Corn Yield Response to Nitrogen Rate and Timing in Sandy Irrigated Soils

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ABSTRACT

Efficient use of N fertilizer for corn (*Zea mays* L.) production is important for maximizing economic return and minimizing NO_3 leaching to groundwater. The objective of this study was to evaluate grain yield response to irrigation rate and N rate and timing for irrigated corn in the sandy soils along major Kansas waterways. Nitrogen treatments included 300 and 250 kg N ha^{-1} applied at planting; 250 kg N ha^{-1} applied at planting (one-half) and sidedress (one-half); 185 kg N ha^{-1} applied at planting (one-third) and sidedress (two-thirds); 125 kg N ha^{-1} applied at planting (one-fifth) and sidedress (two-fifths, two-fifths); and 0 kg N ha^{-1}. Nitrogen treatments were duplicated at one site for each of two irrigation treatments (IS): 1.0× (optimal) and 1.25× (25% > optimal). A split application of 185 kg N ha^{-1} was sufficient to achieve maximum corn yield at every location, and in most instances 125 kg N ha^{-1} was sufficient. These rates were on average 88 kg N ha^{-1} less than the current N recommendation for corn in Kansas, indicating that N rates could be reduced for these soils by an average of about 40% of the current N recommendation when N is split applied. The environmental risk associated with irrigated corn production on these sandy-textured soils, specifically, NO_3 leaching to groundwater, will be minimized only when N fertilizer and irrigation inputs do not exceed crop requirements and N fertilizer is applied to more closely match crop demand (e.g., in-season applications).

NITROGEN FERTILIZER is universally accepted as a key component to high corn grain yield and optimum economic return. In the Midwest, the primary philosophical approach to developing a N fertilizer recommendation for corn is to consider, as independent variables, yield goal, economic return, management level, and some measure of the inherent differences in soil productivity (Oberle and Keeney, 1990a). However, this approach may lead to over application of N fertilizer and result in elevated levels of NO_3 in the soil profile and an increased susceptibility to NO_3 loss by leaching (Ferguson et al., 1991; Schepers et al., 1991; Sogbedji et al., 2000). Fertilizer N applied in excess of crop needs may result when soil inorganic N content is not adequately considered or when predicted yield goals are considerably larger than could be expected for given soil types and climatic conditions (Keeney, 1987). An understanding of the factors affecting corn yield and yield response to N fertilizer is important in providing effective N management recommendations over a wide range of soil–climate conditions, minimizing the potential for negative environmental impacts.

Numerous studies have emphasized the importance of considering the effects of water management on NO_3 movement under irrigated corn (Watts and Martin, 1981; Hergert, 1986; Spalding et al., 2001). Endelman et al. (1974) reported that as little as 2.54 cm of irrigation or rainfall can move soil NO_3 15 to 20 cm in a loamy sand soil. Considering that the average rainfall (1971–2000) from mid-April to mid-June in south-central Kansas is 21.2 cm (Kansas State Univ. Res. and Ext., 2004), the depth to which soil NO_3 could potentially move early in the growing season is as great as 165 cm, exceeding the average corn rooting depth (140 cm; Leonard and Martin, 1963). Maximum corn rooting depth does not occur until about tasseling (about mid-June), by which time only 60% of total N uptake has occurred (Hoeft et al., 2000). Any rainfall or irrigation after planting through mid-June, in excess of evapotranspiration, increases the potential for NO_3 leaching to a depth exceeding the average corn rooting depth (Keeney, 1982). Irrigation is often necessary during this time period to promote early crop growth, and the risk of N loss is particularly enhanced when fertilizer N is applied preplant or at planting, increasing the time of exposure of N to losses by leaching or denitrification.

The negative environmental impacts associated with corn production can be minimized through efficient N management, including accurate N fertilizer recommendations (Fox et al., 1989). Nitrogen applications that meet, but do not exceed, N requirements for maximum corn yield are essential to minimizing environmental risks associated with N fertilizer application. Currently in the USA, grain yield goal is typically used as the primary independent variable for determining corn N recommendations. Corn N recommendations must also incorporate reliable estimates of factors affecting crop productivity, and may be inappropriate if these parameters are unknown or erroneously estimated (Meisinger, 1984; Vanotti and Bundy, 1994). To reasonably estimate crop fertilizer N needs, all potential sources of available N must be considered, as well as crop sequences, soil properties, fertilizer management, and climate effects (Oberle and Keeney, 1990a).

Nitrogen recommendations based on yield response data usually represent large geographic regions. Although these recommendations are generally adequate, they may provide an erroneous N recommendation as a result of field-specific soil–crop–climate conditions. The current N recommendation for corn in Kansas is

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Abbreviations: IS, irrigation schedule or irrigation treatment; MCL, maximum containment level; N_{rec}, nitrogen recommendation for corn, as developed by Leikam et al. (2003); OM, organic matter represented in a single model for the entire state, using the formula developed at Kansas State University (KSU) by Leikam et al. (2003) as follows:

$$N_{\mathrm{rec}} = 28.6\ Y_{\mathrm{grain}} - N_{\mathrm{OM}} - N_{\mathrm{r}} - N_{\mathrm{m}} - N_{\mathrm{o}} + C \qquad [1]$$

where

N_{rec} = recommended N rate (kg ha^{-1})
Y_{grain} = expected attainable grain yield (Mg ha^{-1})
28.6 = internal N requirement of the corn crop per unit of grain yield
N_{OM} = net N produced from mineralization of soil organic matter (kg ha^{-1}), determined as 2.24 × soil OM content (g kg^{-1})
N_{r} = profile N: available preseason inorganic soil N in the surface 60 cm (kg N ha^{-1}), determined as 0.12 × sampling depth (cm) × soil NO_3–N (mg kg^{-1})
N_{m} = inorganic N available from manure application (kg N ha^{-1})
N_{o} = inorganic N from other sources (e.g., irrigation water) (kg N ha^{-1})
C = previous crop adjustments (kg N ha^{-1})

Although parameter coefficients may vary, the University of Missouri (Buchholz et al., 1993), University of Nebraska (Shapiro et al., 2003), and Colorado State University (Mortvedt et al., 1996) provide a N recommendation for corn that is also a linear function of yield goal, whereas Iowa State University (Iowa State Univ. Ext., 1997) no longer uses yield goal in their N recommendation for corn, and the University of Minnesota (Randall et al., 2003) uses a modified approach (constricting N recommendations between 65 and 215 kg N ha^{-1}).

Utilization of soil-specific data may provide an alternative to traditional methods (e.g., the current Kansas N recommendation, Eq. [1]) for determining N fertilizer recommendations, which may result in a given soil receiving more or less N than necessary to satisfy the N rate corresponding to maximum crop yield. Grouping soil types with similar drainage characteristics, rooting depth, and organic matter content is a feasible approach for determining N recommendations, and may result in more environmentally friendly N management (Oberle and Keeney, 1990b). Vanotti and Bundy (1994) proposed utilizing N response data to develop soil-specific N recommendations with annual adjustments for soil NO_3 content. Results from this study indicated that a base economic optimum N rate derived from yield response data, with annual adjustments for soil NO_3, can provide very site-specific N recommendations while minimizing the risk of excessive or unprofitable N rates due to overly optimistic yield goals. Additionally, because optimum N rates are less variable than yields, a relatively small N response database for a given soil could provide enough information to make sound fertilizer recommendations. However, when a yield-based recommendation approach relies on an accurate estimate of the yield response relationship and realistic estimates of its components, a yield-based approach can provide N rate recommendations for a specific soil type nearly identical to that of a soil-specific N rate recommendation (Vanotti and Bundy, 1994).

Nitrogen recommendations must be formulated to address both yield concerns and environmental issues. Applying N within or below the range required for economic optimum yield would contribute less NO_3 contamination to groundwater than applying N in excess of this range. The use of excess N, as an "insurance" mechanism, is perpetuated by the fact that a moderate amount of excess fertilization represents a smaller economic risk than a possible yield reduction associated with inadequate N. The rising costs of N fertilizers may serve to reduce exploitation of N as insurance, though the question remains whether voluntary N and water management practices will provide the intended improvement in groundwater quality, or if mandatory regulations will be required. Regardless, an improved effort is needed to confront the attitudes and motivations that influence the decisions concerning application rates of N fertilizer. Identifying N and water management practices that minimize the NO_3 leaching potential for irrigated corn production will be essential to improving N recommendations in the Great Plains, while maximizing economic return for producers. The objective of this study was to evaluate grain yield response to irrigation rate and N rate and timing for irrigated corn in the sandy soils along major Kansas waterways.

MATERIALS AND METHODS

Field experiments in 2001 and 2002 were established in Kansas, USA, along the Republican, Kansas, and Lower Arkansas Rivers. Locations included Scandia (39°46′23″ N lat; 97°47′19″ W long), Manhattan (39°08′02″ N lat; 96°37′09″ W long), Rossville (39°06′59″ N lat; 95°55′40″ W long), and Ellinwood (two sites: 38°15′01″ N lat; 98°37′18″ W long). Each field was sprinkler-irrigated and continuous corn was the crop rotation at every site except Scandia, which was in a corn–soybean [*Glycine max* (L.) Merr.] rotation before this study. The soils at Scandia were Carr fine sandy loam (coarse-loamy, mixed, superactive, calcareous, mesic Typic Udifluvents). The soils at Manhattan and Rossville were Eudora silt loam (coarse-silty, mixed, superactive, mesic Fluventic Hapludolls). The soils at the Ellinwood site were Pratt loamy fine sand (sandy, mixed, mesic Lamellic Haplustalfs). Geographic plot locations were identical between years at all sites except Manhattan, where plots were moved approximately 180 m south in 2002 to avoid an area that was prone to flooding. Criteria for selecting sites included irrigated corn production on sandy-textured soils with relatively shallow groundwater depths (e.g., 3–15 m). Scandia and Ellinwood were managed by the cooperating producers as part of the entire field, with the exception of N application and grain harvest. The Rossville and Manhattan sites were on university experiment farms and were managed similarly as the other sites following general production practices and to satisfy the objectives of the study. Typical tillage included chisel plow and a seedbed preparation pass, and weed control included preplant or pre-emergence herbicides.

Plot dimensions were 6 m (8 rows, 0.76-m row width) wide and 9.1 m long at all sites except Manhattan, where plots were 4.6 m (6 rows, 0.76-m row width) wide and 9.1 m long. Plots were arranged in a randomized complete block design (RCBD) with four blocks of six N treatments. Nitrogen treatments included 300 kg N ha^{-1} applied at planting; 250 kg N ha^{-1}

applied at planting; 250 kg N ha^{-1} applied at planting (one-half) and sidedress (one-half); 185 kg N ha^{-1} applied at planting (one-third) and sidedress (two-thirds); 125 kg N ha^{-1} applied at planting (one-fifth) and sidedress (two-fifths, two-fifths); and 0 kg N ha^{-1}. Granular NH_4NO_3 fertilizer was surface applied by hand within 2 wk of planting, at the V6–V8 growth stage for the first sidedress application, and at the V10 growth stage for the second sidedress application. There were two irrigation treatments at the Ellinwood site (optimal water rate, 1.0× IS; and 25% greater than optimal water rate, 1.25× IS), each of which included a RCBD with the described N treatments. The optimal water rate for the Ellinwood site was determined using KanSched ET-based irrigation scheduling software (Clark et al., 2004).

Soil samples were collected two times during each study year for NH_4 and NO_3 analyses. Samples were collected within 2 wk of planting (preplant, before fertilizer application) and post-harvest to a depth of 240 cm in 30-cm increments. At Ellinwood, one core within the row and one core from between the rows were collected from each plot using a hydraulic soil probe with a 5-cm i.d. core, and then combined. At the other sites in 2001, preplant soil samples were only collected from plots assigned to the 0 and 300 kg N ha^{-1} treatments. In 2002, preplant samples were collected from every plot at all sites except Manhattan, where preplant samples were only collected from plots assigned to the 0 and 300 kg N ha^{-1} treatments because this site had been moved from the 2001 location. Post-harvest soil samples consisted of one 5-cm i.d. core taken from each plot at all sites except Ellinwood, where two cores were collected and combined for each plot (as already described). All soil samples were dried at 50°C and ground to pass a 2-mm sieve. Soil NO_3 and NH_4 were determined by flow injection analysis of 1 *M* KCl extracts (QuikChem Methods, Lachat Instruments, Milwaukee, WI).

Following harvest in 2002, 15, 2.5-cm i.d. cores (30-cm depth) were randomly collected and combined from each site to make a composite sample. The composite samples were dried at 50°C, ground to pass a 2-mm sieve, and analyzed for 1:1 soil/water pH, Bray 1-P, K, and OM as described by Brown (1997).

Soil samples for dry bulk density determination were collected from each site. Six cores to a depth of 240 cm in 30-cm increments were collected after harvest at each site except Ellinwood using a hydraulic soil probe with a 5-cm i.d. core. Samples (five cores, 240-cm depth) at Ellinwood were collected in May using a hydraulic soil probe with a 6.71-cm i.d core. Samples from all sites were dried at 105°C for 2 d and the dry soil mass recorded. Bulk density was determined by dividing the oven-dry mass by the sample core volume (Blake and Hartge, 1986). Mean dry bulk density (g cm^{-3}) was determined by averaging across all cores for each depth at each site. Textural analysis was completed for each site using a composite of 10-g subsamples from each 30-cm increment collected preplant in 2002. Soil texture was determined using the hydrometer method (Gee and Bauder, 1986), with sodium hexametaphosphate as the dispersing agent.

Grain yield at all sites except Rossville was determined by hand harvesting a 6-m length of each of the middle two rows from each plot. Corn was shelled with a spike cylinder sheller and then weighed, and yields were adjusted to 155 g kg^{-1} moisture content. The middle two rows of each plot at Rossville were harvested with a combine modified for plot work and yield adjusted to 155 g kg^{-1} moisture content.

Nitrogen recommendations (N_{rec}) for each site and year were determined using the formula (Eq. [1]) developed by Leikam et al. (2003). Research data were used to compute each N_{rec}. Yield goal for each site was determined using the highest grain yield mean (for a treatment) from the 2 research years. Soil profile N was calculated using the average of preseason sample NO_3 concentrations, 0 to 60 cm, from a given site for each study year. Nitrogen credits from irrigation were calculated using the average application rates from actual field measurements (Ellinwood, 222 mm, 1.0× IS; 282 mm, 1.25× IS; Rossville, 211 mm) or from values typical for each location (Manhattan, 149 mm; Scandia, 265 mm; Kansas Water Office, 2004). Irrigation at Ellinwood was measured in 2001 and 2002 using 16 nonevaporative rain gauges located along the perimeter of the plots. Water application rates at Rossville were determined using a 3-yr average of the actual applied amounts based on producer records of application rates. Irrigation water NO_3 concentration at each site was estimated from values measured during this study (Ellinwood, 6.1 mg L^{-1}; Manhattan, 0.4 mg L^{-1}) or from previous research conducted at or near each site (Rossville, 1.4 mg L^{-1}; Scandia, 5.5 mg L^{-1}) (Townsend et al., 1998; Heitman, 2003). Water samples collected for this study were analyzed for inorganic NO_3 following rapid flow analyzer (RFA) methodology A303-S170 (Alpkem Corp., 1986). At Ellinwood, the average NO_3 concentration of three samples collected during the 2002 growing season was used to determine water NO_3 concentration. Average NO_3 concentration of three water samples (collected from the sprinkler) was used at the Manhattan location. An adjustment for previous crop (soybean grown in 2000) was used in the N_{rec} calculation at Scandia in 2001.

Table 1. Test of Fixed Effects† with yield as the dependent variable for the Ellinwood site in 2001 and 2002.

Source	df	MSE	Type III *F*	*Pr* > *F*
Year	**1**	**16 582 744**	**8.06**	**0.0059**
Water	**1**	**6 796 373**	**2.99**	**0.1348**
Block (Water)	**6**	**2 276 806**	**1.11**	**0.3669**
Year × Water	**1**	**28 765 445**	**13.99**	**0.0004**
Ntrt	**5**	**85 831 883**	**41.74**	**<0.0001**
Water × Ntrt	**5**	**955 007**	**0.46**	**0.8015**

† Evaluated in PROC GLM (SAS Institute, 1998), df = degrees of freedom, MSE = mean square error.

Statistical analyses were performed using General Linear Procedures (SAS Institute, 1998). The *F*-tests for analysis of variance (ANOVA) were considered significant at the 0.10 probability level. The PROC GLM method (SAS Institute, 1998) was used to analyze treatment differences in grain yield and profile soil NO_3 content for each site. Mean separations for grain yield were determined using least significant difference with $\alpha = 0.10$. Table 1 shows the ANOVA results for the *F*-test with yield as the dependent variable for the Ellinwood site. Repeated measures analysis (SAS Institute, 1998) was used to evaluate time effects on profile NO_3.

RESULTS AND DISCUSSION

Site Characteristics

Soil nutrient characteristics for the surface 30 cm at each study site are given in Table 2. Soil pH ranged from 6.1 to 6.7, which is adequate for irrigated corn

Table 2. Selected soil characteristics (0- to 30-cm) for each location.

Location	pH	Bray 1-P	Extractable K	SOM†
		mg kg^{-1}		g kg^{-1}
Ellinwood	**6.1**	**16**	**53**	**12**
Manhattan	**6.7**	**9**	**301**	**21**
Rossville	**6.5**	**18**	**164**	**15**
Scandia	**6.5**	**8**	**293**	**17**

† SOM, soil organic matter.

Table 3. Sand and clay content by depth for each location.

	Ellinwood		Manhattan		Rossville		Scandia	
Depth	**Sand**	**Clay**	**Sand**	**Clay**	**Sand**	**Clay**	**Sand**	**Clay**
cm	kg kg^{-1}							
0–30	0.93	0.03	0.11	0.35	0.65	0.12	0.73	0.09
30–60	0.92	0.05	0.42	0.24	0.62	0.11	0.38	0.15
60–90	0.90	0.07	0.54	0.16	0.68	0.09	0.33	0.16
90–120	0.89	0.08	0.60	0.13	0.74	0.08	0.52	0.11
120–150	0.90	0.09	0.57	0.19	0.74	0.08	0.83	0.07
150–180	0.90	0.08	0.41	0.25	0.83	0.07	0.91	0.05
180–210	0.87	0.10	0.42	0.27	0.81	0.08	0.94	0.05
210–240	0.88	0.09	0.38	0.30	0.76	0.08	0.94	0.04

grown in the study region (Leikam et al., 2003). Bray 1-P levels ranged from 8 to 18 mg kg^{-1}. In Kansas, corn grown on soils with Bray 1-P levels $<$20 mg kg^{-1} would likely respond to the addition of P fertilizer (Leikam et al., 2003); however, these values are typical of the study region. Extractable K analysis indicated that all locations except Ellinwood had K levels that were adequate for irrigated corn ($>$130 mg kg^{-1}). Despite low soil K levels, K deficiency symptoms were never observed at the Ellinwood site. Soil organic matter ranged from 12 to 21 g kg^{-1}, typical values for these soils (Soil Survey Staff, 2004).

Soil physical characteristics at the study sites were representative of the sandy soils in Kansas. Dry bulk densities ranged from 1.31 to 1.71 g cm^{-3} across all locations and depths, and are consistent with values previously determined for the study soils (Soil Survey Staff, 2004). Analysis of soil texture at each site indicated that sandy-textured soils were predominant in the 0- to 240-cm soil profile at each site, with sand content often exceeding 0.80 kg kg^{-1} (Table 3).

Precipitation for the 2001 growing season exceeded the 30-yr average for each location (Table 4). Rainfall in 2002 exceeded the 30-yr average only at Ellinwood, by 9.0 cm. Precipitation at Scandia, Manhattan, and Rossville was less than the 30-yr average by 25.8, 11.3, and 18.3 cm, respectively (Kansas State Univ. Res. and Ext., 2004).

Grain Yield

Maximum grain yield was achieved with a split application of 185 kg N ha^{-1} at all sites, and in most instances 125 kg N ha^{-1} was sufficient to achieve maximum yield (Table 5). This was less than the current Kansas N recommendation (N_{rec}) for these sites. Using the formula (Eq. [1]) developed by Leikam et al. (2003), the recommended N rate (kg ha^{-1}) was (for years 2001 and 2002, respectively) 248 and 237 for Ellinwood 1.0×; 249 and 215 for Ellinwood 1.25×; 270 and 273 for Rossville; 172 and 222 for Scandia; and 220 for Manhattan (2001 and 2002). Different N recommendations between years for these sites were a result of yearly changes to the profile N credit, as well as the N credit attributed to soybean in the crop rotation at Scandia before the beginning of this study. One reason for the discrepancy between our observations and the recommendation provided by Leikam et al. (2003) is that the 125 and 185 kg N ha^{-1} rates were applied as a split application, and there is no mechanism in the current recommendation to accommodate this improved efficiency in N management (Keeney, 1982; Aldrich, 1984).

An evaluation of the results from specific sites indicated that in three out of four water–year combinations at Ellinwood, maximum grain yield was achieved with 125 kg N ha^{-1} (Table 5). For these three instances, yield for only the control (0 kg N ha^{-1}) was less than yield for all other N treatments. The addition of fertilizer N (regardless of rate) increased mean grain yield 5.7 Mg ha^{-1} across both irrigation treatments and years, when compared with the control. Mean grain yield for the 1.25× IS was 1.9 Mg ha^{-1} greater than for the 1.0× IS in 2001, but there was no difference between irrigation treatments in 2002, as indicated by the year × water treatment interaction (Table 1). However, the difference between irrigation treatments did not change the practical interpretation of the response to N fertilizer. The N_{rec} for this site overestimated N required to achieve maximum yield by 63 to 124 kg N ha^{-1} among all water–year combinations, despite using a modest yield goal (Table 6) to determine the N_{rec}—one that was achieved in nearly half of the treatments receiving any N fertilizer. For the 1.0× IS in 2001, the 185 and 250 kg N ha^{-1} split

Table 4. Irrigation and precipitation data for each location.

	April–September irrigation†		Annual precipitation			April–September precipitation				
Location	**2001**	**2002**	**30-yr**	**2001**	**2002**	**30-yr**	**2001**	**Dev‡**	**2002**	**Dev**
	cm									
Ellinwood			66.1	64.8	76.4	45.6	51.6	6.0	54.6	9.0
1.0×	25.1	19.3								
1.25×	32.0	24.4								
Manhattan	14.9	14.9	82.4	90.8	66.0	57.9	68.6	10.7	46.6	−11.3
Rossville	8.2	27.9	92.0	107.1	65.9	63.4	78.4	14.9	45.2	−18.3
Scandia	26.5	0.0	78.5	91.2	50.6	56.7	70.8	14.1	30.9	−25.8

† Field-measured values at Ellinwood and Rossville, values typical for each location at Manhattan and Scandia (Kansas Water Office, 2004).

‡ Deviation from 30-yr average.

Table 5. Corn grain yield as a function of N treatment for each location.

	Ellinwood†									
	1.0×		1.25×		Rossville		Scandia		Manhattan	
Treatment	**2001**	**2002**	**2001**	**2000**	**2001**	**2002**	**2001**	**2002**	**2001**	**2002**
kg N ha^{-1}	Mg ha^{-1}									
0	2.7c‡	7.2b	3.5b	7.0b	7.9b	6.4b	7.4b	2.7	2.8c	6.4c
125 split§	9.1b	11.1a	11.2a	10.9a	12.0a	10.5a	11.1a	3.6	6.2b	8.9b
185 split¶	10.1ab	11.6a	11.3a	11.4a	13.5a	10.7a	11.8a	3.5	9.3a	9.6ab
250 split#	11.1a	11.6a	12.0a	10.4a	12.6a	11.0a	11.4a	4.1	8.9a	9.9ab
250	9.3b	11.1a	12.7a	9.7a	12.4a	11.4a	11.6a	4.0	10.6a	9.6ab
300	9.0b	10.5a	11.9a	10.3a	12.6a	11.3a	11.5a	3.8	10.5a	10.7a
Mean	8.5	10.5	10.4	10.0	11.8	10.2	10.8	3.6	8.0	9.2
LSD(0.10)	1.2	1.3	1.5	2.0	2.0	1.2	1.2	NS	1.6	1.2

† Irrigation treatments of 1.0× (recommended rate) and 1.25× at Ellinwood.

‡ Means labeled with the same letter for a given location and year are not different as determined by LSD at $a = 0.10$.

§ Split N application: 20% applied at planting, 40% at V-6 crop stage, 40% at V-10 crop stage.

¶ Split N application: 33% applied at planting, 67% applied at V-6 crop stage.

Split N application: 50% applied at planting, 50% applied at V-6 crop stage.

applications provided greater grain yield than either single, preplant application and is indicative of enhanced N uptake by the crop when N was applied during the growing season (Gerwing et al., 1979). Also, Kansas State University's model used to determine N_{rec} was developed for both irrigated and dryland corn, and may not accurately account for the additional mineralization of N, which occurs under irrigated conditions (Ferguson et al., 1991).

Grain yield was statistically similar among all treatments receiving N fertilizer at Rossville in both 2001 and 2002, and yields for these treatments were significantly greater than the control (Table 5). An increase in average grain yield of 4.7 Mg ha^{-1} across both years resulted with the addition of N fertilizer, regardless of rate, when compared to the control. The N_{rec} at Rossville was 270 and 273 kg N ha^{-1} for 2001 and 2002, respectively, while maximum yield was observed with an N rate as low as 125 kg N ha^{-1} applied as a split application. The yield goal used in determining N_{rec} (12.2 Mg ha^{-1}, Table 6) appears reasonable, as observed yield exceeded yield goal for all but one treatment receiving N in 2001. Although the split application may provide some measure of improved N uptake not accounted for in Kansas State University's N_{rec} formula (Eq. [1]), a single preplant application of 250 kg N ha^{-1}, at least 20 kg N ha^{-1} less than the recommended rate, was sufficient to attain maximum corn yield at this location.

Large differences in mean grain yield were observed at Scandia between 2001 and 2002, with a 2001 mean yield across all treatments of 10.8 vs. 3.6 Mg ha^{-1} in 2002 (Table 5). Lower yields in 2002 were primarily due to drought conditions during the growing season. Natural precipitation was 25.8 cm lower than the 30-yr average (Table 4), and irrigation was not applied due to water-use restrictions for this field. A year × N treatment interaction was observed at this site. While average grain yield across all N treatments was lower in 2002, there was no difference in yield among N treatments in 2002. The 45 kg ha^{-1} adjustment to the 2001 N_{rec} for soybean grown at this site in 2000 resulted in an N_{rec} that was 43 kg N ha^{-1} less than determined for any other site in this study (Table 6). However, a difference of 47 kg N ha^{-1} was observed between the N_{rec} (172 kg N ha^{-1}) and the N rate corresponding to maximum yield (125 kg N ha^{-1} split applied). Grain yield results from 2001 demonstrated a trend similar to that observed at the other sites—a lower N rate could be split applied yet achieve the same yield as higher single preplant applications.

Maximum grain yield at Manhattan in 2001 and 2002 was obtained with a split application of 185 kg N ha^{-1}

Table 6. Kansas N recommendation as determined using the formula (Eq. [1]) developed by Leikam et al. (2003) and minimum N fertilizer application corresponding to maximum grain yield (N required).

Location	Year	Yield goal†	SOM‡	Profile N§	Irrigation N¶	Previous crop#	N_{rec}††	N required
		Mg ha^{-1}	g kg^{-1}	kg N ha^{-1}				
Ellinwood 1.0×	2001	11.3	12	35.3	13.6	0	248	185
	2002			46.0		0	237	125
Ellinwood 1.25×	2001	11.3	12	31.0	17.2	0	249	125
	2002			64.3		0	215	125
Rossville	2001	12.2	15	42.7	3.0	0	270	125
	2002			39.6		0	273	125
Scandia	2001	11.9	17	71.2	14.5	45	172	125
	2002			66.2		0	222	0
Manhattan	2001	10.7	21	36.8	0.6	0	220	185
	2002			37.7		0	219	185

† Yield goal determined using the highest treatment mean for the 2 study years.

‡ SOM, soil organic matter content of composite sample at each location.

§ Determined using average of pre-season sample NO_3–N concentrations for all plots at a given location, 0 to 60 cm.

¶ Value estimated using typical application rates and water NO_3–N concentration at each location.

Nitrogen adjustment for crop grown at location in previous year.

†† N_{rec} from Eq. [1].

(Table 5). Mean grain yield for the highest yielding N treatments (>125 kg N ha^{-1}) was 9.8 Mg ha^{-1} in 2001 and 9.9 Mg ha^{-1} in 2002. Grain yield was lowest for the control treatment in each year, 2.8 and 6.4 Mg ha^{-1} in 2001 and 2002, respectively. In 2001, the 125 kg N ha^{-1} split application treatment grain yield was less than that observed for all other treatments receiving N fertilizer. The 2002 grain yield for the 125 kg N ha^{-1} split application was also greater than that of the control, but was similar to yields observed for the 185 split, 250 split, and 250 kg N ha^{-1} treatments and was less than yield for the 300 kg N ha^{-1} treatment. Additionally, a year × N interaction was observed at this location. While average yield across all N treatments was lower in 2001, 8.0 vs. 9.2 Mg ha^{-1} in 2002, yields for the 0 and 125 kg N ha^{-1} split treatments were relatively smaller in 2001 compared with the differences between years for the other N treatments. The N_{rec} at this site (using Eq. [1]) was similar for 2001 and 2002, with recommended rates of 220 and 219 kg N ha^{-1}, respectively (Table 6). This result was due to similar pre-season soil NO_3 concentrations in the 0- to 60-cm profile for each year (36.8 vs. 37.7 kg N ha^{-1} for 2001 and 2002, respectively), and other variables used in the formula (Eq. [1]) were not changed between years. Despite a greater soil organic matter content in the surface 15 cm and a lower yield goal at Manhattan compared with the other sites, the N_{rec} here was similar to that calculated for other sites (Table 6). The N_{rec} for both years at Manhattan was greater than the observed N rate to achieve maximum yield, but the difference was not as great as that observed for most other sites. The lower yield goal at Manhattan relative to the other study sites is a likely source for this discrepancy, and an indicator that the formula to determine the N_{rec} (Eq. [1]) may be overestimating the N required at sites with high corn yields. Research by Ferguson et al. (1991) also found that a formula similar to Eq. [1] tended to overestimate N recommendations on high yielding corn fields.

For all locations in which grain yield responded to fertilizer N addition, a split application of 185 kg N ha^{-1} was sufficient to obtain the greatest corn grain yields. This result is consistent with previous research indicating that similar yields were achieved with lower N rates when N was split applied compared with single preplant applications. Guillard et al. (1999) reported no differences in corn dry matter yield among N treatments that included a preplant application of 196 kg N ha^{-1} and split N applications totaling 135 kg N ha^{-1}. Rasse et al. (1999) showed similar corn grain yields among N treatments that included a single preplant N application of 202 kg N ha^{-1} and a split N application totaling 101 kg N ha^{-1}.

The optimum N rate observed for each study site was considerably less than the corresponding N_{rec} (Table 6). Using Eq. [1] for each location except Scandia (2002), the N_{rec} ranged between 172 and 273 kg N ha^{-1}, corresponding to between 34 and 148 kg N ha^{-1} in excess of that required to achieve maximum grain yield. On average, across all sites except Scandia (2002), the N_{rec} was 88 kg N ha^{-1} greater than required to reach maximum yield. The major contributor to maintaining crop yield with reduced rates of N fertilizer has been attributed to the increased recovery of N by the corn plant when N is split applied (Herron et al., 1971; Gerwing et al., 1979; Bundy et al., 1994 Guillard et al., 1999). The increased efficiency of split N applications probably results from the application of N just before the period of rapid N uptake by corn and a shorter exposure time to leaching or denitrification (Bundy et al., 1994). Split applications provide some measure of N use efficiency not accounted for in Eq. [1], although a single preplant application of 250 kg N ha^{-1} (23 kg N ha^{-1} less than the maximum N_{rec}) was sufficient for maximum yield for all but one site year (Ellinwood 1.0×, 2001). Results from this study suggest that the N_{rec} overestimates N requirements on these high-yielding sandy soils along Kansas' main waterways.

Although Eq. [1] accounts for N in the 0- to 60-cm soil profile, the possibility exists that the relatively high preplant profile (0–240 cm) N content observed at many of the sites (Tables 7 and 8) contributed to corn yields that were maximized below the N_{rec}. Previous research has shown that corn grain yields are relatively insensitive

Table 7. Profile NO_3–N (0–240 cm) as a function of N treatment at Ellinwood.

	Ellinwood†							
	1.0×				1.25×			
	2001		2002		2001		2002	
Treatment	Preplant	Post-harvest	Preplant	Post-harvest	Preplant	Post-harvest	Preplant	Post-harvest
kg N ha^{-1}	kg NO_3–N ha^{-1}							
0	154	68c‡	121	90	168	96d	129	89
125 split§	215	109bc	116	103	172	137cd	148	100
185 split¶	181	151ab	110	106	219	160bc	187	143
250 split#	141	153ab	153	156	145	162abc	159	112
250	178	153ab	149	161	182	187ab	166	134
300	179	193a	128	119	193	205a	146	110
Mean	175	138	130	122	180	158	156	115
LSD(0.10)	NS	44	NS	NS	NS	43	NS	NS

† Irrigation treatments of 1.0× (recommended rate) and 1.25× at Ellinwood.

‡ Means labeled with the same letter for a given location and sampling event are not different as determined by LSD at $a = 0.10$.

§ Split N application: 20% applied at planting, 40% at V-6 crop stage, 40% at V-10 crop stage.

¶ Split N application: 33% applied at planting, 67% applied at V-6 crop stage.

Split N application: 50% applied at planting, 50% applied at V-6 crop stage.

Table 8. Profile NO_3–N (0–240 cm) as a function of N treatment at Rossville, Scandia, and Manhattan.

	Rossville				Scandia				Manhattan			
	2001		2002		2001		2002		2001		2002	
Treatment	Preplant	Post-harvest	Preplant	Post-harvest	Preplant	Post-harvest	Preplant	Post-harvest	Preplant†	Post-harvest	Preplant	Post-harvest
kg N ha^{-1}												
0	171	40c‡	69b	44b	376a	99c	118d	64d	37	52	154	89d
125 split§		61bc	67b	52b		112bc	136cd	120cd		77		107cd
185 split¶		95ab	94b	96b		220a	209ab	147cd		126		168b
250 split#		132a	140b	226a		266a	225ab	287bc		138		253a
250		88b	88b	210a		202ab	197bc	335ab		121		155bc
300	164	94ab	242a	238a	290b	236a	276a	475a		137	139	265a
Mean	168	85	117	144	333	189	193	238	37	108	147	173
LSD(0.10)	NS	45	80	82	82	92	70	176		NS	NS	56

† Sampling depth 0 to 60 cm.
‡ Means labeled with the same letter for a given location and sampling event are not different as determined by LSD at $a = 0.10$.
§ Split N application: 20% applied at planting, 40% at V-6 crop stage, 40% at V-10 crop stage.
¶ Split N application: 33% applied at planting, 67% applied at V-6 crop stage.
# Split N application: 50% applied at planting, 50% applied at V-6 crop stage.

to N fertilizer application when substantial NO_3 levels exist in the soil profile (Ferguson et al., 1991). Bundy and Malone (1988) showed that profile (0–90 cm) NO_3 significantly affects corn yield response to applied N on some soils, and corn yields were not increased by applied N when profile NO_3 exceeded 150 kg N ha^{-1}. Fox et al. (1989) showed that corn yield did not respond to N fertilizer when the NO_3–N concentration in the surface 30 cm of soil was >25 mg kg^{-1} (approximately 100 kg N ha^{-1}) 4 to 5 wk after planting. Perhaps an inflated N credit for soil profile N is required for these sandy soils where root exploration may not be restricted to the top 60 cm of soil.

The N recommendation determined with Eq. [1] was closest to the minimum N rate to achieve maximum yield for the Manhattan location, which had the lowest yield goal of all the study sites (Table 6). This suggests that for sites used in this study, the N recommendation should not be a linear function of yield goal, similar to conclusions reached by Ferguson et al. (1991). When excess N applied ($N_{rec} -$ N required from Table 6) for eight site-years (excluding Scandia because 2001 followed soybean and 2002 was a drought year) was regressed on yield goal, there was a positive linear relationship ($y = 72.3x - 729$, $r^2 = 0.81$). Additionally, good management practices should be recognized in a N recommendation, reducing recommended N rates for producers who utilize N management practices on these irrigated, sandy-textured soils that minimize the potential for N loss, namely split fertilizer N applications. Results from this research suggest that N rates can be reduced by an average of 40% of the current N_{rec} when N is split applied, while maintaining corn grain yields on these soils.

The optimum N rate (needed to achieve maximum grain yield) is influenced by factors including soil type, tillage, irrigation, fertilizer timing and placement, and crop yield potential. These factors, as well as the interaction of these factors, will vary greatly from one location to another in a given geographic region. While developing a N recommendation for large geographic areas that address these issues at the field scale might be difficult, grouping soils with similar physical characteristics and yield potential as an approach for adjusting the N recommendation should be possible (Oberle and Keeney, 1990b). Utilization of this approach to separate regions that are especially prone to NO_3 leaching and providing unique N recommendations for these areas should result in more environmentally friendly and economically improved N management.

Profile Soil Nitrogen

Profile soil NO_3 was evaluated each year before planting (preplant) and subsequent to harvest (post-harvest). Preplant soil NO_3 in the first year of the study was used to evaluate preexisting conditions that might impact treatment response. Preplant soil NO_3 in the second year of the study was used to evaluate effects among treatments from the first year and to consider the potential impact on treatment responses in the second year. Post-harvest profile soil NO_3 provided one measure of treatment impacts. However, because these soils are sandy textured, similar results among treatments was not necessarily an indication that the potential for NO_3 movement was similar among treatments. Given sufficient rainfall and irrigation, NO_3 leaching proportional to the N treatments could result in similar post-harvest profile soil NO_3.

Preplant profile soil NO_3 (0–240 cm) at the beginning of the study (2001) was not significantly different among N treatments at any site, except for Scandia (Table 8). At this site, only those plots designated to receive the 0 and 300 kg N ha^{-1} treatments were sampled in 2001. Soil NO_3 in the control plots was 376 kg N ha^{-1} compared with 289 kg N ha^{-1} for the 300 kg N ha^{-1} plots. Although plots assigned to the 300 kg N ha^{-1} treatment had less soil N in the 240-cm profile, grain yield in the control was less than all other N treatments in 2001 (Table 5). Mean preplant soil NO_3–N in the 240-cm profile for all other sites in 2001 ranged between 168 and 180 kg N ha^{-1} (Tables 7 and 8).

A significant difference in 2001 post-harvest profile soil NO_3 was observed among N treatments at all sites except Manhattan. The 300 kg N ha^{-1} treatment at Ellinwood (2001, 1.0× IS) had a soil NO_3–N content of 193 kg N ha^{-1} compared with 68 and 109 kg N ha^{-1} for the control and 125 split kg N ha^{-1} treatments, respectively (Table 7). Although soil NO_3–N in the control treatment was similar to the 125 kg N ha^{-1} split N application, grain yield was less for the control treatment than for any treatments receiving N fertilizer (Table 5). For the 1.25× IS at Ellinwood (2001), the 300 kg N ha^{-1} treatment resulted in a soil NO_3–N content of 205 kg N ha^{-1}, which was greater than the control and 125 and 185 kg N ha^{-1} split treatments. While post-harvest soil NO_3 content was less for the 125 kg N ha^{-1} split treatment compared with the single, preplant N treatments, grain yield was not different among any of the treatments receiving N fertilizer.

Differences in post-harvest profile soil NO_3 among N treatments were observed at Rossville in 2001, although grain yield at this site was not different among any treatments receiving N fertilizer (Table 5). The 250 kg N ha^{-1} split treatment had a profile soil NO_3 content of 132 kg N ha^{-1}, which was greater than the 40 and 61 kg N ha^{-1} observed for the control and 125 kg N ha^{-1} treatments, respectively (Table 8). The control treatment had less profile NO_3 than any other treatments except the 125 kg N ha^{-1} split treatment.

Similar results were observed at the Scandia site in 2001. The 125 kg N ha^{-1} split treatment had a profile NO_3 content of 112 kg N ha^{-1}, which was less than that observed for the 185 split, 250 split, and 300 kg N ha^{-1} treatments (220, 202, and 236 kg N ha^{-1}, respectively), although no yield differences were observed among these N treatments (Table 5).

Preplant profile soil NO_3 (0–240 cm) for the second year of the study (2002) was significantly different among N treatments at Rossville and Scandia (Table 8). At Rossville (2002), preplant profile soil NO_3 was 242 kg N ha^{-1} for the 300 kg N ha^{-1} treatment, which was greater than the profile soil NO_3 for any other N treatments (Table 8). The 300 kg N ha^{-1} treatments at Scandia had a preplant (2002) profile soil NO_3 content of 276 kg N ha^{-1}, which was greater than that observed for the control, 125 split, and 250 kg N ha^{-1} treatments (118, 136, and 197 kg N ha^{-1}, respectively). At Rossville and Scandia, the impact of N applied in excess of crop uptake in 2001 was still observed in the 2002 preplant soil samples. The same result was not observed for either irrigation treatment at Ellinwood, but the soils at Ellinwood had a greater sand content throughout the soil profile than soils at Rossville or Scandia (Table 3), so differences in preplant soil NO_3 could have been moderated by percolating water at Ellinwood. A significant irrigation effect was observed for the Ellinwood preplant NO_3 profile in 2002, where the 1.25× IS had a greater mean NO_3 content (156 kg NO_3–N ha^{-1}) than the 1.0× IS (130 kg NO_3–N ha^{-1}). Greater preplant NO_3 content with the 1.25× IS may have resulted from greater N mineralization during the winter fallow period due to increased soil profile moisture. No other differences in profile (preplant or post-harvest) NO_3 were observed between the irrigation treatments in 2001 or 2002. The Manhattan site could not be compared in the same context because this site was moved between 2001 and 2002.

Differences in post-harvest (2002) soil NO_3 among N treatments did not occur at Ellinwood but were observed at Rossville, Scandia, and Manhattan (Table 8). Profile (0–240 cm) soil NO_3 for the three highest N treatments at Rossville was in excess of 210 kg N ha^{-1}, whereas profile NO_3 for the control and the 125 and 185 kg N ha^{-1} split treatments was less than 96 kg N ha^{-1}. At Scandia, the differences observed in post-harvest soil NO_3 were proportional to the N rates and application time (Table 8), but the high amounts of N remaining in the soil for all N treatments (475 for the 300 kg N ha^{-1} treatment) was in large part due to the very low yield obtained in 2002 at this site, a consequence of the severe drought. The Manhattan site received ample water, and the higher N rates resulted in more NO_3 remaining in the post-harvest soil profile (as much as 265 for the 300 kg N ha^{-1} treatment) compared with only 107 kg N ha^{-1} when only 125 kg N ha^{-1} was split applied. Any excess N applied to these sandy soils and not used by the crop is at risk to NO_3 leaching whenever water infiltration exceeds evapotranspiration, conditions which might explain why differences in post-harvest soil NO_3 were not observed among the N treatments at the Ellinwood site in 2002 (Table 7).

SUMMARY

Efficient N management is important to minimizing agricultural contributions to NO_3 pollution of groundwater and optimizing profits for corn producers. A principal component of efficient N management is the N recommendation used as a tool in planning N applications. Results from this study suggest that the N recommendation model currently used in Kansas may be overestimating the N requirement for high-yielding irrigated corn grown on sandy-textured soil. Average grain yield achieved at the study sites ranged from 3.6 to 11.8 Mg ha^{-1}. Maximum grain yield for 10 site-years was always achieved with a split application of 185 kg N ha^{-1}, and in most instances a split application of 125 kg N ha^{-1} was sufficient. At sites where grain yield responded to the addition of N fertilizer, the minimum N rate corresponding to maximum yield averaged 88 kg N ha^{-1} less than the Kansas N_{rec} (Leikam et al., 2003). Improvement in N uptake associated with split fertilizer applications is not accounted for in the current N recommendation formula, which may provide some explanation for the observed differences. However, these results suggest that for corn grown in similar conditions as this study, the yield goal component of the formula may need to be adjusted to develop appropriate N recommendations (perhaps not a simple linear relationship between N_{rec} and yield goal). Management practices that improve N uptake should also be recognized in the recommendation by reducing recommended N rates for producers who implement these practices.

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