Site-Specific Nitrogen and Plant Density Management in Irrigated Maize

J. L. Ping, R. B. Ferguson,* and A. Dobermann

ABSTRACT

Economic or environmental benefits resulting from variable-rate (VR) application of N and seed are uncertain in irrigated maize (*Zea mays* L.) systems with high yield potential. We evaluated different plant population and N management strategies in two irrigated maize fields in Nebraska. Inputs were varied according to yield zones derived from yield maps, detailed maps of soil organic matter (SOM), and sampled seasonal NO_3 status. Uniform management following Best Management Practices (BMPs) resulted in high levels of grain yield (>15 t ha^{-1} at Site 1; >12 t ha^{-1} at Site 2), nitrogen use efficiency (NUE), and gross return above input cost. Management of high-yielding irrigated systems on relatively flat terrain was not improved through the predictive site-specific approaches tested in this study, which relied on available historical field information (yield maps, weather) and seasonal soil sampling. Among four site-years, only one site-year showed significant increases in yield and NUE and decrease in N input with the VR N. Yield interactions between VR N management strategies and plant population were not significant. More potential for increasing yields, resource efficiency, and profitability may exist through integrating such approaches with dynamic, in-season management of water and N. Such approaches are emerging, but remain to be evaluated thoroughly, particularly under high-yielding conditions and against conventional BMPs.

Site-specific crop management (SSCM) aims at improving crop performance and environmental quality by matching resource application and agronomic practices with soil and crop requirements as they vary in space and time (Pierce and Nowak, 1999). Practical steps include (i) characterization: measure extent, scales, and dynamics of variation; (ii) interpretation: assess significance, identify major causes of uncertainty, and formulate management targets; (iii) management: apply inputs at the appropriate scale and in a timely manner; and (iv) monitoring the outcome (Dobermann et al., 2004). This may be accomplished in discrete steps, as dynamic processes executed in real-time, or as combinations of both.

Climate, soil, and management factors cause crop response to N and the optimal N rate to vary, both spatially within and between fields and from year to year (Mamo et al., 2003; Scharf et al., 2005; Schmidt et al., 2007). Crop growth simulation modeling (Batchelor et al., 2002) and stochastic modeling (Bullock and Bullock, 2000) suggest that if this variation and the relevant production functions were known in advance, significant economic and environmental benefits could arise from VR applications of nutrients as compared with uniform field management. Under practical conditions, a post-hoc analysis of yield response to N application is often of limited use for making decisions for the subsequent growing season because yield responses are difficult to predict, particularly in rainfed environments (Liu et al., 2006).

Previous research has illustrated that the practical implementation of SSCM strategies such as VR application of N or seed rates is affected by a wide range of uncertainties as well as application errors (Doerge, 2002; Chan et al., 2005; Liu et al., 2006). Integrating traditional agronomic research with economic principles, precision farming technologies, and spatial statistics may allow collecting more site-specific crop response information and thus help overcome such problems (Bullock and Bullock, 2000; Bullock et al., 2002; Ruffo et al., 2006). However, the methodologies involved tend to be complex, and the empirical results obtained are likely to be of little generic value for extrapolation to other locations. For practical applications, relatively simple algorithms and guidelines are required for VR application of crop inputs at the beginning of the growing season (predictive) as well as during critical growth periods of the crop (predictive or corrective), based on collectable soil and crop information and with knowledge about the yield potential (Yang et al., 2006) and the expected yield increase over a control (Dobermann and Cassman, 2002).

In early studies with irrigated maize in Nebraska, an existing N recommendation equation (Shapiro et al., 2003) with a uniform yield goal for the entire field was applied to kriged maps of SOM and soil NO_3–N to develop N prescription maps for VR N application (Ferguson et al., 2002). Probably because the VR N rate prescription only considered spatial variability in soil N supply and all fertilizer-N was applied in one application, no significant differences in maize yield or soil

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Abbreviations: BMPs, best management practices; EC_a, apparent soil electrical conductivity; GRC, gross return above fertilizer and seed cost; NUE, nitrogen use efficiency, defined as kg grain yield per kg N applied; SOM, soil organic matter; SSCM, site-specific crop management; VR, variable rate.

residual NO_3–N were observed between VR and uniform N application, although a reduction in N rates was possible without significant yield loss at most sites (Ferguson et al., 2002). Similar findings from other studies have triggered interest in alternative approaches for SSCM, in which within-field spatial and temporal variability is captured by defining management zones that integrate information from farmers' knowledge, soil sampling and soil sensing, yield maps, topography, and remote sensing (Ferguson et al., 2003; Wang et al., 2003; Chang et al., 2004; Koch et al., 2004).

The management zone approach is not without problems either. Definition of management zones remains rather empirical, more continuous variation in soil-landscape features across the field is ignored, and management zones may mean little in fields where spatial yield variability is small relative to temporal yield variability (Dobermann et al., 2003; Schepers et al., 2004). Moreover, evaluation of site-specific management of maize hybrids and plant density (Bullock et al., 1998; Shanahan et al., 2004) in combination with VR N application has generally been scarce.

The primary objective of our study was to evaluate different site-specific N management strategies for high-yielding irrigated maize that were considered to be scientifically sound and practically feasible by the participating scientists, crop consultants, and farmers. A secondary objective was to evaluate interactions between N management and plant population densities. The management strategies tested were tailored to the cropping practices and farm equipment available at each site. Because with current technology it has become easy to process a time series of yield maps for delineating relatively stable yield zones in irrigated fields (Ping and Dobermann, 2005), we tested the hypothesis that varying plant density and/or N inputs according to yield zones and soil properties leads to increased yield, NUE (defined as kg grain yield per kg N applied), and profitability of maize compared with uniform management of the whole field that follows recommended BMPs.

MATERIALS AND METHODS

Study Sites

This study was conducted in two production fields in central Nebraska during 2003 and 2004. Site 1 (62 ha) was located near Cairo, NE (40°58′43.5″ N, 98°35′36.5″ W). Continuous maize was grown in a ridge-till system from 1996 to 2004, except for soybean in the south half of the field in 2000. The field was managed with furrow irrigation (in west–east direction) until 2001, when it was converted to center-pivot irrigation. Soil types at Site 1 included Hall (fine-silty, mixed, mesic Pachic Argiustolls) and Wood River (fine, smectitic, mesic Typic Natrustolls) silt loams and their eroded phases along a ridge crossing the field from southwest to northeast (Soil Survey Staff, 1999). Wood River soils occupied about 55% of the total area, mainly in the eastern half, whereas the more fertile Hall series was mostly found in the western half. Most of the field was gently sloping or flat. About 20% of the field was below the currently recommended critical soil test P level of 15 mg kg^{-1} for the 0- to 20-cm depth (Shapiro et al., 2003). However, P response trials conducted during 2002 and 2003 showed no significant yield increase beyond the P amounts that were applied as a blanket dose in all treatments of our VR study through starter fertilizer (data not shown).

Site 2 (68 ha) was located near Bellwood, NE (41°19′34″ N, 98°20′08″ W). This field has been managed as continuous corn in a ridge-till system with pivot irrigation, including a center pivot and a second half pivot on the southern end of the field. A drainage ditch crossed the whole field from south to north in the western half of the field. Four soil series occurred at this site: Thurman loamy fine sand (mixed, mesic Udorthentic Haplustolls), Muir silt loam (superactive, mesic Cumulic Haplustolls), Ovina-Thurman coarse-loamy sand (mixed, mesic Fluvaquentic Haplustolls), and Brocksburg sandy loam (mixed, mesic Pachic Argiustolls). Most of the field was flat with slopes in the 0 to 3% range. Soil test K was below 125 mg kg^{-1} for 16% of the field area, but, due to large enough subsoil-K reserves, K response was not found in trials conducted during 2002 and 2003 (data not shown).

At both sites, maize was planted in late April and harvested in early to mid October. Crop management generally followed recommended practices for irrigated maize in Nebraska. Except for plant density and fertilizer application, all treatment strips (see below) received the same management for maize hybrids, planting, tillage, irrigation, weeds, and insect control as the whole surrounding field area. Maize hybrids grown were Pioneer 33P67 (Site 1 in 2003, Site 2 in 2003 and 2004) and Pioneer 31N28 (Site 1 in 2004). One major difference between the two sites was that due to more sandy soils, N applications at Site 2 included two to four uniform fertigation applications of urea [$CO(NH_2)_2$]-ammonium nitrate (NH_4NO_3) solution (UAN, 32% N, 30 to 40 kg N ha^{-1} per application) through the center-pivot system, resulting in total fertigation amounts of 123 and 74 kg ha^{-1} in 2003 and 2004, respectively (Table 1). Those amounts were accounted for in the N prescriptions made for the different treatments.

Site Characterization for SSCM

In relative terms, spatial variation in soil properties measured in the top 20 cm of soil in 2002 was less at Site 1 than at Site 2 (Table 2). Figure 1 shows the general process of site characterization and developing prescription maps for VR input applications. Figure 2 provides an example for Site 1. Intensive soil sampling (about four samples ha^{-1}) was conducted in spring 2002 at both sites. The sampling design included a triangular grid (about 70 m spacing, 70% of the total number of samples collected), stratified transects chosen to represent major soil-landscape classes (12 transects with 5 sampling locations per transect in a 0-, 4-, 8-, 16-, and 32-m progression), and 20 random locations. Soil-landscape classes for sampling were mapped by applying fuzzy-k-means clustering (Minasny and McBratney, 2003) to four layers of previously collected, spatially dense (4- by 4-m cells) datasets: elevation (real-time kinematic laser survey), soil type, apparent soil electrical conductivity [EC_a, measured with Veris-2000 (Veris Technologies, Salina, KS) or EM-38 instruments (Geonics Ltd., Mississauga, ON, Canada], and surface reflectance derived from blue, green, and red bands of IKONOS satellite images (GeoEye, Dulles, VA) (4-m resolution, bare soil). At both sites, five soil-landscape classes were delineated for stratified transect sampling. At each sampling location, two soil cores were collected from the 0- to

20-cm depth and bulked for laboratory analysis. For VR prescriptions of N and P fertilizers, detailed (4- by 4-m) maps of SOM and Bray 1-P were produced by regression kriging (Hengl et al., 2004) with elevation, EC_a, and surface reflectance as secondary information (Ping and Dobermann, 2004).

Yield zones were delineated anew from yield monitor data of the previous 6 yr (Fig. 1), following a sequence of previously described procedures (Ping and Dobermann, 2005): screening (Simbahan et al., 2004) and normalization of yield monitor data, interpolation to 4- by 4-m grids by kriging, cluster analysis of multi-year yield maps, and post-classification spatial filtering to create spatially contiguous yield zones (Ping and Dobermann, 2003). At both sites, this resulted in six yield classes in an ascending order of average yields. Because the two lowest-yielding classes always occurred together along headlands and in other marginal areas, they were merged, and only five yield zones were used for VR prescriptions of fertilizer-N and seed.

Table 1. Summary of site-specific management treatments evaluated at two sites in Nebraska.

Treatments	Preplant N†	Sidedress N†	Late N†	P	Plant density (D)
	kg ha^{-1}				1000 seeds ha^{-1}
Site 1, 2003					
T1 uniform preplant N, uniform D	79	56		6	79
T2 variable preplant N and P, uniform D	63 (36–82)‡	56		9 (6–16)	79
T3 uniform preplant N, variable D	79	56		6	79 (54–91)
T4 variable preplant N and P, variable D	83 (50–96)	56		17 (6–42)	79 (54–91)
Site 1, 2004§					
T1 uniform preplant N, uniform D	140	56		9 (6–23)	79
T2 variable preplant N, uniform D	138 (67–161)	56		9 (6–23)	79
T3 uniform preplant N, variable D	140	56		9 (6–23)	75 (54–91)
T4 variable preplant N, variable D	141 (68–169)	56		9 (6–24)	75 (54–91)
T5 uniform preplant, late N, uniform D	84	56	56	9 (6–24)	79
T6 variable preplant, late N, uniform D	60 (24–74)	55 (32–62)	55 (32–62)	10 (6–24)	79
Site 2, 2003¶					
T1 uniform preplant N, normal D	81	42	123	10	79
T2 variable preplant N, normal D	80 (33–116)	42	123	10	79
T3 uniform preplant N, high D	81	42	123	10	91
T4 variable preplant N, high D	91 (33–131)	42	123	10	91
Site 2, 2004#					
N1 uniform preplant N, 3 densities (D1,D2,D3)	79	44	74	10	67, 79, 91
N2 variable preplant N1, 3 densities (D1,D2,D3)	72 (47–106)	44	74	10	67, 79, 91
N3 variable preplant N2, 3 densities (D1,D2,D3)	95 (52–142)	44	74	10	67, 79, 91

† Preplant N: applied in April, before planting. Sidedress: applied at V5–6 stage of maize. Late N: applied at V10–12 to silking of maize.

‡ Area-weighted mean rate and minimum and maximum rate in parentheses.

§ In 2004, all treatments at Site 1 were treated with VR applications of P. Late N in treatments T5 and T6 was applied at V12 stage.

¶ At Site 2, late N was applied through two to four fertigations from V10 to silking stage of maize.

In 2004, all N treatments at Site 2 had substrips with three different seed rates (low, normal, high). Two different VR N strategies were tested: variable preplant N1: more N on high-yielding areas, less on low-yielding (same as T2 in 2003); variable preplant N2: more N on low-yielding areas, less on high-yielding.

Management Strategies

Site 1

Strip trials of four treatments using three replicates were conducted at Site 1 in 2003 and 2004 to compare uniform and VR management of fertilizer and plant density (Table 1). Treatments were: T1, uniform N + uniform plant density (baseline, i.e., recommended BMP); T2, variable N + uniform plant density; T3, uniform N + variable plant density; T4, variable N + variable plant density. In 2004, two additional treatments were included to evaluate the response to late N application at V12 (Ritchie et al., 1986) stage of maize: T5, uniform preplant and late N at V12 stage with uniform plant density; T6, variable preplant and late N with uniform plant density.

In all treatments, N rates were prescribed using the University of Nebraska N algorithm for maize, which estimates the N rate based on the effective difference between crop N requirement and N supply from soil and other sources (Shapiro et al., 2003):

$$\text{N rate} = 1.12 \times [35 + (1.2 \times \text{EY}) - (8 \times \text{NO}_3\text{–N}) - (0.14 \times \text{EY} \times \text{SOM}) - \text{other credits}] \qquad [1]$$

where N rate = recommended amount of N (kg ha^{-1}); EY = expected yield (yield goal, bushels acre^{-1}; 1 bu acre^{-1} = 62.8 kg

Table 2. Spatial variation of topography as derived from real-time kinematic laser measurements and soil properties determined with apparent soil electrical conductivity (EC_a) and soil samples taken from 0 to 20 cm in 2002 at the two study sites in Nebraska, kriged to 4-m grid cells.

Attributes†	Mean	Min.	Max.	CV %
Site 1				
Elevation, m	597.9	594.7	601.7	1
Slope, %	0.6	0.0	3.5	104
Soil EC_a, mS m^{-1}	20	15	65	26
Sand, %	34	26	47	16
Silt, %	46	30	59	14
Clay, %	20	15	30	18
CEC	13.0	7.6	17.9	14
pH	6.2	5.0	7.8	9
SOM, %	2.5	1.6	3.9	18
Soil NO_3–N, mg kg^{-1}	14.2	4.0	30.9	38
Soil test P, mg kg^{-1}	28	< 1	101	61
Soil test K, mg kg^{-1}	476	258	852	23
Site 2				
Elevation, m	455.1	451.5	460.6	1
Slope, %	0.7	0.0	4.6	89
Soil EC_a, mS m^{-1}	22	3	74	49
Sand, %	66	31	93	25
Silt, %	21	4	47	54
Clay, %	12	3	24	43
CEC, $cmol_c$ kg^{-1}	9.9	3.5	19.8	36
pH	5.7	4.5	7.0	8
SOM, %	1.7	0.3	4.6	53
Soil NO_3–N, mg kg^{-1}	13.8	2.3	58.6	63
Soil test P, mg kg^{-1}	35	5	113	56
Soil test K, mg kg^{-1}	198	68	496	42

† CEC, Cation exchange capacity; SOM, soil organic matter.

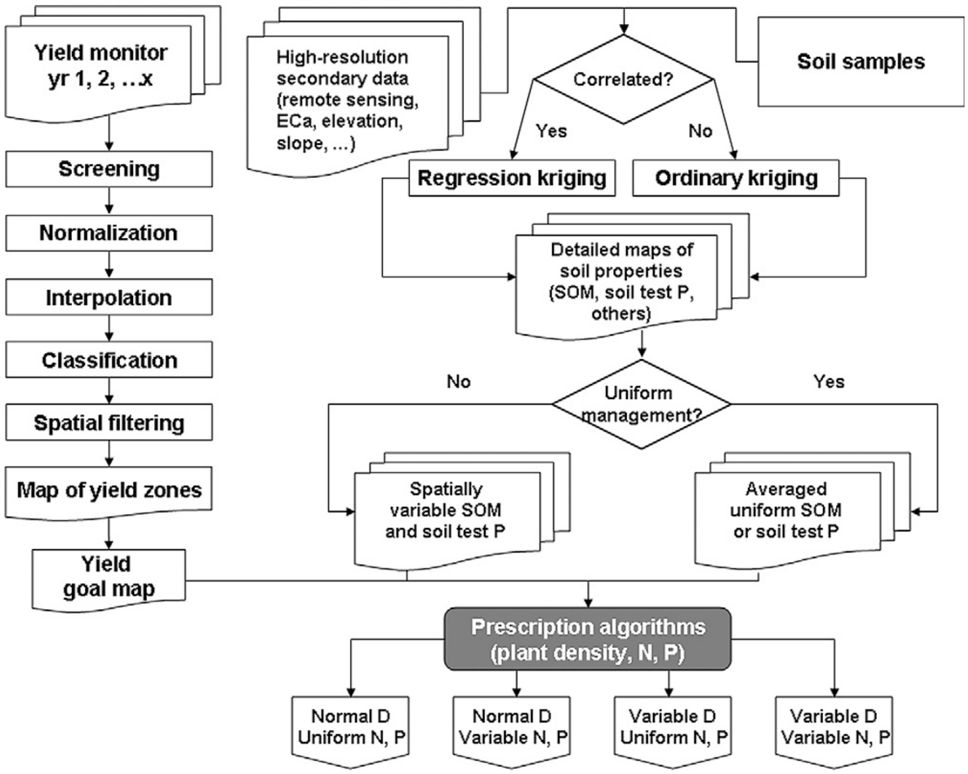

Fig. 1. Spatial data processing and prescription of VR fertilizer applications (N, P) and variable seed rates (plant densities, D). The detailed procedures for delineating yield goal map from yield monitor data are described by Ping and Dobermann (2005). Regression kriging was conducted for mapping those soil properties that were significantly correlated with high-resolution secondary data; otherwise, ordinary kriging was performed. For whole-field uniform management, soil properties for making recommendation were averaged over the entire field.

ha^{-1}); NO_3–N = average NO_3–N concentration in the root zone (0- to 120- or 0- to 90-cm depth, mg N kg^{-1}); SOM = soil organic matter content (%), other credits = any further deductions due to N credits assigned to legumes as previous crop, manure, or irrigation. Following current guidelines for irrigated maize in Nebraska (Dobermann and Shapiro, 2004), average (T1, T3, T5) or zone-specific yield goals (T2, T4, T6) were calculated as the average yield of the past 5 yr plus 10%, but not exceeding 90% of the historical, climatic yield potential. The latter was simulated for each site with the Hybrid-Maize model (Yang et al., 2006). Values for SOM were either whole-field averages (T1, T3, T5) or continuous values from the 4- by 4-m SOM map (all other treatments, Fig. 2). Deep (0–120 cm) soil samples for determination of residual NO_3–N were collected in spring of each year at multiple sampling locations within each treatment strip, which resulted in about four to six samples per strip and about three samples per yield zone. Because there were no significant differences in residual soil NO_3–N among yield zones, average site NO_3–N values were used for uniform and VR N prescriptions. Table 3 summarizes the yield zones and VR N prescriptions in T2.

The VR N was primarily dependent on SOM content (detailed grid) and yield goal (map of yield zones), but the latter also varied slightly by years because yield zone delineation incorporated new information of the past cropping season. The SOM content instead of soil residual NO_3–N was chosen as one of the spatially varying factors for making VR N recommendations because SOM is a stable soil fertility characteristic whereas NO_3–N changed more across years. For practical VR N recommendations, attempting to capture the spatiotemporal variation in residual NO_3–N in the whole profile is uneconomical. In previous studies, we used maps of NO_3–N as input for VR N and this did not result in better performance of the VR N (Ferguson et al., 2002). Moreover, residual NO_3–N was not significantly different among the yield zones (Table 3), suggesting that zone-specific annual sampling for NO_3–N would be unlikely to result in improved VR N recommendations.

Average seed rate in strategies with uniform plant density was set at 79,000 seeds ha^{-1}. For T3 and T4, seed rates varied by yield zones (Fig. 2): from 54,000 ha^{-1} in yield classes 1 and 2 (low-yielding) to a maximum of 91,000 ha^{-1} in yield class 5 (high-yielding). A 12-row planter with 76-cm row spacing and a VR controller were used to vary the seed rates in T3 and T4 strips by yield zones; each strip was 9.12 m wide. All treatments received the same amount of starter fertilizer at planting (5 kg N and 6 kg P ha^{-1}). To correct major variation in soil test P levels, treatments T2 and T4 in 2003 and all treatments in 2004 (Table 1)

Table 3. Major components of the N prescription equation and average recommended N rates by yield zones.

Site-year	Mean	Yield zones derived from yield history				
		Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
		% of total field area				
S1-2003	–	5	6	18	24	47
S1-2004	–	7	5	16	35	37
S2-2003	–	3	16	32	34	15
S2-2004	–	3	10	29	35	23
		Yield goal, Mg ha^{-1}				
S1-2003	13.9	10.4	12.0	12.9	14.2	14.9
S1-2004	14.0	10.7	12.3	13.4	14.4	15.0
S2-2003	14.1	11.7	12.8	13.9	14.5	15.0
S2-2004	14.0	11.7	12.7	13.7	14.4	14.8
		Soil organic matter, %				
S1-2003	2.5	2.6	2.4	2.5	2.6	2.6
S1-2004	2.5	2.5	2.4	2.5	2.5	2.6
S2-2003	1.7	1.2	1.5	1.5	1.9	1.9
S2-2004	1.7	1.2	1.5	1.5	1.9	1.9
		Soil NO_3–N, mg kg^{-1}				
S1-2003	13.0	–	10.2	11.0	16.3	12.4
S1-2004	3.6	–	1.9	2.2	4.9	3.5
S2-2003	4.1	1.6	3.3	4.5	4.6	4.4
S2-2004	1.9	1.5	2.2	1.8	1.8	2.7
		N rate in Treatment 2, kg ha^{-1}				
S1-2003	119	65	92	105	122	130
S1-2004	194	139	177	194	198	204
S2-2003	245	225	217	240	257	274
S2-2004	190	172	181	194	196	199

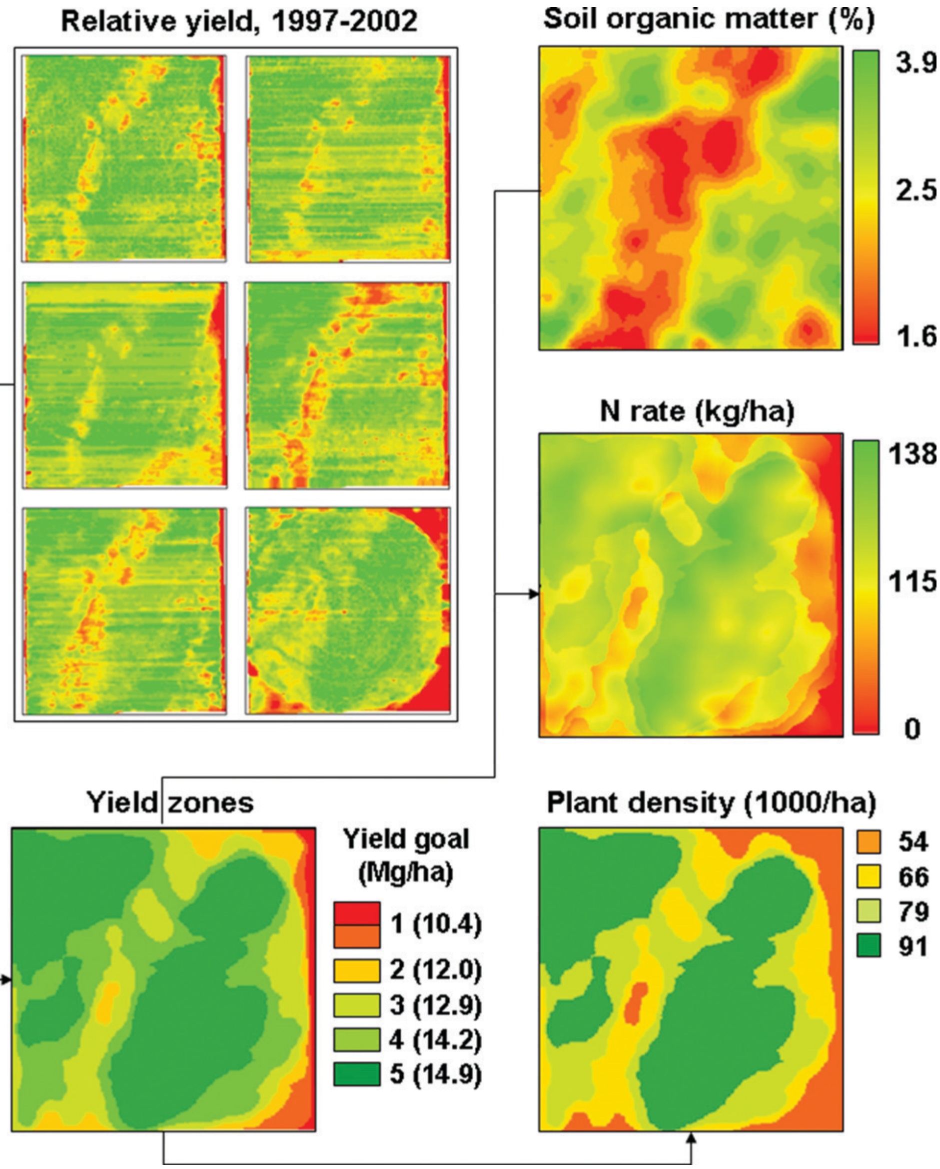

Fig. 2. Prescription maps for VR seeding and N application in management strategy 2 at Site 1 in 2003. The field was approximately 800 m by 800 m in size. Yield zones were delineated by screening, interpolation, and spatial classification of yield monitor data of the previous 6 yr (Ping and Dobermann, 2005). Within agronomically accepted ranges, plant densities were varied in four discrete steps by yield zones. The soil organic matter (SOM) map was developed using regression kriging that incorporated elevation, surface electrical conductivity measured with a Veris-2000, and bare soil reflectance from IKONOS satellite images at 4-m resolution. The N prescription map was based on Eq. [1], with SOM as continuously varying input, yield goals set by yield zones, and averaged residual soil NO_3 values.

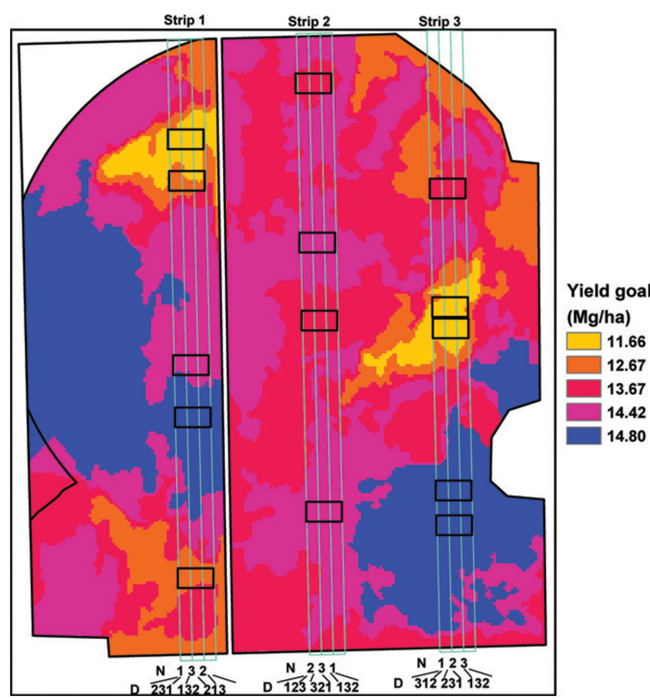

Fig. 3. Yield goal zones, replicated treatment strips, and the location of sampling plots at Site 2 in 2004. N1, N2, and N3 were the main plots that had uniform preplant N, more N on high-yielding areas and less N on low-yielding areas, and more N on low-yielding areas and low N on high-yielding areas, respectively; D1, D2, and D3 were subplots that had uniform plant densities at 67,000, 79,000, and 91,000 seeds ha^{-1}, respectively.

also received VR applications of P fertilizer that were based on detailed maps of soil test P. Phosphorus was applied when soil Bray-P was lower than or equal to 25 mg kg^{-1} according to the UNL P recommendation equation [P rate (kg P ha^{-1}) = (25 – soil test P) × 4.48; Shapiro et al., 2003]. Phosphorus was mainly applied in the western part of the field, but at relatively low overall rates (Table 1). A nutrient response trial conducted in the same area during 2003 and 2004 indicated that P had no significant influence on maize yields (data not shown). However, because P was part of the VR farming package requested by the farmer, it was included in the economic analysis at Site 1. Preplant N was injected in the soil as anhydrous NH_3 about 2 wk before planting, whereas sidedress N at V6 (all treatments) and late N (T5 and T6 only, high-clearance applicator) were applied as liquid fertilizers (UAN).

Site 2

There were four treatments at Site 2 in 2003 (Table 1): T1, uniform preplant N + normal plant density; T2, variable preplant N + normal plant density; T3, uniform preplant N + high plant density; T4, variable preplant N + high plant density. Nitrogen prescriptions followed the same approach as at Site 1 (Eq. [1]), that is, the N management strategies in treatments T1 to T4 were comparable among the two sites. Due to lack of VR planting equipment, plant density was evaluated only at two uniform levels: 79,000 ha^{-1} (normal) and 91,000 ha^{-1} (high).

In 2004, the experimental design was modified (Fig. 3) to evaluate randomized factorial combinations of three N management strategies (main plots) and three levels of plant density (subplots, 67,000, 79,000, and 91,000 ha^{-1}). Although some main plots spanned more than one yield zone for fertilizer application, the actual harvested areas were smaller and fell within the desired yield zone. Nitrogen strategy N1 (uniform) was the same as in T1 and T3 in 2003. Nitrogen strategy N2 repeated the approach used in T2 and T4 in 2003 (Eq. [1]), with more N applied on high-yielding areas (high yield goal) as opposed to less N applied on low-yielding areas with a low yield goal. In contrast to this, strategy N3 was designed to increase N application rates on low-yielding areas and decrease N rates on high-yielding areas to test the hypothesis that this could lead to more uniform yields across the different yield zones. Preplant N was applied as NH_4NO_3. In addition, all treatments received the same amount of starter fertilizer at planting (9 kg N and 10 kg P ha^{-1}) as well as uniform applications of liquid N at V6 (sidedress) and from V8 to R1 stages (fertigation). In 2003, fertigation amounted to about 50% of all N applied (four applications between 18 June and 26 July), whereas it was only 35 to 40% in 2004 (two applications). An 8-row planter with 76-cm row spacing was used for planting and starter fertilizer application. Table 3 summarizes the yield zones and VR N prescriptions in treatments at Site 2. Phosphorus at Site 2 was applied uniformly (10 kg P ha^{-1} as starter fertilizer).

Measurements and Data Analysis

Daily weather data were obtained from automatic weather stations near each site, which were operated by the High Plains Regional Climate Center (www.hprcc.unl.edu). Seasonal rainfall (280–320 mm from emergence to maturity) was close to the long-term averages and any variations in rainfall patterns were evened out by irrigation. However, 2003 and 2004 were years with relatively cooler temperatures, particularly during grain filling. At Site 1, average mean temperature from 1 May to 30 September was 20.0°C in both years, as compared with 20.8 to 21.5°C in other years of the 2000 to 2006 period. Likewise, average maize growing season mean temperature was 20.2°C in both years at Site 2 as compared with 21.1 to 21.7°C in other recent years. The cooler temperatures extended the growing seasons and resulted in a high yield potential. Maize yield potential for each site-year was simulated with the Hybrid-Maize model (Yang et al., 2006) using actual dates of planting, silking, and maturity and the average plant densities observed. Note that these simulations refer to yield potential defined as the maximum yield of a crop cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting, and pests and diseases effectively controlled (Evans, 1993).

Grain yield data were collected in two ways: (i) hand harvest of two 6.1-m rows in four to five sampling plots (located in different yield zones) of each replicated treatment strip (Fig. 3) and (ii) yield monitor data covering one treatment strip width (12 rows for Site 1 and 8 rows for Site 2) for a length of 30.5 m centered around the hand-harvest locations (about 20 yield monitor points for each 30.5-m segment). Because the two methods agreed well, yield data were combined for statistical analysis as area weighted averages. All grain yields were adjusted to a standard moisture content of 0.155 g H_2O g^{-1} grain. In 2003, no yield measurements were conducted in yield zone 1 at both sites, which only covered 3 to 5% of the total field area.

An ANOVA was conducted using PROC MIXED (SAS Institute, Cary, NC) to test for treatment effects, with replicated strips as random terms or strip and strip-main plot as random terms for the split design at Site 2 in 2004. Except for the split design at Site 2 in 2004, the main effects and their interaction in the other three site-year sets were analyzed using single degree-of-freedom contrasts in a one-way ANOVA, which provides a formal test for effects and interaction for imbalanced factorial treatments, also called *augmented factorial* or *factorial plus* (Federer, 1955; Marini, 2003; Littell et al., 2006). Consequently, the model used is described as $Y_{ij} = \mu + \alpha_i + r_j + e_{ij}$, i.e., the response Y_{ij} is from applying treatment i in strip j, plus the experimental errors e_{ij}, which are assumed to be normally distributed N(0, δ^2). Due to the change in treatment design at Site 2 in 2004, the split-design there followed the model of $Y_{ijk} = \mu + \alpha_i + r_j + e_{ij}^* + \beta_k + (\alpha\beta)_{ik} + e_{ijk}$, where e_{ij}^* = whole strip error; β_k = subplot treatment effect; $(\alpha\beta)_{ik}$ = interaction; e_{ijk} subplot experimental error. In this study, we predefined the combination of uniform N and normal seed rate as the baseline, that is, other treatments were compared with this treatment to determine if other changes in VR N or seed rate were beneficial. Economic analysis focused on the costs of seed and fertilizer that differed among the management systems. Costs for other field operations were excluded from the analysis. Likewise, extra costs associated with SSCM technologies such as soil sampling, spatial data processing, guidance, and VR control systems were also excluded from the analysis because proper economic evaluation of those requires taking into account several variable factors, including total acreage treated, maintenance, and depreciation.

An average maize sales price of \$92.50 Mg^{-1} (\$2.35 bu^{-1}) was used for economic analysis, which represented the average of monthly prices received by Nebraska producers in 2003 and 2004 (Nebraska Agricultural Statistics Service, 2005). Input costs for fertilizer and seed were derived from statewide average crop budgets (Selley, 2004). Seed cost was \$125 ha^{-1} for a seed rate of 79,000 seeds ha^{-1}. Fertilizer sources and their prices varied between the two sites, with average prices used of \$0.55 kg^{-1} (\$0.25 lb^{-1}) for N and \$0.91 kg^{-1} (\$0.37 lb^{-1}) for P in the economic analysis.

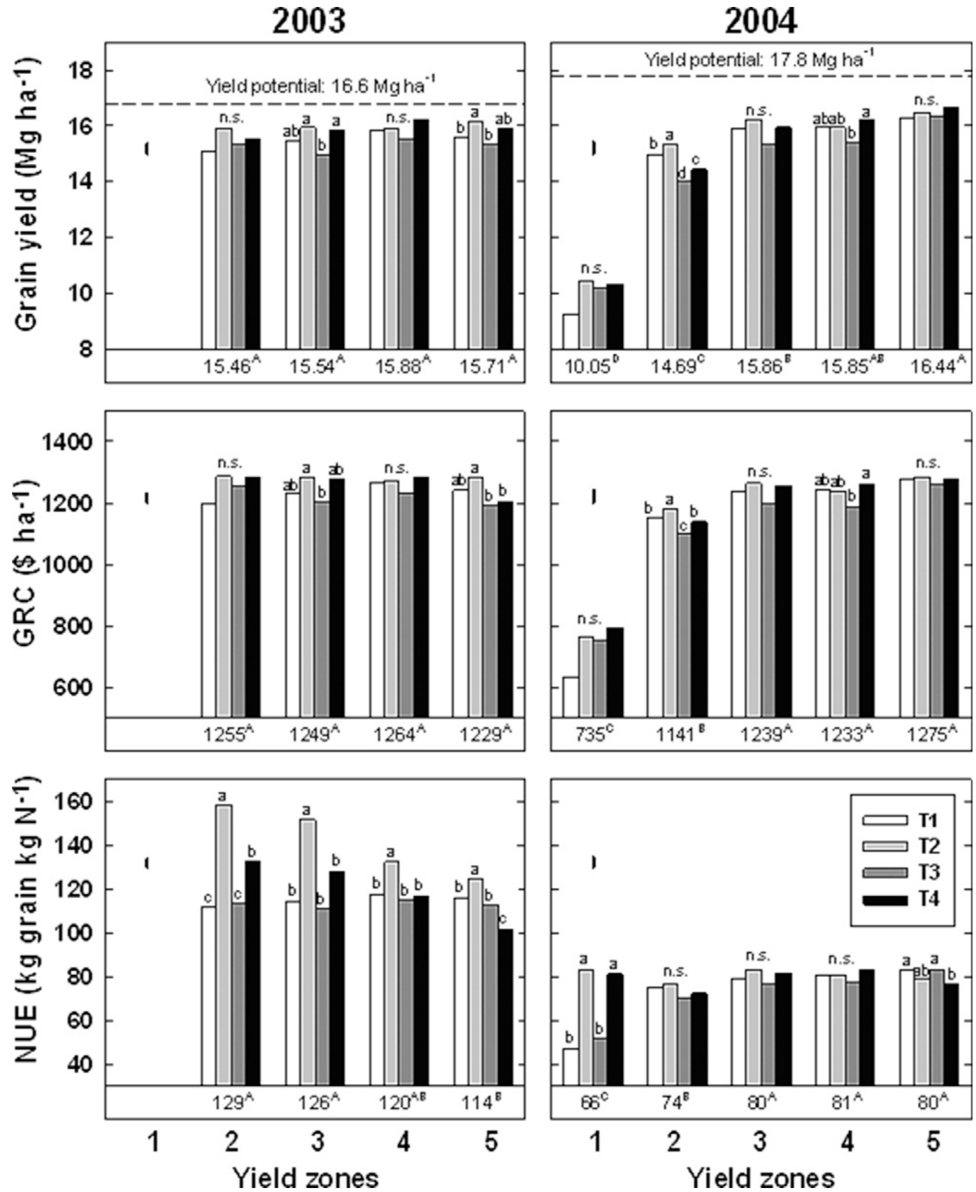

Fig. 4. Maize grain yield, gross return above fertilizer and seed cost (GRC), and N-use efficiency (NUE) at Site 1. Error bars show the weighted standard error of means across all treatments and yield zones. Numbers at the bottom of each graph indicate yield zone means of all treatments evaluated in each year. Uppercase letters indicate significance of mean differences among yield zones at *P* < 0.05. Lowercase letters indicate significance of treatment differences within each zone at *P* < 0.05. The seasonal yield potential was simulated with the Hybrid-Maize model (Yang et al., 2006) using actual climatic data collected with an automated weather station in the field.

RESULTS

Grain Yield

Assuming no limitations by water, nutrients, or pests, the simulated maize yield potential at Site 1 was 16.6 Mg ha^{-1} in 2003 and 17.8 Mg ha^{-1} in 2004 (Fig. 4). Average actual yields in the four treatments ranged from 15.1 to 16.0 Mg ha^{-1} in both years. This represented 92 to 96% of the yield potential in 2003 or 85 to 88% in 2004 (Table 4), indicating excellent management.

At Site 2, simulated yield potential ranged from 16.0 to 17.4 Mg ha^{-1} (Fig. 5). Average actual yields were within 83 to 86% of the yield potential in 2003, but only 70 to 71% in 2004 (Table 5). On average, the 2004 yields at Site 2 were about 1 to 1.5 Mg ha^{-1} lower than in 2003, probably due to insufficient N supply during later growth stages on this sandy soil. Only two fertigations were made in 2004 as compared with four in 2003, resulting in 50 kg N ha^{-1} less N than in 2003.

Except for Site 1 in 2003, average grain yields measured (Fig. 4 and 5) followed the order of the historical yield zones (Table 3). Across all treatments, yields were generally highest in yield zones 4 and 5 (Fig. 4 and 5), which accounted for 71% of the total area at Site 1 and 49% at Site 2 (Table 3). At both sites, yield zone 1 represented small areas (3–7% of the total field area) with the lowest yields. Average grain yields at Site 1 in 2003 were not significantly different among yield zones (Fig. 4). The relatively homogenous, high crop yields across the whole field probably resulted from a combination of high residual soil NO_3–N in the profile in all yield zones (10.2 to 16.3 mg kg^{-1}) and climatic and management conditions that allowed full utilization of the available growing season and of nutrient resources in all yield zones sampled.

Uniform management generally resulted in high yields in all four site-years and the different site-specific management strategies (Table 1) resulted in only small or no significant yield increases (Tables 4 and 5). Significant average yield differences between uniform and comparable VR management were only observed at Site 1 in 2003 (0.2 to 0.6 Mg ha^{-1}). There were neither significant seed rate effects nor interactions of N and seed rate on maize yields in all four site-years. At Site 1, grain yields in VR nutrient management strategies (T2 and T4) tended to be greater than those with uniform management of fertilizer and/or seed (T1 and T3), and those differences were

Table 4. Performance of site-specific management strategies for maize at Site 1. Treatments are defined in Table 1.†

Treatment or effect‡	Yield	N	Seed rate	NUE	Cost	GR	GRC	ΔCost	ΔGR	ΔGRC
	Mg ha^{-1}	kg ha^{-1}	1000 ha^{-1}	kg kg^{-1}	$ ha^{-1}					
2003										
T1	15.5bc§	134a	79.0a	116b	196b	1436bc	1240b			
T2	16.0a	119b	79.0a	136 a	198ab	1478a	1281a	ns¶	43	41
T3	15.2c	134a	77.3a	113b	197ab	1408c	1211b	ns	ns	ns
T4	15.8ab	138a	77.3a	116b	215a	1467ab	1252ab	19	ns	ns
VRN-UniN	0.6	-6	ns	12	ns	ns	ns			
VRD-UniD	ns	10	ns	-11	ns	ns	ns			
Interaction	ns	10	ns	-9	ns	ns	ns			
CV, %	4.0	9.8	11.9	12.2	12.5	4.0	4.9			
2004										
T1	15.3a	198a	79.0a	77b	228b	1412a	1184a			
T2	15.6a	194a	79.0a	81b	233ab	1441a	1208a	ns	ns	ns
T3	15.1a	198a	76.0a	76b	228b	1394a	1165a	ns	ns	ns
T4	15.5a	197a	76.0a	79b	228b	1436a	1208a	ns	ns	ns
VRN-UniN	ns	ns	ns	ns	ns	ns	ns			
VRD-UniD	ns	ns	ns	ns	ns	ns	ns			
Interaction	ns	ns	ns	ns	ns	ns	ns			
With late N applications:										
T5	15.1a	198a	79.0a	76b	243a	1399a	1156a	14	ns	ns
T6	15.3a	167b	79.0a	93a	231ab	1418a	1187a	ns	ns	ns
VR N-UniN	ns	-31	ns	17	ns	ns	ns			
CV, %	14.4	12.1	11.1	16.7	9.3	14.4	16.4			

† NUE, N use efficiency calculated as kg grain yield per kg N applied; Cost, cost of fertilizer and seed; GR, gross return of grain; GRC, gross return above fertilizer and seed cost (GRC = GR –Cost); ΔCost, ΔGR and ΔGRC, difference in cost, gross return, and gross return above cost relative to uniform management (T1), respectively.

‡ VRN-UniN, contrast between VR N and uniform N; VRD-UniD, contrast between VR seed rate and uniform seed rate; Interaction, the interaction between N and seed rate.

§ Within columns and years, treatments with the same letters are not significantly different according to Fisher's LSD at the 0.05 probability level.

¶ ns, not significant.

Table 5. Performance of site-specific management strategies for maize at Site 2. Treatments are defined in Table 1.†

Treatment or effect‡	Yield	N	Seed rate	NUE	Cost	GR	GRC	ΔCost	ΔGR	ΔGRC
	Mg ha^{-1}	kg ha^{-1}	1000 ha^{-1}	kg kg^{-1}	$ ha^{-1}					
2003										
T1	13.4a§	246a	79b	54a	280c	1240a	965a			
T2	13.3a	245a	79b	55a	279c	1231a	952a	ns¶	ns	ns
T3	13.7a	246a	91a	56a	295b	1267a	972a	15	ns	ns
T4	13.5a	256a	91a	53a	306a	1246a	940a	26	ns	ns
VRN-UniN	ns	ns	ns	ns	7	ns	ns			
HD-ND	ns	ns	ns	ns	23	ns	ns			
Interaction	ns	ns	ns	ns	ns	ns	ns			
CV, %	12.8	8.3	7.3	13.6	6.0	12.8	16.3			
2004										
N1	12.2a	197b	79a	62ab	259b	1126a	867a			
N2	12.4a	190b	79a	65a	259b	1141a	882a	ns	ns	ns
N3	12.2a	213a	79a	58b	277a	1121a	843a	18	ns	ns
D1	12.2a	200a	67c	62a	245c	1127a	882a			
D2	12.4a	200a	79b	63a	265b	1147a	882a	ns	ns	ns
D3	12.1a	200a	91a	61a	285a	1114a	829a	ns	ns	ns
CV, %	12.9	11.1	12.8	16.7	9.1	12.9	17.4			

† NUE, N use efficiency calculated as kg grain yield per kg N applied; Cost, cost of fertilizer and seed; GR, gross return of grain; GRC, gross return above fertilizer and seed cost (GRC=GR-Cost); ΔCost, ΔGR and ΔGRC, difference in cost, gross return, and gross return above cost relative to uniform management (T1), respectively.

‡ VRN-UniN, contrast between VR N and uniform N; HD-ND, contrast between high seed rate and normal seed rate; Interaction- the interaction between N and seed rate.

§ Within columns and years, treatments with the same letters are not significantly different according to Fisher's LSD at the 0.05 probability level.

¶ ns, not significant.

statistically significant in 2003. In both years, average yields in the strategies with VR N (T2) were similar to those with VR nutrient inputs and seed rate (T4). Late application of N in 2004 (T5 and T6) did not result in additional yield increases as compared with all other strategies (Table 4). There were no consistent, statistically significant treatment effects on grain yield by yield zones (Fig. 4) and there was no interaction in yield responses between treatments and yield classes. Our study included potentially confounding effects of the VR P with VR N at Site 1. Although it is likely that the VR P effect on maize yields was very small, the design and analysis did not allow it to be dismissed as a potential factor.

At Site 2, there were no significant yield differences among the management approaches (Table 5), possibly because 35 to 50% of the total fertilizer-N was uniformly applied through the center pivot sprinkler system. Likewise, there were no consistent treatment effects on yield in the different yield classes (Fig. 5). Yield interactions between VR N management strategies and plant population were not significant at Site 2 (data not shown).

Fertilizer Nitrogen Use Efficiency

The NUE was high at Site 1 in both years (Table 4). In 2003, due to the high residual NO_3–N levels (Table 3), N rates prescribed at Site 1 were low and average NUE ranged from 113 to 136 kg grain kg^{-1} N in the four management strategies evaluated, which is about twice the national level for maize grown in the United States (Dobermann and Cassman, 2002). Average NUE at Site 1 in 2003 was highest in the management strategy that combined VR nutrients with uniform seed rate (T2), mainly because this strategy resulted in the lowest average fertilizer N amount applied, but also the highest average yield (Table 4). The increase in NUE due to VR management of nutrients was largest in yield zones 2 and 3 (Fig. 4). In 2004, lower levels of indigenous N supply at Site 1 resulted in higher amounts of fertilizer-N required and hence lower NUE than in 2003. Although not statistically significant, average NUE in the two VR nutrient treatments (T2 and T4) tended to be 3 to 4 kg kg^{-1} higher than in comparable treatments with uniform nutrient management (T1 and T3, respectively, Table 4). This was primarily due to a large reduction in N use and slight increases in yield with T2 and T4 in yield zone 1 (Fig. 4). The highest NUE in 2004 (93 kg kg^{-1}) was observed in the strategy that included VR applications of N at all three stages, preplant, V6, and V10 to V12 (T6), primarily because the total amount of N was about 30 kg N ha^{-1} less than in all other treatments. However, late N application did not increase yield (Table 4).

On the sandy soils of Site 2, N supply from indigenous soil sources was generally less than at Site 1, resulting in higher total fertilizer-N amounts. Nevertheless, average NUE levels of 53 to 65 kg kg^{-1} in both years (Table 5) were approximately equal to or greater than national averages, probably because of the detailed N prescription algorithm used (Eq. [1]) and because N was split into four to six doses to avoid leaching losses. There was no advantage in NUE of VR N application over uniform N application on average in 2003 (Table 5). However, lower NUE was observed in VR N treatments in the high yielding zones, while slightly higher NUE was observed in VR N treatments in the lower yielding zones, probably due to the law of diminishing returns with increasing N input (Fig. 5). In 2004, the VR N management strategy in which more N was applied on high-yielding areas and less in areas with low-yield zones (N2, Table 1) resulted in the highest average NUE (65 kg kg^{-1}). In contrast, strategy N3 (Table 1), applying more N to historically low-yielding areas (yield zones 1 and 2) caused a significant reduction in NUE because yields did not increase in these areas (Fig. 5).

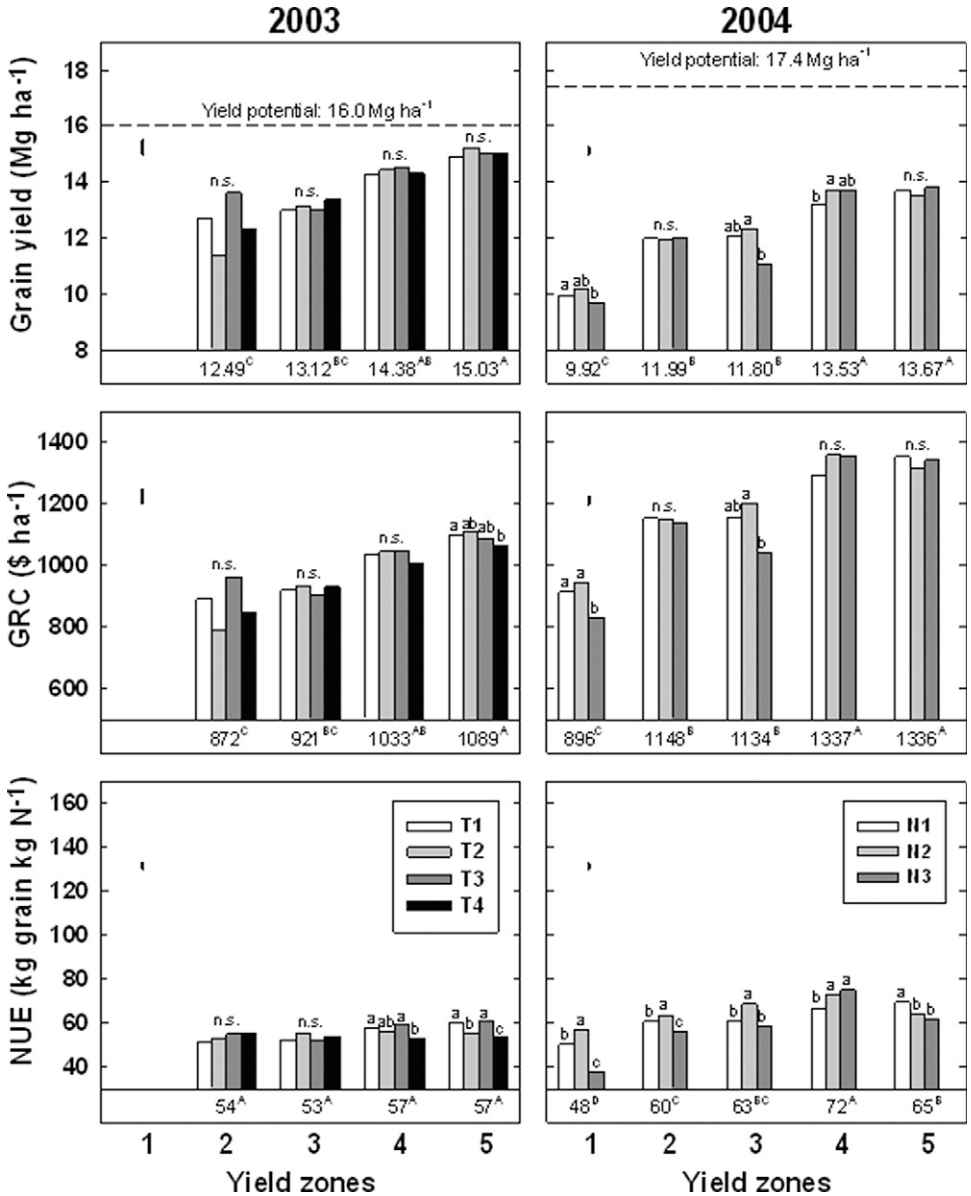

Fig. 5. Maize grain yield, gross return above fertilizer and seed cost (GRC), and N-use efficiency (NUE) at Site 2. Error bars show the weighted standard error of means across all treatments and yield zones. Numbers at the bottom of each graph indicate yield zone means of all treatments evaluated in each year. Uppercase letters indicate significance of mean differences among yield zones at $P < 0.05$. Lowercase letters indicate significance of treatment differences within each zone at $P < 0.05$. The seasonal yield potential was simulated with the Hybrid-Maize model (Yang et al., 2006) using actual climatic data collected with an automated weather station in the field.

Economic Performance

Economic analysis was restricted to differences in input costs and gross return above fertilizer and seed cost (GRC), excluding costs associated with the site-specific management technologies. At Site 1, VR management of nutrients increased the average GRC by \$41 ha^{-1} in 2003; however, no significant differences in GRC were observed in 2004, except for yield zone 1, probably due to substantial spatial variation (Table 4; Fig. 4). Most of this apparent small increase in profit came from small yield increases (T2 and T4), whereas a reduction in input costs accounted for most of the GRC increase in the management strategy with VR N at all three growth stages (T6, Table 4). The preplant P application for the VR P treatments generally had no effect on maize yields, probably because the P amounts that were blanket applied as starter fertilizer in each year turned out to be sufficient to overcome the existing levels of P deficiency. Hence, although the VR P applications in 2003 could be considered a capital investment, they increased the overall cost of the VR management relative to the other treatments in 2003 by about \$3 ha^{-1} in T4. In 2004, all treatments received similar amounts of P within each segment of the treatments (Table 3), which thus did not influence the economic return of VR treatments relative to the uniform treatments.

No significant differences in economic returns between VR and uniform N, different seed rates, and the interaction of N and seed rate were found at Site 2 in both years. In 2003, compared with uniform N and normal seed rate, high plant density (T3) and VR N plus high plant density (T4) resulted in additional inputs by \$15 ha^{-1} and \$26 ha^{-1}, respectively (Table 5). In 2004, the two VR N strategies showed no significant differences in GRC, but N3 (less N on high-yield areas – more N on low-yield areas) caused \$18 ha^{-1} more in N fertilizer input than T1 (uniform N) (Table 5). Significantly lower GRC was observed in yield zones 1 (very low) and 3 (low-medium, Fig. 5.).

DISCUSSION

For a farmer, reliable yield increase and economic return with SSCM are crucial. Given the large variability and uncertainties evident in the determinants of crop yield and economic performance, the null hypothesis to test is that the optimal risk aversion and management strategy is uniform management (Whelan and McBratney, 2000).

In the two irrigated environments studied, we failed to demonstrate that SSCM approaches such as those outlined in Fig. 1 may result in significant economic and environmental gains. One likely reason for this was that the uniform field management followed recommended BMPs that accounted for major site-year differences in crop N demand and N supply, thus resulting in high levels of grain yield, NUE, and GRC. Site-specific nutrient management increased yields only slightly at one site (≤0.6 Mg ha^{-1}) and resulted in some increases in NUE and only small potential economic advantages (Tables 4 and 5). Depending on prices, changes in profit due to site-specific management approaches such as those tested here will rarely exceed \$10 to 50 ha^{-1}. The VR application of fertilizer-N will be most profitable in situations with relatively wide maize-to-N price ratios and a significant yield increase over uniform management. Net profit gains over uniform management would be even smaller than our values (Tables 4 and 5) once additional costs such as extra labor, equipment, laboratory costs, software for GPS positioning, detailed soil sampling, yield monitoring, remote sensing, spatial data analysis and interpretation, and VR application of fertilizers are fully included.

Our results are in line with many published studies on VR N application in cereal crops, which have shown an increase in NUE as compared with uniform N application due to a 10 to 20% reduction in total N use, but often only small profit increases or environmental benefits relative to the extra costs and complexity of management involved (Ferguson et al., 2002; Doerge, 2002; Dobermann et al., 2004). Using a VR N approach similar to our study, Koch et al. (2004) reported \$18 to 30 ha^{-1} net profit increases from VR N for three site-years of irrigated maize in Colorado with full-cost accounting. Similar or somewhat larger gains may be achieved in some rainfed environments where yield variation within fields is large and can be traced to soils, elevation, management, or other known factors (Wang et al., 2003), particularly those that determine moisture and nutrient supply. Likewise, plasticity in yield components in response to the different plant populations tested was probably the major reason for the lack of benefits from VR seeding (Site 1) or increased plant populations (Site 2) in combination with uniform or variable nutrient applications. Analyzing a large data set for the Midwest Corn Belt, Bullock et al. (1998) also concluded that there was very little potential for profitable use of VR seeding as long as seed rates remain above the minimum level recommended to avoid yield losses. Since the actual-, hybrid-, and site-specific response to plant density is rarely known in advance, adjusting seed rates in narrow ranges is unlikely to be economical. Hence, at best, site-specific management of plant populations in maize could include few within-field adjustments where appropriate, for example, savings in seed cost in extremely low-yielding areas with known constraints (soil problems, drought risk).

Several recent studies have demonstrated that the use of more detailed site-specific information collected with precision farming technologies may improve VR management strategies, particularly when empirical site-specific production functions can be found that link yield responses with moisture supply, terrain attributes, and unknown soil effects (Bullock et al., 2002; Ruffo et al., 2006). Collecting and processing such data in a standardized and practical manner remain a challenge. Moreover, the influence of terrain on crop response to inputs is likely to be stronger in rainfed systems with undulating topography (Wang et al., 2003; Anselin et al., 2004) than in relatively flat irrigated fields where more stable yield zones can be delineated (Dobermann et al., 2003).

Further improvements may be possible through designing tactical N management concepts that involve a combination of anticipatory (before planting) and reactive (during the growing season) decisions (Dobermann and Cassman, 2002). The VR N management approaches assessed here were predictive: the decisions about the N amounts needed were made at the beginning of the growing season based on available soil information and an expected zone-average yield potential. Combining this with in-season assessment of crop N and biomass status during mid-vegetative to silking stages of maize may improve the performance of site-specific management by accounting for seasonal variation. Although many sensing devices and approaches have been developed for such purposes (Schroeder et al., 2000; Lammel et al., 2001; Scharf et al., 2006; Varvel et al., 2007), they are not yet widely used in maize. Specific algorithms for in-season prescription of uniform or VR N based on crop diagnostics have to be evaluated more rigorously. In any case, because *crop greenness* can only be sensed reliably after about V6 stage of maize and is also affected by numerous factors other than N, the reactive N management approach tends to *correct* for differences in crop N status. It should also be noted that yield potential in maize is, to a large degree, determined by factors such as solar radiation, temperature, moisture, and nutrient supply during grain filling, i.e., long after most of the N has been applied (Yang et al., 2006). Hence, for optimal performance, reactive N management should be integrated with predictive algorithms that aim at preventing deficiencies or excess of N at the critical stages for yield component formation.

CONCLUSIONS

Science-based BMPs are the major contributor to achieving yields near the yield potential, high NUE, and high profit in intensive production systems. Uniform field management with such BMPs set a benchmark that, in economic terms, was not improved on through site-specific management of N or other inputs. A VR application of seed and nutrients resulted in an increase in NUE in some site-years, but yield and economic gains over uniform management remained insignificant. The SSCM strategies tested were predictive, that is, historical field information (yield maps, weather) and seasonal sampling (soil) provided all information used to prescribe inputs at the beginning of the growing season. This process can be kept simple in irrigated environments with relatively stable yields. There is probably more potential for increasing yields, resource efficiency, and profitability through integrating such a priori decisions with real-time, in-season decisions. Approaches for this are emerging, but remain to be evaluated thoroughly, particularly under high-yielding conditions.

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