Site-Specific Nitrogen Management of Irrigated Maize: Yield and Soil Residual Nitrate Effects

R. B. Ferguson,* G. W. Hergert, J. S. Schepers, C. A. Gotway, J. E. Cahoon, and T. A. Peterson

ABSTRACT

Site-specific N management (SSNM) has been suggested as one means of further increasing the efficiency with which N fertilizers are used and reducing environmental impact. Field studies to evaluate the potential for SSNM to reduce NO3-N leaching from irrigated maize (Zea mays L.) were conducted from 1994 to 1997. Uniform management (UM) was compared with a SSNM strategy (variable rate technology, VRT) based on an existing N recommendation algorithm for maize using grid sampled soil organic matter and root zone soil residual NO3-N. A third treatment (reduced variable rate technology, RVRT) evaluated the potential for a reduced rate of N to adequately supply crop N demand when combined with variable rate application. Averaged across all site-years, there was no significant difference in the total amount of N applied, 142 kg N ha−1 with UM, 141 kg N ha−1 with VRT. Treatment mean grain yields ranged from 4.5 to 13.9 Mg ha−1 and were influenced relatively little by treatment, with VRT yield significantly reduced compared with UM in two site-years, and UM yield significantly reduced with VRT in one site-year. Treatment mean soil residual NO3-N in the 0.9-m root zone ranged from 2.7 to 14.0 mg kg−1, and was low (<6 mg kg−1) for eight site-years, with no effect of treatment on NO3-N concentration. For the five site-years with elevated NO3-N concentrations (>6 mg kg−1), there were no significant differences between UM and VRT treatments, while VRT treatment reduced residual NO3-N for three site-years. We conclude that the spatial application of the existing recommendation algorithm developed for uniform application may be inappropriate, at least for these sites, and that unique recommendation equations for major soils and climatic regions may be necessary to achieve substantial increases in N-use efficiency. This study also suggests that improved recommendation algorithms may often need to be combined with methods (such as remote sensing) to detect crop N status at early, critical growth stages followed by carefully timed, spatially adjusted supplemental fertilization to achieve optimum N-use efficiency.

Site-specific management (SSM) of soil fertility inputs is an attractive and intuitive approach to increasing fertilizer use efficiency, for which there is limited experimental evidence (Sawyer, 1994). Early research studies evaluating SSM of fertilizers found potential for improved profitability with SSM (Wollenhaupt and Buchholz, 1993), especially when applied to fields with contrasting texture and low soil test P and K levels. As the spatial and temporal variability of soil- N status began to be quantified (Hergert et al., 1992; Cahn et al., 1994), researchers began considering VRT as a tool to improve N management for environmental protection (Robert et al., 1991). Concerns related to NO3-N contamination of groundwater, frequently resulting from inefficient use of N fertilizer as well as irrigation water in some regions, prompted research in the 1990’s evaluating the potential for SSNM to increase N-use efficiency beyond best management practices already available. Early investigations into the potential for SSNM were frequently modeling studies, because of the relative ease and short time frame of conducting model evaluations compared with field studies. Mulla (1993) calculated the recommended N rates for three management zones for a winter wheat (Triticum aestivum L.) field in Washington based on soil organic matter content. He found that the recommended N rates for each zone (37, 45, and 28 kg N ha−1) were significantly different from the grower’s uniform N rate of 73 kg N ha−1 in the year of the study. Later researchers have applied crop and soil simulation models to the SSNM question. Engel (1997) described a simplified interface to facilitate use of multiple simulation models in evaluating spatial N requirement. Larson et al. (1997) used the LEACHM model to compare UM with SSNM on two Minnesota fields. For both locations, SSNM reduced the amount of N leached, and reduced the potentially leachable N remaining in the soil. Paz et al. (1999), using the CERES-Maize crop growth model, found that grid-level management of N fertilizer used less N, produced higher yields, and was more profitable than uniform N application. Although most model evaluations depict positive results for SSNM (either reduced N application, increased or static yield, and reduced leachable N, or combinations thereof), that has not always been the case. De Koeijer and Oomen (1997), using the N-DICEA simulation model to analyze relationships among yield, N applied and N leaching from a 4-yr rotation in the Netherlands (potato [Solanum tuberosum L.], winter wheat, sugarbeet [Beta vulgaris L.], and spring barley [Hordeum vulgare L.]), found SSNM did not reduce the average N applied or N leached below the root zone if current rate recommendations were followed. Site-specific N management did limit the income reduction resulting from reducing N rates to the point that leachate was below 50 mg NO3-N L−1.

The earliest VRT field studies attempted to use soil series as mapped in existing county soil surveys as the basis for controlling N rate with varying success. Carr

Abbreviations: RVRT, reduced variable rate technology; SSM, site-specific management; SSNM, site-specific N management; UM, uniform management; VRT, variable rate technology.
et al. (1991), in a study with barley, spring wheat, and winter wheat, found that SSNM based on soil series did not significantly increase economic return, although there was a trend for increased economic return at three of five locations. Grain yields were similar for SSNM and UM. For the most part, current county soil surveys have been found to be too coarse and to not contain the information necessary to accurately direct SSNM, but can be useful when combined with other sources of spatial information (Ferguson and Hergert, 1999).

Soil management zone strategies for spatial nutrient management generally have included some aspect of soil series combined with other measures of productivity, such as slope or fertility levels. Kitchen et al. (1995) defined management units according to an expected yield based on yield differences observed in the previous 1 or 2 yr. They found little economic impact by the use of VRT (discounting the cost of implementing VRT). They did observe a significant reduction in soil residual N in one management unit at one site. Ostergaard (1997) divided five fields into 12 to 17 subfields based on variations in soil type, yield, topography, aerial photos, and the producer’s experience. Fertilizer requirements for individual subfields were determined from soil samples collected within each subfield. The subfields were planted with winter wheat, spring barley, or perennial ryegrass (*Lolium perenne* L.) for seed. They concluded that, over the 2-yr study period, the economic gain because of implementation of VRT would be $15 to $35 per hectare. Robert et al. (1996) developed management zones based on soil depth for winter wheat in France. They found yield and yield components to not be significantly different between SSNM and UM. Bhatti et al. (1998) compared uniform N application on wheat with variable rate application based on crop productivity patterns and found no difference in grain yield, while the site-specific approach used less total N.

The use of grid soil samples has probably been the most common commercial approach to creation of VRT maps for P and K fertilization. However, grid soil sampling to generate N rate maps is less common commercially because of the cost required for more frequent sampling for N status. Redulla et al. (1996) used a combination of grid soil samples for soil residual N and yield maps from previous years to generate VRT N maps. They found grain yield to be unaffected by SSNM compared with UM over four site-years. The use of SSNM did result in trends for higher N-use efficiency, significantly so in the one site-year, resulting from both slightly increased yield and reduced N applied with SSNM. Thompson and Robert (1995) compared SSNM strategies based on soil type and grid sampling with UM. Field length treatment strips of each VRT strategy were compared with uniform management. They found no statistically significant differences in economic return among treatments, although there were distinct trends favoring VRT. They suggested that the experimental design, incorporating predetermined variable rates, restricted the potential for statistical analysis. They suggested a better design would be to subdivide the field into transects and apply uniform, but different, N rates to each transect, allowing the measurement of crop response to applied N across all landscape positions.

The use of yield maps, as well as organic matter content and soil fertility status, to determine variable rate N for winter wheat was evaluated by Mulla and Bhatti (1997). They suggested that, because of costs and labor required to determine spatial soil fertility status, soil organic matter content (remotely sensed) and grain yield would be the most practical criteria for dividing fields into management zones. Based on fixed fertilizer costs and wheat prices, they noted that the economic return in their study was greatest when the field was subdivided based on organic matter rather than on grain yield. Other studies (Kitchen et al., 1995; Redulla et al., 1996) have used yield maps in combination with soil fertility factors to guide SSNM. The use of yield maps to control SSNM carries significant risk because of the influence of a multitude of additional factors on yield other than N supply. Lamb et al. (1996) and Jaynes and Colvin (1997) mapped grain yields from fields for five and six consecutive years, respectively, and found in both cases a lack of temporal stability in yield patterns. Both urged caution when basing fertilizer recommendations on yield maps from individual years or even across several years. However, other researchers have shown success in using techniques such as fuzzy cluster analysis (Lark and Stafford, 1997) to classify yield patterns over years, which can then be related to crop nutrient demand.

Vetsch et al. (1995) applied constant N rates (including unfertilized checks) to field-length strips of corn over four site-years. They observed considerable variability in check-plot yield (N supplying power) and response slope (fertilizer efficiency), suggesting that SSNM may be warranted. They suggested that topographic information might be useful in predicting site-specific N requirements. Both Davis et al. (1996) and Kachanoski et al. (1996) observed, in studies within well-fertilized fields or those fertilized at a single N rate, that patterns in crop response revealing underlying spatial N needs will be difficult to discern. Both suggest the implementation of unfertilized check strips to create yield maps reflecting spatial N requirements.

To investigate the impact of spatially implementing an existing recommendation algorithm for N, field studies were initiated in 1994 on irrigated maize in Nebraska. Specifically, our objective was to evaluate a VRT approach to SSNM and its potential to reduce NO$_3$-N loss to groundwater. The primary criterion used to evaluate potential NO$_3$-N leaching was soil residual NO$_3$-N remaining in the root zone after harvest. A variable N rate approach based on grid soil sampling was used, because of the reliance of current N recommendation procedures on soil organic matter and soil residual NO$_3$-N, and uncertainty at the time the study was initiated about the accuracy or relevance of other sources of spatial information, such as existing county soil surveys or yield maps.

**MATERIALS AND METHODS**

Two separate studies were initiated in 1994, one conducted at a center-pivot irrigated site (Buffalo County 1), and one...
The sites were resampled each year following the growing season in late autumn or early spring for residual N to evaluate treatment impacts on residual N and to determine N requirements for the following year. All treatments were applied to randomized field length strips, with five replications of each treatment. Each treatment strip was the length of the field (Clay County, 512 m; Lincoln County, 288 m; Buffalo County 1, 774 m; Buffalo County 2, 329 m). The total area within each study was: Clay County, 4.8 ha; Lincoln County, 2 ha; Buffalo County 1, 56.7 ha; Buffalo County 2, 2.7 ha. The cooperating farmers managed all field operations other than N application and harvest, including planting, cultivation, herbicide application, and irrigation. Generally a starter fertilizer containing N, P, and Zn was applied at planting. Nitrogen fertilization algorithm for maize (Eq. [1]):

\[ NR = 35 + (1.2 \times EY) - (8 \times NO_3-N) - (0.14 \times EY \times SOM) \]  

where NR equals recommended N fertilizer rate (lb acre\(^{-1}\)); EY is the expected yield (bu acre\(^{-1}\)); \(NO_3-N\) is the mean soil root zone residual nitrate N (mg kg\(^{-1}\)); and SOM represents the soil organic matter (%). The algorithm uses expected yield, soil organic matter, and soil residual NO\(_3\)-N to make N fertilizer recommendations (Hergert et al., 1995). For these studies, expected yield was held constant, while N rate varied with soil organic matter and residual N. Yield-mapping technology was just becoming available at the time of the study and no yield map history existed for these fields, so no spatial adjustment was made for expected yield.

Expected yield was determined based on yields from previous years and consultation with the cooperating farmer. Soil organic matter and residual N were determined by intensive grid soil sampling, with slightly different grid densities used at each site. Samples were collected at the center of cells that typically were 6.1 m wide (eight rows of 0.76-m width) and 15.2 m in length (Fig. 1). The width of the cell equaled the width of each treatment strip.

Soil samples were collected from alternate cells down the length of the treatment strip. Initial soil samples were collected with a hydraulic sampler to a depth of 0.9 m. Single cores, 4.1 cm in diam., were collected at each grid point. The surface 20-cm soil layer was analyzed for organic matter. Bray-1 P, K, pH, Zn, and \(NO_3-N\). The 20- to 90-cm increment was analyzed only for \(NO_3-N\). Additional detail on the soil sampling and interpolation procedures are given in Gotway et al., 1996.
application rates were adjusted to account for N in starter fertilizer. Nitrogen fertilizer was applied as a sideward application of anhydrous NH$_3$ at growth stage V6 to V9 (Ritchie et al., 1993). Anhydrous NH$_3$ was applied with a toolbar-mounted coulter/knife injection unit placed into the furrow midway between plant rows. Nitrogen-application rate was set either manually for the UM treatments, or adjusted according to field position by a SoilTeq Falcon® controller (AGCO Corp., Minnetonka, MN) for the VRT and RVRT treatments. Nitrogen-application maps were developed using SoilTeq SGIS software (AGCO Corp., Minnetonka, MN) with grid soil sample data. Treatments were applied to the same strips at each site each year. The furrow-irrigated sites were conducted from 1994 to 1996; the sprinkler-irrigated site was conducted from 1994 to 1997. A total of 13 site-years are included in these studies.

Grain yield was measured with a yield mapping combine at all locations except Lincoln County, where a research plot combine was used to harvest the center three rows of each treatment strip. At the Lincoln County site, grain weights were measured for each cell in each treatment strip. At the remaining sites, care was taken to accurately calibrate the yield monitor in buffer areas adjacent to the study. Lag time for grain flow through the combine was set according to the yield monitor manufacturer. Yield data were collected at 1-s intervals, with position determined by a differentially corrected GPS system. Yield data were initially screened to remove evident outliers, then integrated into a single yield measurement that could be directly compared with soil information collected at the center of alternating cells (Fig. 1).

Semivariograms for grain yield and soil residual NO$_3$-N were determined for each site-year using GS+ software, v. 3.1a (Gamma Design Software, 1998). The resulting isotropic semivariogram model, nugget, sill, and range were then used when appropriate in mixed models analysis (Littell et al., 1996) to calculate differences in least squares treatment means of either grain yield or root zone soil residual NO$_3$-N while accounting for spatial structure in the model. Treatment (uniform, variable, or reduced variable) was considered a fixed effect in the model; replication and the replication by treatment interaction were random effects.

### Results and Discussion

#### Nitrogen Applied

The amounts of fertilizer N applied with uniform and variable rate treatments are shown in Table 2. The software used to control the fertilizer applicator at the time these studies were conducted was not capable of recording actual applied rates at specific locations. Consequently the fertilizer weight applied to each treatment strip was recorded and used to calculate treatment means. There was little or no difference in total applied N between the UM and VRT treatments for most site-years (the RVRT treatment was preset by design to be either 15 or 25% below the VRT rate, depending on the site). For nine site-years, the UM mean rate was slightly higher, while for four site-years the VRT mean rate was slightly greater. At the Lincoln County site in 1995, miscalibration of the radar gun (which regulated the output of the applicator according to actual ground speed) resulted in significant overapplication of N for all three treatments. The greatest reduction in total fertilizer N applied was at the 1996 Lincoln County site, where the average VRT treatment rate was 95.7% of the UM treatment rate. On average over 12 site-years, (excluding the 1995 Lincoln County site), variable rate N application applied 99% of the uniform rate application.

#### Grain Yield

Table 3 provides isotropic semivariogram parameters for grain yield for the four locations. Figure 2 shows

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Model</th>
<th>Nugget</th>
<th>Sill</th>
<th>Spatial parameter</th>
<th>Maximum lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
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<td>Exponential</td>
<td>0.067</td>
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<td>50</td>
<td>300</td>
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<td>300</td>
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<td></td>
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<td>180</td>
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<td>180</td>
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<td>1996</td>
<td>Linear</td>
<td>0.828</td>
<td>1.270</td>
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</table>
the impact of UM versus SSNM on grain yield. In general, grain yield was not impacted by the N-treatment strategy. At the Buffalo 1 site in 1996, there was a statistically significant reduction in yield with the VRT treatment compared with UM treatment, but the actual difference in yield was relatively minor, only 0.14 Mg ha\(^{-1}\) (2 bu acre\(^{-1}\)). At the Clay County site, the VRVT treatment yielded significantly less than the UM and VRT treatments in 1995 and 1996, and significantly less than the VRT treatment in 1994. This trend suggests that for this site, the University of Nebraska—Lincoln N-rate algorithm is close to optimum, and any reduction in total N applied from the algorithm recommendation is likely to result in yield reduction in most years. In 1996 at the Clay County site, the VRT treatment yielded significantly less than the UM treatment, 0.57 Mg ha\(^{-1}\) (9 bu acre\(^{-1}\)). At the Lincoln County site in 1995, there was statistically greater yield with the VRT treatment than either UM or RVRT treatments, although the actual difference was small, 0.2 Mg ha\(^{-1}\). This site-year also received N rates that were, overall, greater than the target rates because of miscalibration of the radar gun. The relative differences between UM and VRT treatments still existed, but yield results from this site-year should be considered somewhat uncertain because of calibration error. On average, the VRT treatment received 20 kg N ha\(^{-1}\) more than the UM treatment (Table 2). At the Buffalo County 2 site, there were no yield differences for any year as influenced by N application strategy. Yields at this site were depressed in 1995 because of problems with irrigation water distribution that were corrected in 1996.

### Soil Residual Nitrate-Nitrogen

A primary focus of these studies was to evaluate the impact of variable rate N application on potentially leachable NO\(_3\)-N after harvest compared with UM. Consequently, substantial effort was made to collect root zone NO\(_3\)-N concentrations on a grid basis after harvest either in late autumn or early spring. A N budget cannot be calculated for these studies since neither crop N removal nor NO\(_3\)-N leached below 0.9 m were measured. However, since irrigation was managed uniformly over all treatments, soil residual NO\(_3\)-N can provide an estimate of potentially leachable N that is comparable among treatments. Table 4 provides isotropic semivariogram parameters for soil residual NO\(_3\)-N for the four locations. Figure 3 illustrates treatment effects from each growing season on soil residual NO\(_3\)-N after harvest. For most site-years, soil residual NO\(_3\)-N levels were relatively low, independent of treatment. Eight of the thirteen site-years have, on average, soil residual NO\(_3\)-N of ≪6 mg kg\(^{-1}\) and would be considered to have relatively low levels of soil NO\(_3\)-N. For those eight site-years the N treatment strategy had no effect on the soil residual NO\(_3\)-N.

At the Buffalo County 1 site in 1995, the residual soil NO\(_3\)-N values were much higher than in the other 3 yr at this site. No simple explanation for these high values is available, other than perhaps ideal conditions for N mineralization during the 1995 growing season. Fertilizer N rates were moderate in 1995 (Table 2), although higher than 1994 because of reduced residual NO\(_3\)-N at the end of the 1994 season. The VRVT treatment did result in significantly lower residual NO\(_3\)-N than the UM or VRT treatments, with no reduction in yield (Fig. 2). There were no other treatment effects on soil residual NO\(_3\)-N for this site in any year.

The Clay County site had consistently low soil residual NO\(_3\)-N with no treatment effects. Soil residual NO\(_3\)-N at the Lincoln County site was not significantly influenced by treatment in 1994 or 1996, although there were trends for reduced NO\(_3\)-N with the VRVT treatment in both years. The 1995 NO\(_3\)-N levels at the Lincoln County site are elevated and reflect the impact of the higher than 1994 because of reduced residual NO\(_3\)-N at the end of the 1994 season. The VRVT treatment did result in significantly lower residual NO\(_3\)-N than the UM or VRT treatments, with no reduction in yield (Fig. 2). There were no other treatment effects on soil residual NO\(_3\)-N for this site in any year.

The Clay County site had consistently low soil residual NO\(_3\)-N with no treatment effects. Soil residual NO\(_3\)-N at the Lincoln County site was not significantly influenced by treatment in 1994 or 1996, although there were trends for reduced NO\(_3\)-N with the VRVT treatment in both years. The 1995 NO\(_3\)-N levels at the Lincoln County site are elevated and reflect the impact of overapplication of N because of miscalibration of the radar gun. However, there was a reduction in soil residual NO\(_3\)-N for this site year with the VRVT treatment (although only the VRVT-UM difference was statistically significant). The Buffalo 2 site showed no treatment differences in soil residual NO\(_3\)-N in 1994 or 1995. In 1996, there were elevated soil NO\(_3\)-N levels that are not explainable other than perhaps again ideal conditions for N mineralization. For this site-year, there was a significant reduction in soil residual NO\(_3\)-N with the RVRT treatment.

Over the 13 site-years of these two studies, there were no situations where variable N application resulted in significantly lower soil residual NO\(_3\)-N than UM. For three site years (Buffalo 1-1995, Lincoln-1995, Buffalo 2-1996), the reduced rate variable treatment did significantly reduce soil residual NO\(_3\)-N compared with one or both of the other treatments (UM or VRT), but then only when soil NO\(_3\)-N levels were elevated.

### Table 4. Isotropic semivariogram parameters for soil residual NO\(_3\)-N.

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Model</th>
<th>Nugget</th>
<th>Sill</th>
<th>Spatial parameter</th>
<th>Maximum lag</th>
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1 (2 bu acre\(^{-1}\)). At the Clay County site, the VRVT treatment yielded significantly less than the UM treatment in 1996 at the Clay County site, the VRT treatment yielded significantly less than the UM treatment, 0.57 Mg ha\(^{-1}\) (9 bu acre\(^{-1}\)). At the Lincoln County site in 1995, there was statistically greater yield with the VRT treatment than either UM or RVRT treatments, although the actual difference was small, 0.2 Mg ha\(^{-1}\). This site-year also received N rates that were, overall, greater than the target rates because of miscalibration of the radar gun. The relative differences between UM and VRT treatments still existed, but yield results from this site-year should be considered somewhat uncertain because of calibration error. On average, the VRT treatment received 20 kg N ha\(^{-1}\) more than the UM treatment (Table 2). At the Buffalo County 2 site, there were no yield differences for any year as influenced by N application strategy. Yields at this site were depressed in 1995 because of problems with irrigation water distribution that were corrected in 1996.
Soil Residual Nitrate-Nitrogen Patterns

Patterns of soil residual NO\textsubscript{3}-N for the Clay County site (from 1996) are shown in Fig. 4. To develop separate soil residual NO\textsubscript{3}-N maps for each treatment, data for each treatment were extracted from the full dataset, then kriged with common easting–northing extents and grid spacing. This generated interpolated maps of soil residual NO\textsubscript{3}-N for each treatment that covered the
Fig. 4. Kriged maps of soil residual NO$_3$-N (mean concentration to a 0.9-m depth) for the Clay County site in 1996, and soil organic matter (0.2-m depth) in 1994.

Fig. 5. Kriged maps of soil residual NO$_3$-N (mean concentration to a 0.9-m depth) for the Buffalo County 1 site, 1994 through 1997.

Fig. 6. Kriged map of soil organic matter (0.2-m depth), Buffalo County 1 site, 1994.
extent of the entire study area, and illustrates that both treatments show evidence of higher soil residual NO$_3$-N in the central portion of the field. These patterns of soil residual NO$_3$-N were similar to the soil organic matter pattern also shown in Fig. 4, where soil organic matter is also higher in the central portion of the field. A similar relationship between patterns of soil organic matter and soil residual NO$_3$-N was observed at this site in most years. Even though fertilizer N was adjusted according to soil organic matter with the VRT treatment, and thus fertilizer N was reduced where soil organic matter was higher, soil residual NO$_3$-N still tended to be elevated after harvest where soil organic matter was higher. This may have resulted from N mineralized between crop physiological maturity and soil sampling, or may suggest that the recommendation algorithm underestimates N mineralization from soil organic matter at this site. For eight of the 13 site-years, there were relatively small but significant positive correlations between soil organic matter and end-of-season soil residual NO$_3$-N (Table 5) for either UM or VRT treatments or both treatments.

The only site that exhibited significant differences in the pattern of soil residual NO$_3$-N between treatments was Buffalo County 1 (Fig. 5). Separate interpolated maps for UM and VRT treatments were generated as in Fig. 4. Particularly in 1995, when substantial soil residual NO$_3$-N remained after harvest, differences are evident in soil residual NO$_3$-N between UM and VRT treatments. An east-west oriented region in the south-central part of the field was higher in soil residual NO$_3$-N with UM application, and lower with VRT application. Because this site is center-pivot irrigated, these patterns are not because of differences in irrigation water infiltration that might exist in a furrow-irrigated field. Similar, but less pronounced, east-west patterns are evident in the 1994 UM and 1996 VRT maps of soil residual NO$_3$-N. In 1997, there was little difference between patterns of UM and VRT soil residual NO$_3$-N, and the correlation between soil organic matter and soil residual NO$_3$-N was relatively high (Table 5). A map of soil organic matter for the Buffalo County 1 site is provided in Fig. 6 for comparison. In 1997, it is likely that soil residual NO$_3$-N was influenced primarily by soil organic matter, while in other years soil residual NO$_3$-N was influenced by N fertilizer treatment as much or more than soil organic matter. The row direction in this field is east-west, and N treatments were applied with an east-west orientation. However, application records from 1995 indicated that individual treatment strip mean rates did not exceed the target uniform application rate by more than 10%, suggesting that application error did not generate elevated NO$_3$-N levels for the 1995 season. Also, patterns of grain yield from the Buffalo 1 site in 1995 show quite uniform and typical yields over the field (data not shown), suggesting that low or differential crop removal of N was not the reason for elevated NO$_3$-N levels in 1995.

## SUMMARY

The primary objective of these studies was to evaluate one approach to variable rate N application, using an existing decision rule applied on a spatial basis according to grid sampled soil data. Soil residual NO$_3$-N remaining after harvest was the primary factor used to estimate any reduced potential for NO$_3$ leaching with the use of variable rate N application. Over 13 site-years, no consistent benefit (either increased yield or reduced soil residual NO$_3$-N) was observed with variable rate N application. There was no disadvantage to using variable rate N application in terms of N applied or grain yield, but no advantage that would justify the cost and effort of variable rate application with procedures used in this study.

The RVRT treatment reduced yield consistently only at the Clay County site. At other locations, there were slight trends for yield reduction with either 15 or 25% less N than the VRT treatment, but actual declines in yield were quite small and insignificant. Significant reductions in soil residual NO$_3$-N with RVRT treatment occurred only in three site-years where soil residual NO$_3$-N was elevated. At the Clay County site, although RVRT treatment significantly reduced yield in all three years, it never significantly reduced soil residual NO$_3$-N. These results taken together suggest there is some potential for increased N-use efficiency with SSNM that targets an overall lower N rate than UM. However, such a strategy will increase the risk of reduced yield, such as at the Clay County site, unless a better understanding of spatial soil N supply and crop N demand can be gained.

In examining the results of these studies, particularly in light of modeling results of other researchers that suggest variable rate N application can increase the efficiency with which N fertilizers are used, we conclude that the spatial application of the existing decision rule developed for uniform application may be inappropriate, at least for these sites. The University of Nebraska N recommendation algorithm for maize was developed from research conducted in the late 1970s and early 1980s.

### Table 5. Pearson correlation coefficients between soil organic matter and soil residual NO$_3$-N for uniform (UM) and variable (VRT) treatments.

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<td></td>
<td>0.003</td>
<td>0.004</td>
<td>0.016</td>
<td>NS†</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.001</td>
<td>0.006</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
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<tr>
<td>VRT</td>
<td>0.378</td>
<td>0.568</td>
<td>0.136</td>
<td>0.373</td>
<td>0.145</td>
<td>0.203</td>
<td>0.069</td>
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<tr>
<td></td>
<td>0.001</td>
<td>0.001</td>
<td>0.015</td>
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† Not significant.
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We appreciate the help of many who participated in the collection of field data for these studies. In particular, we thank the producers who allowed us to conduct these studies on their farms—Paul Gangwish, Steve Yost, and Craig Bombeck.

REFERENCES


