

Interactions of Nitrogen, Weather, Soil, and Irrigation on Corn Yield

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ABSTRACT

Numerous factors that affect corn yield in the Northern Great Plains are not considered in current N fertilizer recommendations. A linear model to describe the interactions of N fertility, weather, soil, and irrigation on corn (*Zea mays* L.) yield was developed for a 6-yr field study in southeastern North Dakota. Varying rates of postemergence fertilizer N were applied to plots in four quadrants of a sprinkler-irrigated field. Four irrigation-scheduling methods varied by year (Y) and quadrant (Q). Grain yield, stover yield, and N uptake response to a covariate (soil N plus starter fertilizer N), N treatment (Nt), Q, Y, irrigation treatment (I), previous irrigation treatment (P), and the two-way interactions that included Nt, were investigated using standard regression techniques. Yield increased significantly with Nt up to a rate of 135 kg N ha⁻¹ for most Y, Q, and I. Average yearly yield was adversely affected by cool climatic conditions in 2 yr. Soil conditions in two quadrants resulted in a 1.25 Mg ha⁻¹ average annual yield reduction compared with the other quadrants. An irrigation scheduling method utilizing a water balance algorithm resulted in higher yields compared with the other scheduling methods. The interactions of Nt with Q, Y, and I were significant. Optimized total N rates (the sum of soil nitrate N, starter N, and postemergence Nt) derived from quadratic-linear plateau analysis varied (232–374 kg N ha⁻¹) with Y, Q, and I and averaged 295 kg N ha⁻¹. Soil properties, soil moisture availability, and yearly climatic factors should be considered when making fertilizer recommendations.

MAXIMUM CORN GRAIN YIELDS are influenced by a number of factors, including N fertility, growing season conditions, water availability, and soil conditions. Studies investigating N fertility rates have shown that corn yields increase in a quadratic fashion with increased applied N to a plateau level (Cerrato and Blackmer, 1990). Maximum yields have been observed at N rates less than the maximum rates applied in various studies (Onken et al., 1985; Schlegel and Havlin, 1995). Albus and Moraghan (1995) found marked yield responses to N fertilizer in a number of short-season corn hybrids.

In the Northern Great Plains, favorable growing conditions are important due to the short growing season. Derby et al. (2004) found that yield was adversely affected by cool growing season conditions. Similarly, Swan et al. (1987) reported decreased corn yields with insufficient cumulative growing degree days (CGDD). Wienhold et al. (1995) found 60% greater yields with increasing N fertility when the growing season was warm

but no difference in yields with increased N when the season was cool.

Soil moisture status is also important in maintaining maximum corn yields, and maintaining optimal soil moisture is facilitated by irrigation in areas of coarse-textured soils. Stegman (1982) found that yields decreased with increased water stress, but if the water stress is limited to one portion of the growing season and irrigation replenishes the profile moisture, high yields can still be achieved. Some research has indicated that crop N requirements are lower for irrigated versus rainfed soils (Oberle and Keeney, 1990), unless rainfed condition results in water stress.

Current recommendations for corn fertilization in North Dakota indicate that 21.4 to 26.8 kg of N is needed per Mg of corn grain yield, which is equivalent to 1.2 to 1.5 lb of N per standard (56 lb) bushel of corn in conventional units (Dahnke et al., 1992; Berglund and McWilliams, 1999). Typically, the N recommendations are adjusted for soil test N, date of sampling, and previous crop. Current nutrient recommendations, which are based on many site-years of yield response curves, make no adjustments for variation in weather conditions, soil type, and management factors on a site-specific or year-specific basis (Dahnke and Olson, 1990).

The objective of this study was to determine the yield response of corn in the Northern Great Plains to the combined effects of increased applied N fertilizer, irrigation scheduling method, soil type, and yearly climatic variation.

MATERIALS AND METHODS

Field Experiments

For the 1990 through 1995 growing seasons, a field-scale study of irrigation and fertilizer N management effects on groundwater quality was conducted near Oakes, ND, USA. Meteorological data were measured at an automated weather station approximately 2.4 km from the site. The weather station was located at 46°04' N, 98°06' W, and 401 m elevation and is part of the North Dakota Agricultural Weather Network (NDAWN) (Enz et al., 1997). Growing degree units were calculated from NDAWN data based on a lower limit of 10°C and an upper limit of 30°C (Gilmore and Rogers, 1958). Rainfall and irrigation amounts were measured directly at the field site. This site was 64 ha, of which 53.4 ha was irrigated by a sprinkler (center pivot) irrigation system. The soil at the site (Fig. 1) was primarily Hecla loamy fine sand (sandy, mixed, frigid Oxyaquic Hapludoll) on the south portion of the field and Wyndmere fine sandy loam (coarse-loamy, mixed, superactive, frigid Aeric Calciaquoll) and Stirum fine sandy loam

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Abbreviations: CGDD, cumulative growing degree days; ET, evapotranspiration; I, irrigation treatment; NE, northeast; Nt, nitrogen treatment; Ntot, total nitrogen; NW, northwest; P, previous irrigation treatment; Q, quadrant; SE, southeast; SW, southwest; Y, year.

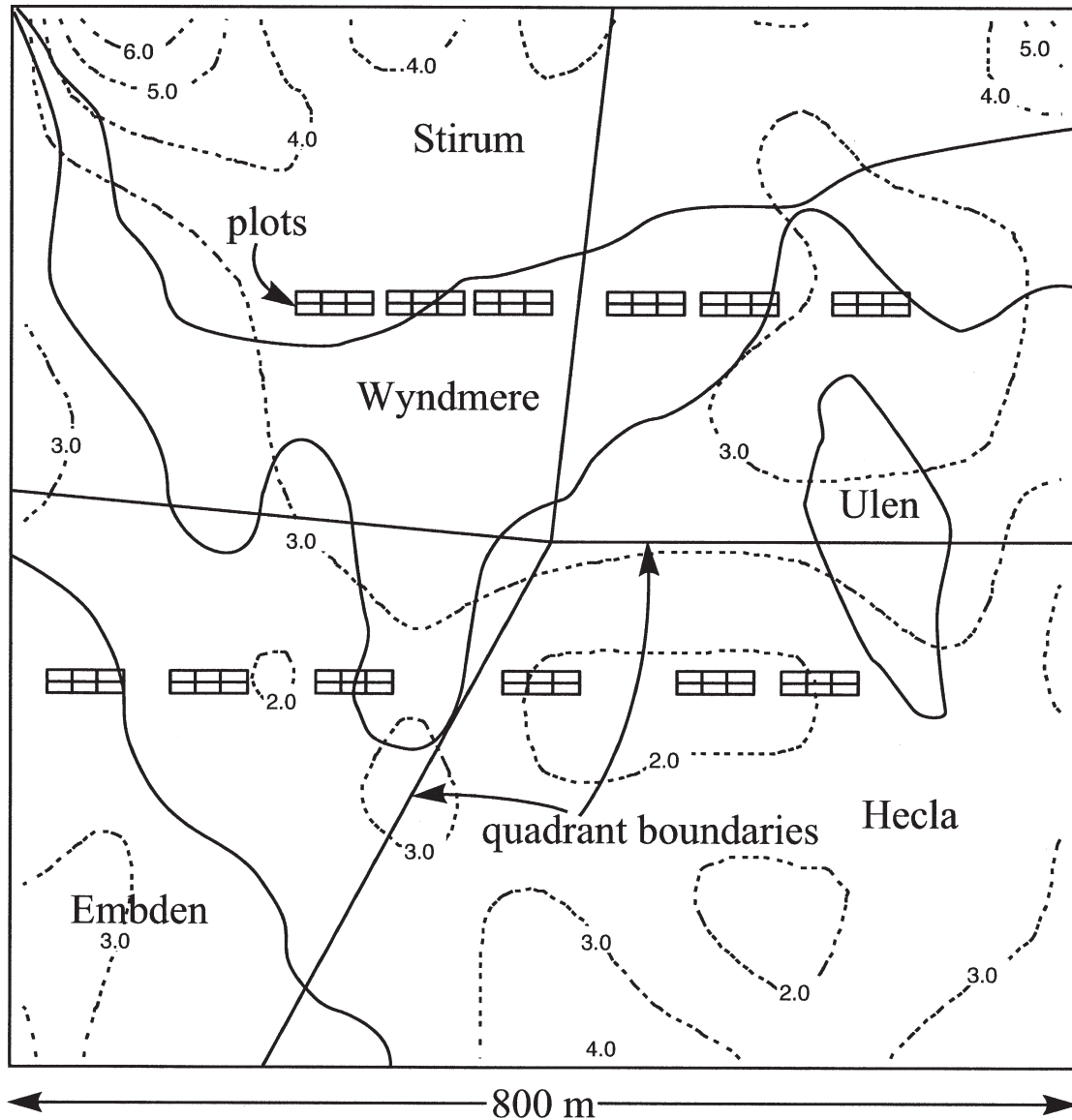


Fig. 1. Order 1 soil survey, plot locations, and quadrant boundaries on research quarter section. Soil electrical conductivity (dS m^{-1}) is indicated by dashed contour lines.

(coarse-loamy, mixed, superactive, frigid Typic Natraquolls) on the north portion of the field.

The field was divided into four quadrants (denoted NW = northwest, NE = northeast, SW = southwest, and SE = southeast) to accommodate differences in soil types and for four different irrigation scheduling method purposes. Irrigation treatments were assigned to quadrants every year based on a statistical design (Cochran and Cox, 1957) in which years and quadrants were the dimensions of a modified Latin square. Steele et al. (2000) described the irrigation aspects of the experiment in detail, including complete descriptions of the treatments, irrigation scheduling criteria, application depths targeted for each irrigation event (32 mm per event for Method A, B, and D and 25 mm per event for Method C), and seasonal (1991–1995) irrigation totals (averaged 136, 125, 106, and 122 mm for Methods A, B, C, and D, respectively). The irrigation scheduling methods were (A) irrigation when tensiometer readings at 0.30-m depth reached 40 ± 10 kPa and/or crop water stress index (CWSI) values reached 0.25 ± 0.05 ; (B) irrigation based on a water balance algorithm (Stegman and

Coe, 1984) that allowed 60 to 70% estimated depletion of plant-extractable water before the first irrigation, full evapotranspiration (ET) replacement from the first irrigation through the blister kernel (R2) stage, followed by irrigation whenever soil moisture depletion reached 60 to 70% for the period R2 through maturity; (C) irrigation based on a water balance algorithm that replaced 80% of estimated crop ET, i.e., the same criteria as Method B, but each irrigation was 20% smaller; and (D) irrigation based on CERES–Maize crop growth model (Jones and Kiniry, 1986) predictions of plant-extractable soil water (PESW), i.e., irrigations occurred when the estimated PESW was at 60 to 70% depletion. Steele et al. (1994) described the CWSI method used in this study. Analysis of irrigation efficiency values showed no significant differences due to irrigation methods (Steele et al., 2000). Irrigation events were applied by on-site research personnel.

Tillage, planting, cultivation, pesticide application, and starter fertilization were done by the farmer cooperater. Spring seedbed preparation tillage was done with a combination disk/chisel plow implement, usually two times before planting. The

Table 1. Planting, harvest, and fertilizer split dates; average spring soil N; and starter fertilizer rates for plots.

Year	Planting date†	Emergence date	Spring soil N kg ha ⁻¹	Starter N kg ha ⁻¹	Starter P kg ha ⁻¹	Dates of split N			Harvest date
						V6	V15	R1	
1990	7 May	23 May	57	14	67‡	22 June	17 July	1 Aug.	25 Sept.
1991	13 May	22 May	61	14	67‡	27 June	15 July	22 July	18 Sept.
1992	30 Apr.	12 May	62	14	67	15 June	22 July	4 Aug.	30 Sept.
1993	5 May	18 May	38	14	67	22 June	2 Aug.	11 Aug.	21 Sept.
1994	22 Apr.	16 May	55	48	58	14 June	12 July	25 July	28 Sept.
1995	5 May	23 May	34	11	56	20 June	20 July	2 Aug.	20 Sept.

† Corn variety Pioneer 3737 planted at a rate of 69 200 to 74 100 seeds ha⁻¹.

‡ Additional fertility corrections applied with starter: 16.8 kg ha⁻¹ ZnSO₄ yielding 5.6 kg ha⁻¹ Zn; 56 kg ha⁻¹ IRON-SUL yielding 0.8 kg ha⁻¹ K₂O, 28 kg ha⁻¹ S, 11.2 kg ha⁻¹ Fe, and 0.4 kg ha⁻¹ Cu.

corn was planted in rows spaced 76.2 cm apart at a seed density of approximately 74 000 seeds ha⁻¹. Starter fertilizer was applied with the seed during the planting operation. Weed control was a combination of between-row cultivation at about V6 and spraying of selective herbicides at appropriate times. Pesticide applications were done on an as-needed basis to control insect infestations.

The research team scheduled the irrigations and managed the postemergence fertilization of 72 small plots. These plots were established along two transects within the irrigated portion of the field (Fig. 1). Each plot was 9.1 m (12 rows) wide by 18.3 m long, and the plots were arranged in groups of six plots with three six-plot groups per field quadrant. The location of each plot area was referenced by angle and distance from fixed points for identification in subsequent years. The fertilizer treatments within each block of six plots ranged from a reference regime of zero applied N to what was considered a nonlimiting regime, with four intermediate regimes. Treatments were designated as Nt1 = 0 kg N ha⁻¹, Nt2 = 45 kg N ha⁻¹, Nt3 = 90 kg N ha⁻¹, Nt4 = 135 kg N ha⁻¹, Nt5 = 180 kg N ha⁻¹, and Nt6 = 225 kg N ha⁻¹, not including the starter N. These N application treatments were randomly arranged within each block at the outset of the study. Each Nt was applied to the same plot for each year of the study to facilitate a “mining down” of residual soil N at the lower, yield-limiting rates, i.e., plots were not annually re-randomized.

Postemergence fertilizer Nt was applied in three splits, starting when the corn reached the six-leaf stage (V6) (Hanway, 1966, p. 3–18). Dates of planting, spring soil test N, fertilizer application, and starter fertilizer rates are shown in Table 1. The amount of starter fertilizer varied in 1994 and 1995 because the farmer cooperated planted the field. The fertilizer N amounts, forms, and application methods for each Nt are summarized in Table 2. The last two applications of N were applied by hand as urea because of lack of equipment and the practicality of injecting urea ammonium nitrate (UAN) at an advanced stage of corn growth. Soil samples for N were taken from each plot area at the four-leaf stage to a depth of 91 cm.

After the corn reached physiological maturity (R6), two adjacent 4.6-m rows were hand-harvested from each plot. All

ears were harvested, and the whole plants were weighed to calculate stover yield. The ears were dried at 60°C and then shelled. The dry grain was weighed, and yields were calculated on a 15.5% moisture content, wet basis. Grain and stover subsamples were ground and analyzed for N_{tot} by the Kjeldahl method (Bremner and Mulvaney, 1982).

Data Analysis

Linear model techniques were used to analyze the data. The model for the main effects with two-way interactions involving Nt is

$$G_{ijklm} = \mu + \beta X_{ijklm} + Nt_i + I_j + P_k + Y_l + Q_m + (NtI)_{ij} + (NtP)_{ik} + (NtY)_{il} + (NtQ)_{im} + \varepsilon_{ijklm},$$

$$i = 1, 2, \dots, 6; j = 1, 2, 3, 4; k = 1, 2, 3, 4;$$

$$l = 1, 2, \dots, 6; m = 1, 2, 3, 4 \quad [1]$$

where the response G was determined for corn grain yield, stover yield, grain N content, grain N uptake, stover N content, stover N uptake, or total plant N uptake; μ is the overall effect; X is the covariate spring soil N plus starter fertilizer N; Nt_1, Nt_2, \dots, Nt_6 represent the effects of the six N treatments 0, 45, 90, 135, 180, and 225 kg N ha⁻¹, respectively; $I_1, I_2, I_3,$ and I_4 represent the effects of the four irrigation scheduling methods A, B, C, and D, respectively; $P_1, P_2, P_3,$ and P_4 represent the effects of the previous year's four irrigation scheduling methods A, B, C, and D, respectively; Y_1, Y_2, \dots, Y_6 represent the effect of years 1990–1995, respectively; $Q_1, Q_2, Q_3,$ and Q_4 represent the effect of the four quadrants SW, SE, NW, and NE, respectively; (NtI) is the interaction effect of the six N treatments and four irrigation treatments; (NtP) is the interaction effect of the six N treatments and the four previous-year irrigation treatments; (NtY) is the interaction effect of the six N treatments and the 6 yr; (NtQ) is the interaction effect of the six N treatments and the four quadrants; and ε_{ijklm} represents random error. This model contains all of the possible two-way interaction terms involving N treatment. We note that some unforeseen linear dependencies in our design prevented us from fitting a model with other two-way (and higher order)

Table 2. Amounts, forms, and application methods for fertilizer N split applications.

Growth stage	Fertilizer form	Application method	N amount per fertility treatment					
			Nt1	Nt2	Nt3	Nt4	Nt5	Nt6
			kg N ha ⁻¹					
Six leaf (V6)	UAN† (28–0–0)	liquid injection	–	45	90	90	90	90
15 leaf (V15)	urea (46–0–0)	hand application‡	–	–	–	45	90	90
Silking (R1)	urea (46–0–0)	hand application‡	–	–	–	–	–	45
Total			0	45	90	135	180	225

† UAN, urea ammonium nitrate.

‡ Fertilizer was applied in the row and followed by 6 mm of irrigation to prevent volatilization losses.

interactions. However, since N was the main focus, two-way interactions are fairly easy to interpret, the model R^2 is high, and no violations of statistical assumptions were identified (via a residual analysis), we feel that this is the most appropriate model for this data set. Analyses were performed using S-Plus statistical software (MathSoft, 1999).

The yield response to Ntot (the sum of soil nitrate N, starter N, and Nt) was modeled with the SAS NLIN procedure (Ihnen and Goodnight, 1985) and is described by the following quadratic-plus-plateau model:

$$Y = a + bX + cX \quad \text{if } X < C \quad [2]$$

$$Y = Y_p \quad \text{if } X \geq C \quad [3]$$

where Y is grain yield (Mg ha^{-1}); X is the sum of applied and soil N (kg ha^{-1}); a , b , and c are coefficients obtained by fitting this model to the LSMEAN yield values; C is the critical or optimized rate of fertilization (kg ha^{-1}); and Y_p is the plateau yield (Mg ha^{-1}). The values of C and Y_p are obtained from the fitted model. The model (Eq. [2] and [3]) was used to determine the optimized N rate (the N at which maximum yield was achieved) for years, quadrants, and irrigation scheduling method. Since the plateau yield was considered to be the maximum yield, the value of C for maximum yield was calculated by equating the first derivative of the response equations (Eq. [2]) to zero and solving for X (Eq. [4])

$$X = -b/2c \quad [4]$$

This is the point C at which the quadratic and plateau portions of the curve meet and represents the optimized N rate for maximum yield but not necessarily maximum economic return, as will be discussed later.

RESULTS AND DISCUSSION

While corn grain yield is the focus of the discussion, the effects on the response variables grain N content and N uptake, stover yield, stover N content and N uptake, and total plant N uptake are also presented in the tables to illustrate the robustness of the statistical model used. However, the discussion regarding those

parameters will be limited. Discussion of Nt rate pertains to postemergence N application and does not include the N applied as starter or soil test N. We note that although the different Nts varied in timing, form of fertilizer, and application method (Table 2), we feel that this type of split application resulted in the best crop utilization of the applied N by reducing the risk of leaching losses compared with if all of the N had been applied at once.

Analysis-of-covariance summary information is listed in Table 3. The residual standard error for corn grain yield was 1.06 Mg ha^{-1} on 340 degrees of freedom. The R^2 value for the model was 0.91, i.e., 91% of the yield response is explained by Eq. [1]. The F statistic for the model was 36.66 on 90 and 340 df, resulting in $p < 0.001$. Upon further examination, all factors in Eq. [1] for corn grain yield were found to be significant at $\alpha = 0.05$ or lower except the NtP interaction and the covariate soil test N plus starter fertilizer N. High R^2 values and similar significance of terms was observed for the other response variables grain N content, grain N uptake, stover yield, stover N content, stover N uptake, and total plant N uptake. This indicates that the model was appropriate for this study.

Main Effects

Corn grain yields, grain N content and N uptake, stover yield, stover N content and N uptake, and total plant N uptake in this study were influenced significantly by N treatment (Nt), soil properties or quadrant (Q), yearly climatic variations (Y), irrigation scheduling method (I), and the previous year's irrigation scheduling method (P). Corn grain yield, stover yield, plant N content, and N uptake as affected by each main effect are shown in Table 4. Significant differences of yield means within response parameters Nt, I, P, Y, and Q were indicated in the instances where the two-way interactions of I, P, Y,

Table 3. Analysis-of-covariance summary for irrigated corn grain yields, grain N percentage, grain N uptake, stover yield, stover N percentage, stover N uptake, and total plant N uptake.

Model summary†	Grain yield‡	Grain N content	Grain N uptake	Stover yield	Stover N content	Stover N uptake	Total plant N uptake	
RSE	1060 kg ha^{-1}	0.730 g kg^{-1}	13.1 kg ha^{-1}	810 kg ha^{-1}	0.9793 g kg^{-1}	7.33 kg ha^{-1}	15.2 kg ha^{-1}	
R^2	0.91	0.86	0.91	0.81	0.89	0.84	0.90	
$F_{(90, 340)}$	36.66***	23.15***	36.26***	15.8***	29.52***	20.34***	34.28***	
Source§	df	F statistic						
β	1	2.80	9.11**	6.92**	1.36	3.76	4.403*	8.605**
Nt	5	162***	196***	223***	58.1***	101***	116***	260***
I	3	7.43***	4.75**	5.82***	5.32**	1.88	3.58*	6.23***
P	3	12.8***	5.96***	13.1***	9.42***	2.19	5.45**	14.4***
Y	5	224***	99.7***	155***	68.6***	348***	138***	94.4***
Q	3	110***	17.6***	106***	96.4***	7.10***	61.0***	128***
NtI	15	1.90*	1.30	1.34	0.502	0.556	0.556	1.1
NtP	15	0.735	1.14	0.429	0.521	1.80*	1.37	0.424
NtY	25	10.7***	3.24***	10.0***	4.49***	4.19***	2.38***	6.90***
NtQ	15	1.99*	1.60	1.32	1.15	1.28	1.36	1.52

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† RSE = residual standard error, R^2 = coefficient of multiple determination, and $F_{(90, 340)}$ = F statistic on 90 and 340 degrees of freedom.

‡ Adjusted to 15.5% moisture content, wet basis. Note: grain N content is on a dry matter basis.

§ β = covariate of spring soil test N plus applied starter fertilizer N, Nt = N treatment, I = irrigation treatment, P = previous irrigation treatment, Y = year, Q = quadrant, NtI = N \times irrigation interaction, NtP = N \times previous irrigation interaction, NtY = N \times year interaction, and NtQ = N \times quadrant interaction.

Table 4. Corn grain yield (and other response variables) means and statistical groupings for main effects.

Treatment class	Corn grain yield†	Grain N content	Grain N uptake	Stover yield	Stover N content	Stover N uptake	Total plant N uptake
	Mg ha ⁻¹	g kg ⁻¹	kg ha ⁻¹	kg ha ⁻¹	g kg ⁻¹	kg ha ⁻¹	kg ha ⁻¹
N treatment, kg N ha⁻¹ (Nt)							
0	4.93‡	10.3	44.0	3903.2	4.17	16.9	60.8
45	7.21	11.0	68.6	5158.8	4.81	25.0	93.6
90	8.22	12.0	83.3	5660.1	5.61	31.4	114.7
135	9.24	13.2	102.8	5786.7	6.62	37.5	140.3
180	9.50	13.4	107.6	6062.4	7.05	41.7	149.4
225	9.55	13.7	110.9	6037.3	7.54	44.9	155.8
Irrigation treatment (I)							
A	7.86‡	12.1a	83.5a	5262.7a	5.84a	31.0a	114.6ac
B	8.53	12.3a	90.3b	5687.6b	5.93ab	33.4b	123.8b
C	8.16	12.5b	87.6b	5505.3b	6.17b	34.6b	122.2b
D	7.88	12.2a	83.3a	5283.2a	5.92ab	32.5ab	115.8c
Previous irrigation treatment (P)							
A	7.64a§	12.2a	81.0a	5128.1a	5.85	31.0a	112.1a
B	8.11b	12.2a	85.1a	5447.6b	5.89	32.9a	118.0b
C	8.72c	12.6b	94.2b	5830.3c	6.22	35.7b	130.0c
D	7.96ab	12.2a	84.4a	5332.9ab	5.90	31.9a	116.3ab
Year (Y)							
1990	9.95‡	13.3	111.8	7181.1	5.53	40.2	152.0
1991	9.00	12.4	96.4	4759.6	6.09	29.4	125.8
1992	5.97	13.4	68.9	4703.2	4.13	20.0	88.9
1993	5.19	11.7	52.4	4776.5	10.27	50.1	102.5
1994	10.27	11.2	101.2	5545.1	5.19	30.1	131.3
1995	8.28	11.8	86.5	5642.9	4.59	27.5	114.0
Quadrant (Q)¶							
SW	9.14‡	12.5a	99.2a	6227.8a	6.05ac	37.8a	137.0a
SE	8.99	12.5a	96.2a	5993.2b	6.29a	37.8a	134.1a
NW	7.15	12.1b	74.8b	4790.8c	5.74b	28.1b	102.9b
NE	7.15	12.0b	74.6b	4727.1c	5.79bc	27.9b	102.4b

† Pairwise comparisons were done using LSMEANS values, not actual parameter estimates.

‡ Means are not compared because of statistically significant ($\alpha = 0.05$) interactions with another variable.

§ For each response parameter (corn grain yield, grain N content, etc.), means in each treatment class (Nt, I, P, Y, or Q) followed by the same letter are not significantly different at $\alpha = 0.05$.

¶ SW, southwest; SE, southeast; NW, northwest; NE, northeast.

and Q with Nt were not significant (Table 3). If there was a significant interaction, response parameter means could not be compared for that main effect. Further discussion about significant differences within interactions will follow.

With regard to corn grain yield, previous irrigation treatment (P) was the only main effect of which treatment means could be compared since the NtP interaction was not significant (Table 3). Corn grain yield varied significantly by P with a previous year's irrigation treatment of C resulting in the highest yield. The effect of P resulted in an average yield range of 1.08 Mg ha⁻¹.

Comparison of response variable means (other than grain yield due to significant interaction) for I treatments indicated that Irrigation Treatments B and C were not significantly different for all variables except grain N content and resulted in the highest values for grain N content and uptake and stover yield, N content, and N uptake. Response variable means within previous irrigation treatment (P) showed that Treatment C resulted in significantly higher values for all variables (Table 4). Treatments B and C were based on the same water balance algorithm with water applications being 20% smaller for C.

Comparison of means for grain N content and uptake and stover yield, N content, and N uptake for main effect Q showed a clear separation between the two north quadrants, NE and NW, and the two south quadrants, SE and SW (Table 4). Quadrants SE and SW had higher values for all variables. The quadrant effect was basically a soil effect, with less productive salt-affected

soils on the northern portion of the field. Lower productivity was a result of low water permeability and sodium effects on the Stirum soil and the higher salinity in the northern portion of the field [electrical conductivity (EC) = 3.0–3.5 dS m⁻¹] compared with the south (EC = 2.0–2.5 dS m⁻¹) (Fig. 1). Although it would appear that the soil type is not the same for all plots within some quadrants (Fig. 1), we maintain that it is very difficult to delineate exactly where a change in soil type actually occurs in the field. Experience has shown us that the productivity of the soil on the NE and NW quadrants was much lower than the SE and SW. This was confirmed by the statistically significant lower mean values in the north versus the south Q treatments for all variables, a result of reduced plant vigor. Lower plant N uptake may result in excess nitrate leaching and groundwater contamination, not to mention the reduced economic return due to overapplication of fertilizer. Yield potential of different areas of a field needs to be considered when making N fertilizer recommendations and may warrant variable-rate applications.

Two-Way Interactions

The interactions of Nt with the other main effects were also investigated. The two-way interactions of Nt with Y, Q, and I are shown in Tables 5, 6, and 7, respectively. The interaction of Nt with P is not shown because NtP was not significant for any of the response variables except stover N content.

Table 5. Treatment means and statistical groupings for the N × year interaction.

Year	N treatment, kg N ha ⁻¹					
	0	45	90	135	180	225
Corn grain yield†, Mg ha ⁻¹						
1990	8.49a‡	10.00b	10.03b	10.15b	10.62b	10.42b
1991	4.87a	8.91b	9.22bc	10.20cd	10.28cd	10.50d
1992	3.34a	5.07b	6.37c	6.87cd	7.32d	6.83cd
1993	3.73a	4.73b	5.64c	5.61c	5.70c	5.73c
1994	5.99a	8.52b	10.09c	12.23d	12.42d	12.35d
1995	3.14a	6.06b	7.95c	10.38d	10.66de	11.47e
Grain N content, g kg ⁻¹						
1990	12.0a	12.7b	12.7a	13.8b	14.0b	14.5b
1991	9.8a	11.1b	12.3c	13.6d	13.6d	13.8d
1992	11.7a	11.8a	13.3b	14.5c	14.5c	14.5c
1993	9.7a	10.6b	12.0c	12.4cd	12.5cd	12.9d
1994	8.7a	9.7b	10.9c	12.2d	12.8d	12.7d
1995	10.2a	10.3a	10.9b	12.5c	12.8c	13.9d
Grain N uptake, kg ha ⁻¹						
1990	85.6a	105.0b	107.3b	118.4bc	126.3c	127.9c
1991	40.5a	84.6b	95.1b	116.9c	118.6c	122.8c
1992	33.3a	50.9b	71.7c	84.6d	89.5d	83.6d
1993	31.9a	43.2b	57.3c	59.1c	60.5c	62.5c
1994	44.9a	72.7b	94.0c	126.7d	135.0d	133.8d
1995	27.8a	55.0b	74.4c	111.0d	115.9d	134.7e
Stover yield, kg ha ⁻¹						
1990	7155.3a	7075.1a	7194.5a	6943.0a	7594.3a	7124.4a
1991	3100.4a	4520.3b	4935.0bc	5266.0bc	5589.6c	5146.2bc
1992	2395.4a	4352.6b	5177.4c	5315.4c	5588.5c	5390.1c
1993	3615.2a	4685.2b	5229.9b	4911.9b	5043.1b	5173.5b
1994	4356.6a	5134.2b	5292.8bc	5936.8cd	6181.3d	6369.0d
1995	2796.3a	5185.2b	6131.1c	6346.8c	6377.3cd	7020.5d
Stover N content, g kg ⁻¹						
1990	4.29a	5.12ab	4.88ab	5.72bc	6.20cd	7.00d
1991	3.83a	4.58a	5.76b	6.88c	7.51cd	7.97d
1992	3.17a	3.13a	3.72a	4.52b	4.83bc	5.38c
1993	6.83a	8.42b	10.38c	11.88d	12.17d	11.945d
1994	3.36a	4.07a	4.99b	5.93c	6.29c	6.50c
1995	3.56a	3.52a	3.91a	4.81b	5.29b	6.44c
Stover N uptake, kg ha ⁻¹						
1990	30.5a	36.1ab	36.1ab	41.0bc	47.2cd	50.3d
1991	11.4a	19.7b	27.4b	35.7c	41.2c	41.0c
1992	7.9a	13.6ab	19.2bc	23.9cd	26.9d	28.6d
1993	25.7a	39.9b	53.9c	58.2cd	61.2d	61.8d
1994	15.0a	21.6b	27.0b	35.4c	39.6cd	42.1d
1995	10.7a	19.3b	24.6b	30.6c	34.3c	45.7d
Total plant N uptake, kg ha ⁻¹						
1990	116.2a	141.1b	143.4bc	159.4cd	173.5de	178.3e
1991	51.8a	104.3b	122.6c	152.7d	159.8d	163.8d
1992	41.2a	64.5b	90.9c	108.4d	116.4d	112.2d
1993	57.5a	83.1b	111.2c	117.3c	121.7c	124.2c
1994	59.8a	94.3b	121.0c	162.1d	174.6d	175.9d
1995	38.6a	74.3b	99.0c	141.6d	150.2d	180.4e

† Pairwise comparisons were done using LSMEANS values, not actual parameter estimates.

‡ For each response parameter (corn grain yield, grain N content, etc.), means within each row (year) followed by the same letter are not statistically different at $\alpha = 0.05$.

Table 6. Treatment means and statistical groupings for the N × quadrant (NtQ) interaction.

Quadrant†	N treatment, kg N ha ⁻¹					
	0	45	90	135	180	225
Corn grain yield‡§, Mg ha ⁻¹						
SW	5.89a¶	8.54b	9.34c	10.22d	10.51d	10.34d
SE	6.34a	8.48b	9.10bc	9.76cd	10.21d	10.03d
NW	3.70a	6.08b	7.09c	8.39d	8.96d	8.67d
NE	3.76a	5.75b	7.33c	8.59d	8.33de	9.16df

† SW, southwest; SE, southeast; NW, northwest; NE, northeast.

‡ Pairwise comparisons were done using LSMEANS values, not actual parameter estimates.

§ The NtQ interaction was not significant for grain N content, grain N uptake, stover yield, stover N content, stover N uptake, and total plant N uptake.

¶ Means within each row (quadrant) followed by the same letter are not statistically different at $\alpha = 0.05$.

Table 7. Treatment means and statistical groupings for the N × irrigation treatment (NtI) interaction.

Irrigation treatment	N treatment, kg N ha ⁻¹					
	0	45	90	135	180	225
Corn grain yield†‡, Mg ha ⁻¹						
A	4.28a§	6.52b	7.80c	9.40d	9.56d	9.58d
B	5.42a	7.85b	8.71c	9.57d	9.86d	9.75d
C	5.19a	7.91b	8.27bc	9.20d	8.86cd	9.54d
D	4.80a	6.57b	8.09c	8.79cd	9.72e	9.33de

† Pairwise comparisons were done using LSMEANS values, not actual parameter estimates.

‡ The NtI interaction was not significant for grain N content, grain N uptake, stover yield, stover N content, stover N uptake, and total plant N uptake.

§ Means within each row (irrigation treatment) followed by the same letter are not statistically different at $\alpha = 0.05$.

There was a significant interaction between the Nt and Y treatments. For the NtY interaction (Table 5), the grain and stover yield increased significantly with increased Nt up to 135 kg ha⁻¹ in most years, with grain yield increases observed only to Nt of 45 and 90 kg ha⁻¹ in 1990 and 1993, respectively. There were only slight increases in yield when the Nt was increased to 180 kg ha⁻¹. However, N accumulation in the plant did show some increases at higher N rates. There was no significant difference between the yields at 135 and 180 or 225 kg N ha⁻¹ for any year except 1995.

In 1990, the first year of the study, grain and stover yield had the least response to additional applied Nt, and grain yield did not vary significantly for Nt higher than 45 kg ha⁻¹. This was caused by increased availability of soil N resulting from mineralization from the initiation of irrigation in 1989 (Casey et al., 2002). A similar lack of response to fertilizer N was observed by Onken et al. (1985) during a year when the soil had high residual N. The greatest responses to Nt were observed in 1991, 1994, and 1995, which were normal growing seasons (CGDD = 1245, 1255, and 1198°C, respectively). Yield response to Nt was less in 1992 and 1993, which were cool, wet years and had the lowest CGDD (1092 and 982°C, respectively). Yield was highly correlated with CGDD from emergence to harvest ($r = 0.94$) and was dramatically lower in 1992 and 1993. Yields in 1992 were depressed as a result of cooler-than-normal temperatures while 1993 yields were low because of cool weather and a frost in September before the crop matured (Derby et al., 2004). Interestingly, stover N content and stover N uptake were highest across all Nt in 1993. Although early-season temperature was a very important component of the yearly weather effect, Y was likely a combination of many factors. Derby et al. (2004) considered both temperature and solar radiation when calculating CGDD and ET values for midseason N fertility management. Variable precipitation patterns would have also affected crop growth because, even though the site was irrigated, the irrigation regimes were designed to allow soil moisture deficits, so precipitation variation was still an important factor in determining corn yield. This analysis indicated that interannual variability caused by adverse weather conditions can result in substantial yield reductions by shortening the growing season and preventing maturity. Hence, the use of a static yield response curve for N recommendations that averages over interannual variability could result in overfertilization because of unrealized yield goals in unseasonably cool years. If weather conditions warrant, reduced early-season fertilization with a midseason adjustment may be an alternative to current fertilizer management schemes, and Derby et al. (2004) provide a model to adjust in-season rates based on CGDD or ET for the Northern Great Plains.

Although there was definite separation in yields between the north and south portions of the field (NtQ interaction), maximum yield was also obtained at the 135 to 180 kg N ha⁻¹ treatment range with no significant difference in yields between those rates within each quadrant (Table 6). Although response of yield to Nt was

basically identical for the quadrants, it was the magnitude of the response that differed between the south and north quadrants. As discussed above, the SW quadrant had the highest yields overall, and the interaction shows that the yield increased significantly until an Nt rate of 135 kg N ha⁻¹. In comparison, the significant yield increases for the NW quadrant were also observed until an Nt rate of 135 kg ha⁻¹, but the yield was 1.83 Mg ha⁻¹ less than on the SW quadrant.

Mean yields for the N treatment–irrigation treatment interaction (NtI) are shown in Table 7. Yield was again near maximum at 135 kg ha⁻¹ with no significant difference between the 135 and 180 kg ha⁻¹ Nt rates except for Irrigation Treatment D. The NtI interaction showed that no significant increases in grain yields were measured above Nt rates of 135 kg N ha⁻¹, except for D where the maximum yield was obtained at 180 kg N ha⁻¹. Irrigation Treatment B had the highest yields across all Nt rates. This indicated that Irrigation B may have been better suited to providing sufficient amounts of water during critical periods of corn growth when the rate of nutrient uptake was also increasing. The NtP interaction was not significant for any of the response variables; hence, pair-wise comparisons within previous irrigation scheduling methods are not presented.

Optimized Nitrogen Rates and Recommendations

The discussion in this section focuses on Ntot rate at maximum corn grain yields for Y, Q, and I. The Ntot rate for these calculations and yield response curves is the sum of soil nitrate N, starter N, and the postemergence Nt. In general, yield response to Ntot followed a quadratic-plus-plateau relationship (Eq. [2] and [3]). This typical yield response to applied N, often referred to as the Law of Diminishing Returns (Willcox, 1949), has been reported extensively (Cerrato and Blackmer, 1990; Dahnke and Olson, 1990; Vanotti and Bundy, 1994; Schlegel and Havlin, 1995). The quadratic-plus-plateau nonlinear models for each year, quadrant, and irrigation treatment indicated that there were wide ranges of Ntot rates that optimized yield (Fig. 2). The average optimized Ntot rate for all observations for the study period was 295 kg N ha⁻¹. The range of optimized Ntot rates between years (Fig. 2a) was from 232 kg ha⁻¹ in 1993 to 296 kg ha⁻¹ in 1994. Note that the low-yielding years, 1992 and 1993, did not vary much from the other years in terms of optimized Ntot rate.

The highest-yielding quadrants (SE and SW) had the lowest average optimized Ntot rates of 291 kg ha⁻¹ while the lowest-yielding quadrants (NE and NW) had the highest average optimized Ntot rate of 334 kg ha⁻¹ (Fig. 2b). Although the maximum yields varied little between irrigation treatments, Irrigation Treatment D had a higher optimized Ntot rate than the other treatments even though all irrigation treatments had similar maximum yields (Fig. 2c).

To reduce fertilizer N inputs while maintaining near maximum yields, we can consider N application for 98% of maximum yield (Dahnke and Olson, 1990). For example, the optimized Ntot rate considering all observations

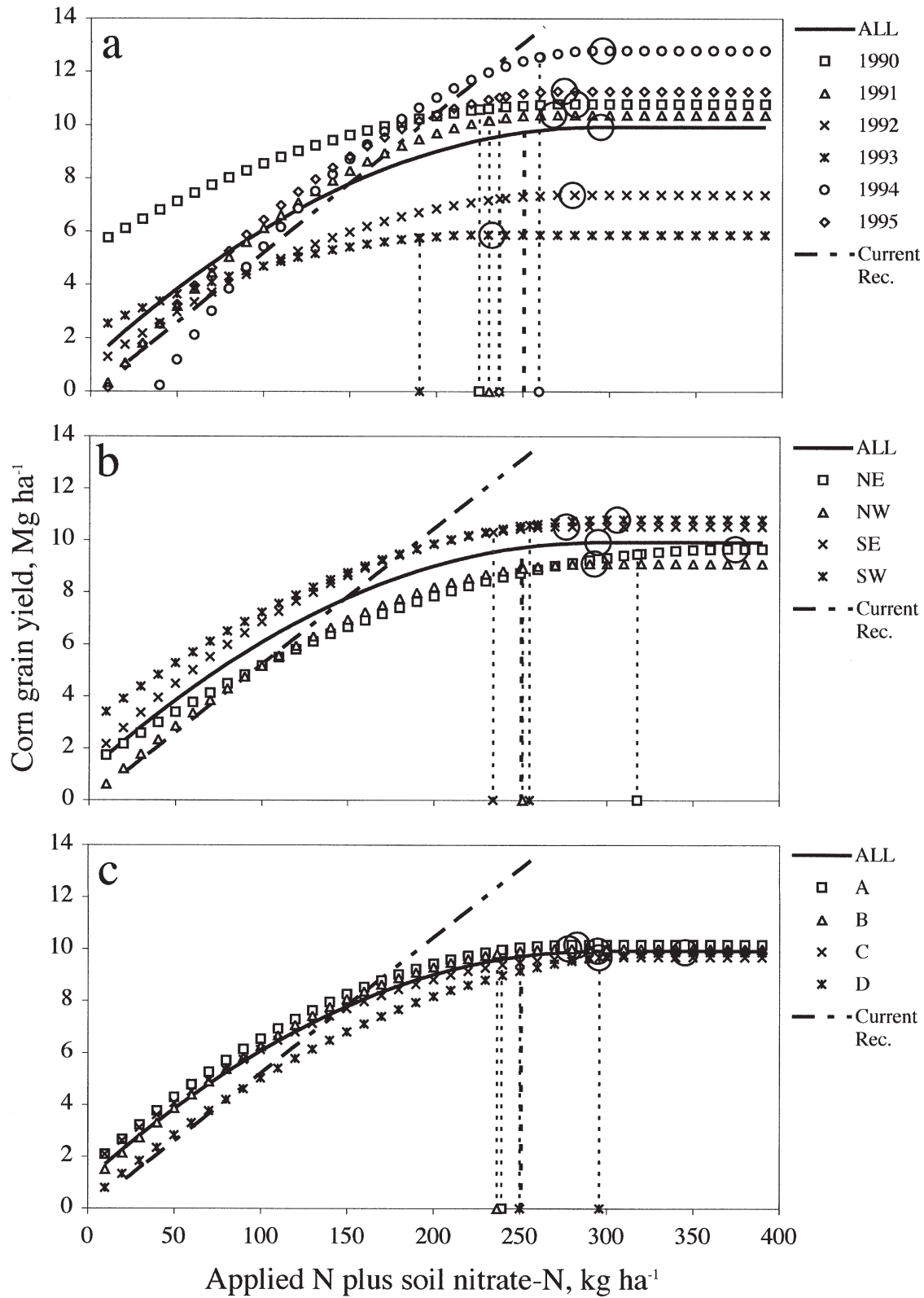


Fig. 2. Quadratic-plus-plateau response curves for (a) years, (b) quadrants, and (c) irrigation treatments. Optimized total N rates at 98% of maximum yield are indicated by vertical dashed lines. Maximum yields are indicated by large circles. Heavy solid and dashed lines are for all yield observations over the course of the study. The current North Dakota State University recommendation (dashed-dotted line) is based on 21.4 kg of N per Mg of corn grain yield, which is equivalent to 1.2 lb of N per standard (56 lb) bushel of corn.

Table 8. Comparison of optimized N rates at maximum yields to N rates at 98% of maximum yield and corresponding change in per-hectare income when fertilizing for 98% of maximum yield.

Variable†	Optimized N rate‡	Yield at optimized N	98% of optimized yield	N at 98% yield	N savings at 98% yield	Change in per-hectare income
	kg ha ⁻¹	Mg ha ⁻¹		kg ha ⁻¹		US\$
All	295	9.93	9.73	251	44	\$8.80
Year = 1990	281	10.78	10.57	225	56	\$13.87
Year = 1991	268	10.38	10.18	231	37	\$4.07
Year = 1992	279	7.37	7.22	237	42	\$11.50
Year = 1993	232	5.87	5.75	190	42	\$13.76
Year = 1994	296	12.80	12.54	260	36	-\$0.02
Year = 1995	274	11.27	11.04	236	38	\$2.96
Quadrant = NE	374	9.66	9.47	318	56	\$16.09
Quadrant = NW	293	9.11	8.93	251	42	\$8.50
Quadrant = SE	277	10.53	10.32	234	43	\$6.70
Quadrant = SW	306	10.80	10.59	256	50	\$10.83
Irrigation = A	283	10.17	9.97	240	43	\$7.82
Irrigation = B	278	10.03	9.83	237	41	\$6.90
Irrigation = C	296	9.67	9.48	250	46	\$9.92
Irrigation = D	345	9.88	9.68	296	49	\$11.70

† All = all observations for the study period averaged over three replicates by N treatment; NE = northeast; NW = northwest; SE = southeast; SW = southwest.

‡ Includes soil N, N applied as starter, and postemergence applied N.

for the study was 295 kg N ha⁻¹ at the maximum yield of 9.93 Mg ha⁻¹ (Table 8). Compare that to a yield of 9.73 Mg ha⁻¹ (98% of 9.93 Mg ha⁻¹) where the corresponding N_{tot} rate for all observations in Fig. 2 is 251 kg ha⁻¹. That is a 15% reduction in applied N for a 2% reduction in yield. Economically, a producer would have a net increase of approximately \$8.80 ha⁻¹ assuming a corn price of \$78.57 Mg⁻¹ (\$2.00 bu⁻¹) and fertilizer N cost of \$0.55 kg⁻¹ (\$0.25 lb⁻¹). An even higher return could be calculated if application costs are considered. Environmentally, the difference of 44 kg N ha⁻¹ would not be available for surface or groundwater contamination.

Current N recommendations are adequate some years because they were developed over many site-years. This is confirmed by the agreement of the current recommendation to the yield response curve for 1994 in Fig. 2a. The current recommendation line [0.0214 kg of N per kg of corn grain yield, which is equivalent to 1.2 lb N per standard (56 lb) bushel of corn] does come close to the point of 98% of maximum yield for 1994. However, the current recommendation fails by over-recommending N in cool, wet years (1992 and 1993) when there is a need to optimize management to avoid environmental degradation. The comparisons are similar for quadrants (Fig. 2b) and irrigation treatments (Fig. 2c) where the current recommendation fits the response curves adequately at lower yields but would result in overfertilization at higher yield goals. Given the current environmental issues, we should not continue to recommend the highest N rates every year assuming the growing conditions will allow for maximum yield potential.

It is clear that there was not simply one optimized N_{tot} rate for maximum corn yield but a range, depending on weather conditions for a given year, timely water applications, and soil properties. Research of this nature provides information that can be used to develop a more robust fertilizer N recommendation scheme that takes into account yearly weather (Derby et al., 2004), soil properties, and soil moisture availability. It may not be environmentally wise to continue N recommendations based on a static yield response curve and assuming

that maximum yield will be achieved every year. Based on readily available information such as early- to mid-season CGDD and soil properties, producers can modify their practices to maximize profits in good years and minimize environmental degradation in poor years.

CONCLUSIONS

Nitrogen fertility has a major role in maintaining maximum corn grain yields; however, a number of other factors limit yields even when N fertility is optimal. In this study of corn yield in the Northern Great Plains, USA, postemergence N rates greater than 135 kg N ha⁻¹ did not significantly increase yield. Based on quadratic response curves, 98% of maximum yield was realized at a N_{tot} rate of 251 kg N ha⁻¹ over the entire study period but ranged between 190 and 318 kg N ha⁻¹ depending on year, quadrant, and irrigation scheduling method. Areas of the field with sodium- and salt-affected soils had significantly lower productivity. Similarly, cool, wet years had lower productivity than years with warm growing seasons. Timely water applications scheduled using a water balance algorithm and in-season soil moisture corrections also maintained high yields compared with other irrigation scheduling methods. Research of this nature should be used to modify existing fertilizer recommendation methods to include adjustments for low-productivity soil, proper irrigation management, and midseason adjustments based on current growing season conditions to minimize costs and water quality impacts.

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