for that cell when fertilized at the EONR; or
4. Yield goal-based N rate for the entire field with the field average yield goal determined as the average of the expected yield for every cell when fertilized at the EONR.

Yield and profit for each cell was then determined for each of the four scenarios based on the N response function and assigned N rate for that cell. Yield, profit, and N rate for the four scenarios were averaged over all cells in each field for comparison.

RESULTS AND DISCUSSION

Values for EONR were highly variable in the corn fields that we studied (Fig. 1). 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. This level of variability suggests that variable-rate N applications may be justified in these fields, and that the performance of any uniform N application would be suboptimal.

In five of eight fields, mass-balance N rates based on experiment-average yields overfertilized more than 80% of the experimental area (Fig. 1). This suggests the presence of a substantial soil N supply in these five fields that is not accounted for by the mass balance system. In two fields, the mass balance recommendation was nearly identical to the median EONR, suggesting that soil N supply was approximately equal to what is implicitly assumed in the mass balance system. And in one field (claypan 2000), the mass balance recommendation underfertilized about 65% of the field, suggesting either a low initial soil N supply or in-season loss of N. In-season loss of N seems to be a likely explanation. The predominant soil map unit in this field is classified as poorly drained, and the nearest weather station to this field received 17 cm of rain during June. It is likely that the field was at or near saturation for significant periods during June. Saturation, in combination with warm soil temperatures, creates the potential for rapid loss of N via denitrification. Although two other experimental fields

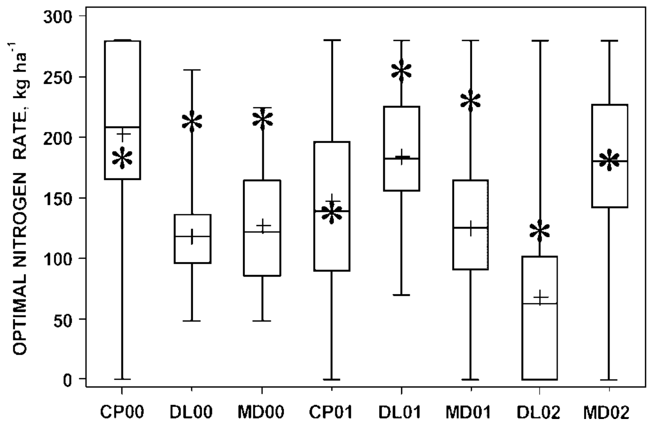

Fig. 1. Box-and-whiskers diagram of economically optimal N rate (EONR) distributions for the eight experimental fields. The upper and lower limits of each box signify the 25th and 75th percentiles for EONR, the horizontal line in the center of the box indicates the median, the "+" in each box indicates the mean, and the "whiskers" or arms represent the full range of EONR observed at an experimental location. Asterisks represent the N rate that was recommended by the mass balance system based on actual field-average yields. 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.

had greater June precipitation, they had better drainage characteristics that would reduce the risk of saturation and denitrification.

Yield level was in general a poor predictor of EONR in these eight fields (Fig. 2). At the claypan soil region experiment in 2001, EONR was higher in the east end of the field (Scharf et al., 2005), as was plateau yield. Although yield level was fairly well related to EONR at this location (Fig. 2, top right), the relationship was not at all similar to the mass balance relationship that is typically used for making N rate recommendations (i.e., regression line and mass-balance line are different). Only in the Mississippi Delta 2002 field did the observed relationship between yield and EONR approximate the mass balance equation, but a large amount of scatter limited the quality of mass-balance-based recommendations in this field as well. Except for the claypan 2001 location, yield level never explained more than 0.22 of the variability in EONR. Averaged over all eight fields, yield level explained only 0.15 of the variability in EONR. When all eight fields are combined into a single analysis, yield level explains only 0.13 of the variability in EONR. These observations are similar to those of Davis et al. (1996), in which yield level explained on average 0.12 of the variability in EONR for corn.

Figure 2 does not give a sense of the spatial relationships between yield and EONR. Although these relationships were different from field to field, Fig. 3 shows one example of how yield and EONR varied in space. In this experiment (Mississippi Delta soil region experiment in 2000), spatial patterns for both yield and EONR included both coarse and fine variability. The coarse patterns can be summarized by saying that more N was needed to optimize N in the eastern half of the field, while yields were slightly higher in the western two-

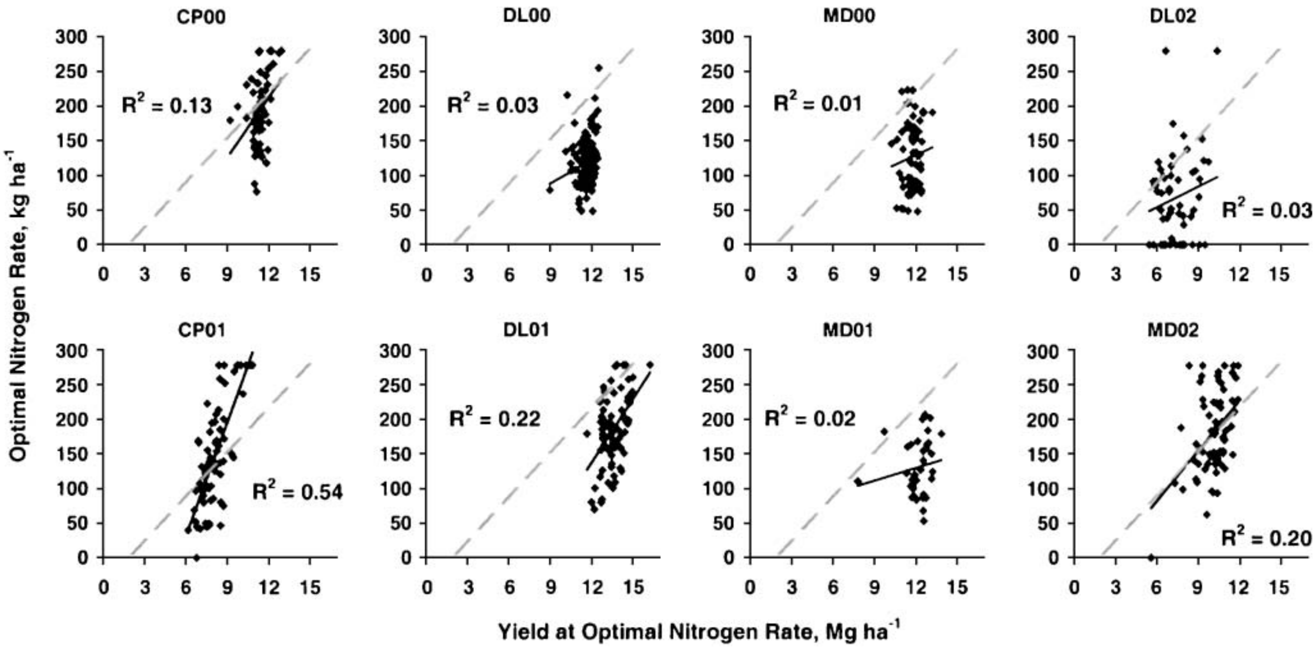

Fig. 2. Graphs of the relationship between yield and economically optimal N rate (EONR) for each of the eight experimental locations. Each data point was derived from an N response function (mainly quadratic-plateau, see text for exceptions) for a 20 m by 40 m area to which six N rates ranging from 0 to 280 kg N ha^{-1} had been applied. We capped EONR at the highest N rate applied (280 kg N ha^{-1}), though actual EONR was probably higher in some cases. The regression line that best describes the relationship between yield and EONR for each field is shown as a solid black line (R^2 is shown on each graph). The dashed gray lines represent a mass-balance-based N rate recommendation system, with 21 kg N applied for each kg of corn grain yield (= 1.2 lb N/bu) and a 35 kg N ha^{-1} N credit for the previous soybean crop. Location abbreviations: CP = claypan soil region, DL = deep loess soil region, MD = Mississippi delta soil region, 00 = 2000, 01 = 2001, and 02 = 2002.

thirds of the field. The scale of the variability was much larger for EONR than for yield at EONR. In only a few locations was EONR as high as the N rate recommended by the University of Missouri to produce the observed yield. In most of the field, EONR was lower than university recommendations, probably due to higher soil N contributions than are accounted for in the recommendations. Check plots receiving zero N looked much better in the western half of this experiment than in the eastern half, suggesting more N availability from soil, thus resulting in lower EONR values. If this is the correct explanation, it appears that there is substantial spatial variability in the amount of N contributed by the soil.

Superimposed on the coarse patterns is a considerable amount of finer-scale variability. In this case, the coarse patterns run, if anything, opposite to the mass-balance notion that higher-yielding areas need more N. However, when the finer-scale variability is added in, there is almost no relationship between yield and EONR in this field (Fig. 2, second from the top on the left).

Poor prediction of EONR by yield suggests that spatial variability in EONR was dominated by variations in soil N-supplying ability, N uptake efficiency, in-season N loss, or combinations of all three, rather than by variations in crop N demand. Experimental error in determining EONR also contributes to the poor relationship, but the median R^2 for the yield response functions was 0.95, suggesting that data quality was generally good. It is apparent in Fig. 2 that EONR varied much more widely than did yield in most experiments, further supporting the dominant effects of variability in soil N supply or N uptake efficiency.

Similar results have been obtained with other crops. Nolan et al. (1999) found substantial variability in EONR for canola and wheat in Alberta, but the zones with the highest yields were not the zones with the highest need for N fertilizer. Godwin et al. (1999) were able to increase profitability on one of two barley fields by varying N rates based on historical yield zones, but the most profitable strategy on that field was to increase N rates on the lowest-yielding area. This is evidence that the low-yielding areas had lower fertilizer N efficiency or soil N supply than other parts of the field, and that these factors predominated over crop demand in determining EONR. Welsh et al. (2003) found that wheat yield was not improved by varying N rates based on historical yields, but was improved by varying N rates based on remote sensing of crop status.

Despite the lack of correlation between yield levels and EONR values in our experiments and the other experiments cited above, it seems possible that crop N demand may have a greater effect on total EONR over the long term than in an individual year. This would be the case where long-term yield patterns are more consistent than patterns of N supply, N uptake efficiency, and N loss. Vanotti and Bundy (1994) concluded that, although yields observed in individual years are often not related to EONR, long-term yield averages often are related to EONR. The relationship between yield and need for N fertilizer may be more appropriate for long-term, large-scale analyses than for making fertilizer N recommendations for individual fields and sub-fields.

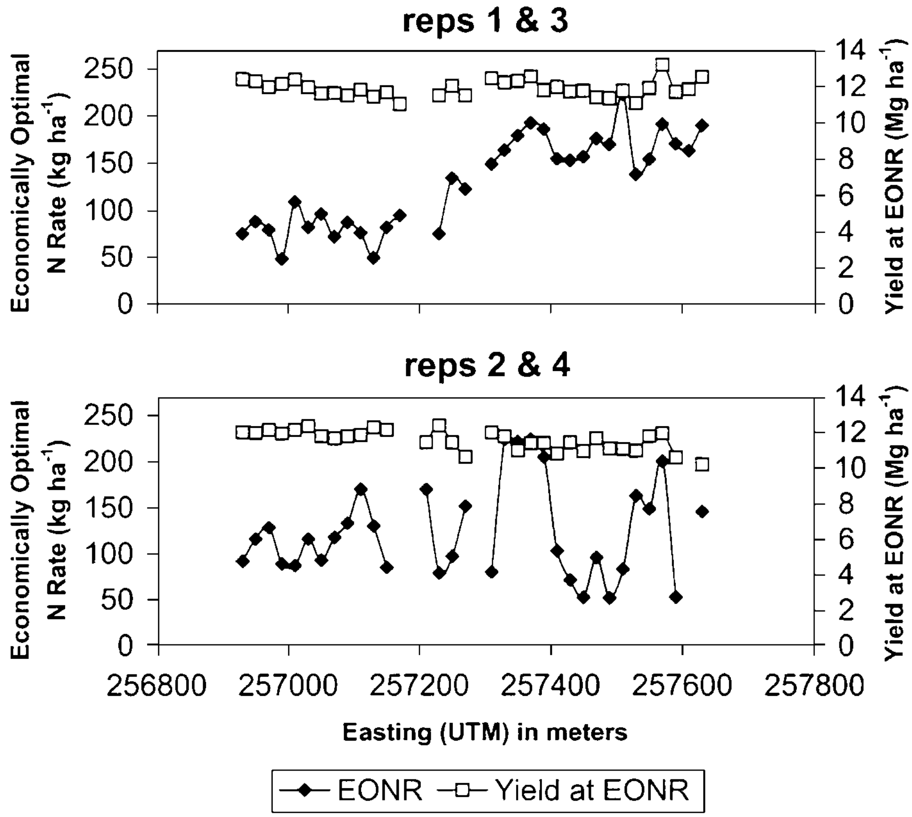

Fig. 3. Spatial comparison of economically optimal N rate (EONR) with yield at EONR for the Mississippi Delta soil region experimental field in 2000. Data are from an experimental area approximately 80 m (north-south) by 720 m (east-west). Replications divide this area into equal quadrants, with Replicate 1 in the northwest, Replicate 2 in the southwest, Replicate 3 in the northeast, and Replicate 4 in the southeast. Each data point represents an area in the field that is 20 m east to west and 40 m north to south (entire width of replication) which contained six N rate treatments ranging from 0 to 280 kg N ha^{-1}. A quadratic-plateau function was fitted to describe yield response to N rate in each 20 m by 40 m area, then this function was used to calculate EONR and yield at EONR. These values are plotted simultaneously against UTM easting, with the two northern replications in the top graph and the two southern replications in the bottom graph. The scales for yield and EONR are chosen so that the N rate recommended by the University of Missouri for a given yield is at the same height as that yield. EONR is much more spatially variable in this field than yield at EONR, with little spatial correspondence between the two variables. In a few places, EONR is as high as the university N rate recommendation for the observed yield, but in most places is lower. The break in the lines at the center (approximately 257300) is the break between replications, the break to the west of center is due to a drainage channel through the field, and the break near the east end of Replicates 2 and 4 is due to severe stand reduction in several N rate plots.

Averaged over the eight fields, variable application of mass-balance N rates based on actual yields would have increased yield by only 31 kg ha^{-1}, and profit by \$2 ha^{-1}, relative to uniform mass-balance N rates based on field average yields (Table 2). Both systems used the same total amount of N, but the variable-rate system reallocated more N to high-yielding areas and less N to low-yielding areas. This reallocation resulted in small yield increases in a few areas and small yield decreases in fewer areas, with the net effect being a very small yield increase averaged over the eight fields. Because the field-average yield-goal-based N rate was, in most cases, well above the median EONR for these eight fields (Fig. 1), there was not much opportunity to increase yields of high-yielding areas by increasing the N application rate. The three locations where yield could be increased above that obtained with a uniform yield-goal-based N rate (Table 2, yield with variable EONR column) were the three locations where these rates were at or below the median EONR (Fig. 1). Even in these cases, the potential yield increase was fairly small.

Although variable-rate application of yield-goal-based N rates had minimal impact on profit, variable application of economically optimal N rates had much greater impact. Applying the EONR for each 20 by 40 m yield cell in these eight fields would have, on average, increased yield by 135 kg ha^{-1}, decreased N rate by 50 kg ha^{-1}, and increased profit by an average of \$38 ha^{-1} relative to a uniform N application based on field-average yield (Table 2). The potential profitability of variable-rate N application was substantial for these fields, but little of this potential was realized when variable applications were based on variability in yield. At least in part, this is because most of the potential profitability of variable N applications was due to savings on N fertilizer, and applications based on variable yields did not reduce N fertilizer usage.

Our results also showed that there was potential to improve the profitability of uniform N fertilizer applications if field-average N fertilizer need could be diagnosed accurately. Uniform application of the median EONR for each field increased estimated profit by

Table 2. Estimates of corn grain yield, N rate, and profit for three N fertilization scenarios relative to the standard N application practice of a uniform N rate based on a mass-balance/yield goal approach. The N rates used for the mass balance approaches were calculated from actual yields (rather than from an anticipated yield goal), either field-average or specific to each 20 m by 40 m yield cell, using a factor of 0.021 kg N (kg corn grain yield)$^{-1}$ and a credit of 35 kg N ha^{-1} for the previous soybean crop (all eight experiments followed a previous soybean crop).

		Difference from field-average yield-goal-based N recommendations for three N fertilization scenarios								
		N rate difference with N based on:			Yield difference with N based on:			Profit difference with N based on:		
Soil region	Year	Variable EONR	Uniform median EONR	Variable yield goal	Variable EONR	Uniform median EONR	Variable yield goal	Variable EONR	Uniform median EONR	Variable yield goal
		kg ha^{-1}			Mg ha^{-1}			\$ ha^{-1}		
CP	2000	17	22	0	0.5	0.2	0.1	33	4	5
DL	2000	−96	−97	0	−0.1	−0.2	0.0	48	37	0
MD	2000	−90	−95	0	0.0	−0.5	0.0	48	16	0
CP	2001	8	−1	0	0.4	0.0	0.1	26	0	7
DL	2001	−70	−72	0	0.0	−0.3	0.0	37	14	1
MD	2001	−107	−107	0	−0.1	−0.3	0.0	54	33	0
DL	2002	−63	−57	0	0.0	−0.3	0.0	35	11	1
MD	2002	−1	−3	0	0.3	0.0	0.1	23	0	4
Average		−50	−52	0	0.1	−0.2	0.0	38	14	2
Average if N price is increased to \$0.88 (kg N)$^{-1}$		−64	−63	0	0.0	−0.3	0.0	55	32	2

Soil region abbreviations: CP = claypan soil region, DL = deep loess soil region, MD = Mississippi delta soil region.

\$14 ha^{-1} relative to uniform rates based on applying mass-balance recommendations for field-average yields (Table 2). This was primarily due to N savings in fields where the median EONR was well below the N rate predicted by the mass balance equation (see Fig. 1). Our results suggest that tools that can accurately predict field-average EONR values will produce larger economic benefits than variable-rate N applications based on spatially variable yield goals. However, it seems clear that there is considerable potential for additional economic benefit from tools that can accurately predict spatially variable EONR. Developing such tools appears to be a challenging task.

Economic calculations in this paper are based on a N price (\$0.55 [kg N]$^{-1}$) that represents the time period when the experiments were done. Since that time, price for N has increased sharply in the USA. Changing the N price used in our analyses to \$0.88 [kg N]$^{-1}$ has little impact on our conclusions, except that economic benefits to identifying EONR increase. Relative to a uniform yield-goal-based N rate, the profit advantage of variably applying N at EONR increases from \$38 ha^{-1} to \$55 ha^{-1}, and the profit advantage of uniformly applying the median EONR increases from \$14 ha^{-1} to \$32 ha^{-1} (Table 2). In contrast, this change in price does not affect the profitability of variable-rate N based on yield goal, which remains at \$2 ha^{-1}.

CONCLUSIONS

We conclude that although we observed considerable spatial variability in optimal N rates, this variability was only weakly related to spatial variability in yield. Yield variability results in differences in N removal across a field, but apparently other factors are more important in determining optimal N rate. These other factors may include spatial variations in soil N supply, in-season N loss, and N uptake efficiency. Yield variability appears to be at best a small part of the information that must be used to make successful variable-rate N recommendations.

ACKNOWLEDGMENTS

We thank Bill Holmes, Bill Stouffer, and Brian Schnarre for their interest, cooperation, comments, and generosity in allowing us to work on their farms. For help with field work and data organization, we are grateful to Matt Volkman, Larry Mueller, Vicky Hubbard, Scott Drummond, Jared Williams, Darren Hoffman, Michael Krumpelman, and Bob Mahurin. This work was made possible by financial support from the USDA National Research Initiative, the Missouri Agricultural Experiment Station, and the Missouri Precision Agriculture Center.

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