Expl Agric. (2013), volume 49 (1), pp. 3–18 © *Cambridge University Press 2012*
doi:10.1017/S0014479712000981

MAIZE GRAIN YIELD RESPONSE TO THE DISTANCE NITROGEN IS PLACED AWAY FROM THE ROW

By E. RUTTO†,‡, J. P. VOSSENKEMPER§, J. KELLY†, B. K. CHIM† *and* W. R. RAUN†

†*Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078-6010, USA and* §*Pioneer Hi-Bred, 12937 S US Hwy 281, Doniphan, NE 68832, USA*

(*Accepted 5 October 2012; First published online 16 November 2012*)

SUMMARY

Correct placement of side dress nitrogen (N) fertilizer could increase nitrogen use efficiency (NUE) and maize yield production. Field studies were established to evaluate application of midseason (V8 to V10), variable liquid urea ammonia nitrate (28%), N rates (0, 45, 90 and 134 kg N ha^{-1}) and different application distances (0, 10, 20 and 30 cm) away from the maize row on grain yield and NUE at Haskell and Hennessey in 2009, Efaw in 2010 and Lake Carl Blackwell, Oklahoma in 2009 and 2010. A randomized complete block design with three replications was used throughout the study. Results indicated that maize grain yield in sites with adequate rainfall increased significantly ($p < 0.05$) with N rate, and poor N response was recorded in sites with low rainfall. Across sites and seasons, varying side dress N application distance away from the maize row did not significantly ($p < 0.05$) influence maize grain yield and NUE even with no prep-plant applied. Environments with adequate rainfall distribution had better maize grain yields when high side dress N rates (90 and 134 kg N ha^{-1}) were applied 0 to 10 cm, and a higher NUE when 45 kg N ha^{-1} was applied 0 to 20 cm away from the maize row. For low N rates (45 kg N ha^{-1}), increased maize grain yield and NUE were achieved when side dress N was applied 0 to 20 cm away from the maize row at locations with low rainfall distribution. Across sites and seasons, increasing side dress N to 134 kg N ha^{-1} contributed to a general decline in mean NUE to as low as 4%, 35%, 10%, 51% at Hennessey, Efaw, LCB (2009) and LCB (2010) respectively.

INTRODUCTION

Nitrogen (N) remains the most limiting and crucial plant nutrient in crop production since the establishment of its essentiality in 1872 by G. K. Rutherford, a chemist from Scotland (Fageria *et al.*, 1997). World food production has increased since 1950s with the introduction and use of inorganic fertilizers, especially N (Fageria and Baligar, 2003; Follett, 2001). However, excess application of N has been demonstrated to contribute to average leaching losses between 25% and 50% of N applied in some cropping systems (McNeal and Pratt, 1978), which ends up in surface and ground water.

High levels of nutrients, especially nitrates and phosphates, in water bodies have led to eutrophication, contributing to excess plant growth, which depletes oxygen in the water. Other pathways where N is lost include crop harvest (Foth and Ellis, 1988; Kuangfei *et al.*, 1999), plant loss (Harper and Sharp, 1995; Kanampiu *et al.*, 1997), volatilization (Xing and Zhu, 2000), denitrification (Davidson, 1992; De Klein and Van Logtestijn, 1994) and surface runoff (Yu-Hua *et al.*, 2007).

‡Corresponding author. Email: emily.rutto@okstate.edu

Corn only takes up limited amounts of N prior to the four-leaf stage and starts accumulating substantial N 40 days after emergence (Sawyer *et al.*, 2006). In maize, this corresponds to V8 to V10 maize growth stages. At V8 to V10, macro-nutrient and micronutrient deficiencies appear the most and maize begins a steady and rapid increase in both nutrients and dry matter accumulation.

Nitrate N (NO_3^--N) is the most mobile N source in the soil and mainly taken up by crops through mass flow and diffusion (Barber, 1995). Available soil moisture and diffusion potential plays a great role in NO_3^--N mobility and subsequent uptake by crops. Consequently, high moisture and diffusion potentials can result in an increase in N movement in the soil (NaNagara *et al.*, 1975). Available soil moisture and how far N fertilizer is placed away from the row will be the determining factors for crop N uptake. For example, where moisture is a limiting factor in arid to semi-arid regions, midseason N application (V8 to V10) needs to be synchronized with correct application distance to enhance uptake of applied N.

Low moisture regimes in some environments can hinder N movement in the soil. Inadequate soil moisture can also affect physiological development of maize by hindering the development of the roots system (Shoup and Janssen, 2009). Roots system plays a crucial role in the uptake of water and mineral nutrients by plants (Gregory, 2006). In corn, the fine roots are the major sites of water and nutrients uptake into mature root systems (Varney and Canny, 1993), and these are concentrated at the basal region of a growing maize plant. As a result, through fine branch roots, substantial nitrate uptakes have been found in basal regions of axile roots of mature plants in the soil (Reidenbach and Horst, 1997). These findings suggest that planting closer to nitrogen bands can enhance the uptake of N by the crops with a poorly developed roots system.

Studies conducted by Edmonds (2007) on midseason application of N applied to every other row indicated that rows that did not have midseason N application had lower yields and did not benefit from midseason N application of the adjacent row. This finding demonstrated that in an environment where moisture is limiting, mass flow might not be enough to move midseason applied N to great distances in a single growing season (76 cm distance between rows). Elsewhere, Vyn and West (2008) established that planting maize using real-time kinematics (RTK) 13 cm away from the pre-plant band of urea ammonia nitrate (UAN) increased yields. Their study showed that maize planted directly over the 10 cm deep band had a higher N concentration, although in most cases with lower yields. Low yields could have been due to local toxicity from direct contact between the seed and fertilizer at planting. These findings identified the need for continued work in N placement distance from the maize row and how it impacts maize grain yield and nitrogen use efficiency (NUE).

OBJECTIVES

The objective of these field experiments was to evaluate the effect of side dress N fertilizer application rates (0, 45, 90 and 134 kg N ha^{-1}) and application distance from the maize row (0, 10, 20 and 30 cm) on maize grain yield and NUE.

MATERIALS AND METHODS

Site description

Field experiments were established in 2009 and 2010 at Haskell, Hennessey, Efaw and Lake Carl Blackwell (LCB), Oklahoma, USA. The soil at Haskell is a Taloka silt loam (fine, mixed, active, thermic Mollic Albaqualfs) and at Hennessey, it is a Bethany silt loam (fine, mixed, superactive, thermic Pachic Paleustolls). The LCB site is predominantly characterized by Pulaski fine sandy loam (coarse-loamy, mixed, superactive, non-acid, thermic Udic Ustifluvent) and Port silt loam (fine-silty, mixed, superactive, thermic Cumulic Haplustolls). The Efaw experimental site is composed of mainly Pulaski fine sandy loam (coarse-loamy, mixed, superactive, non-acid, thermic Udic Ustifluvents) and Grainola silty clay loam (fine, mixed, active, thermic Udertic Haplustalfs). The climatic conditions for each study site during 2009 and 2010 cropping seasons are presented in Figures 1 and 2.

Experiment and management

Before planting each experiment, soil samples (0–15 cm) were collected for site characterization. From each plot 15 cores were collected, mixed well and a composite sample obtained. Samples were dried and passed through a 2 mm sieve. Soil pH was determined by adding 15 ml of water (H_2O) into 15 g of soil, shaken well and left to equilibrate for 1 hour. The reading was then taken using a pH meter. Nitrate N was determined by adding 25 ml of calcium sulfate into 10 g soil. The suspension was then shaken for 30 minutes, filtered and analysed on flow injection analyser using

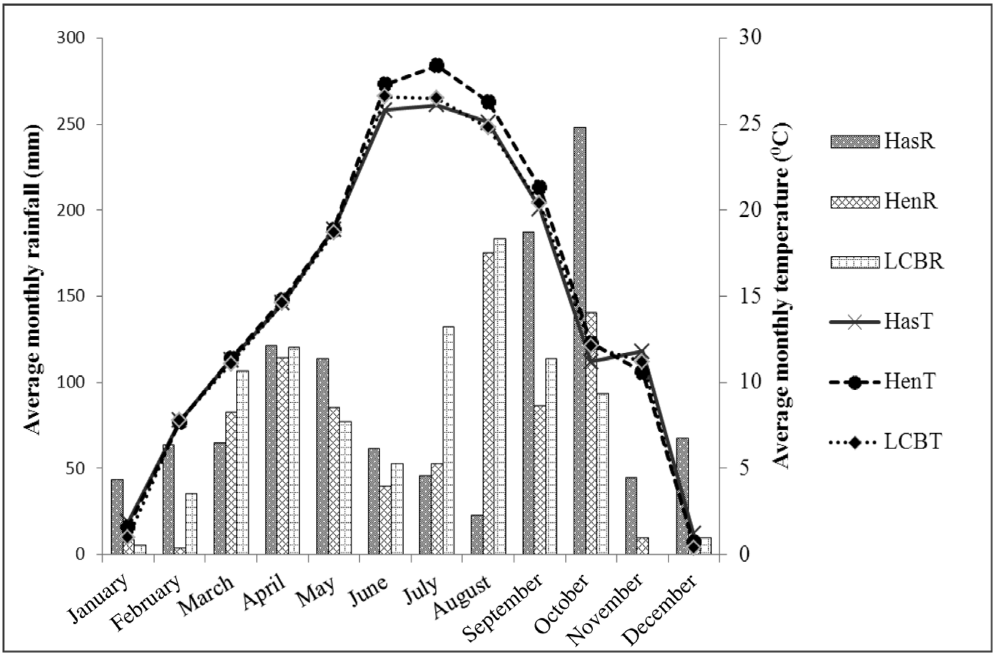

Figure 1. Rainfall and temperature distribution at Haskell, Hennessey and LCB, Oklahoma, 2009.

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

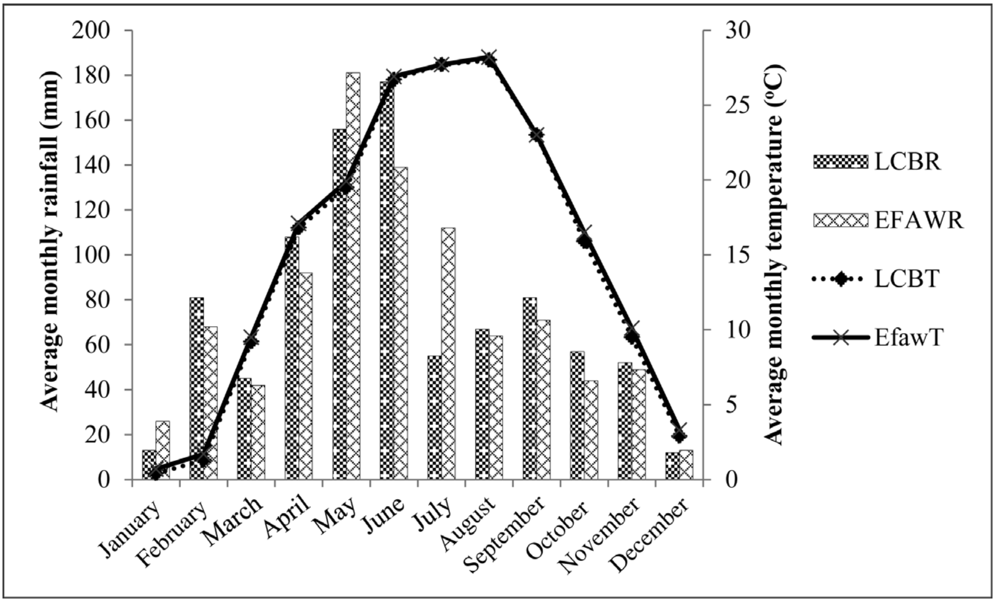

Figure 2. Rainfall and temperature distribution at LCB and Efaw, Oklahoma, 2010.

cadmium reduction chemistry. Ammonium N was determine by adding 15 ml of 2 N KCL solution into already weighed 1.5 g of soil, shaken for 15 minutes on oscillating shaker and filtered immediately. Into a glass tube, 5 ml of the filtrate was pipetted and analysed by flow injection for ammonium N. Total N and percentage carbon was determined using dry combustion LECO analyser. The available potassium (K) and phosphorus (P) was analysed by adding 20 ml Mehlich-3 into 2 g, 2 mm dry sieved soil, shaken for 5 minutes, filtered and analysed on Inductively Coupled Plasma (ICP). The results for the analysis are presented in Table 1.

Table 1. Soil chemical properties determined from initial soil samples (0–15 cm) at four locations, Oklahoma.

Site	Year	pH	Total N	Organic C	NH_4-N	NO_3^--N	P	K
			g kg $^{-1}$		mg kg $^{-1}$			
Haskell	2009	4.6	0.6	3.8	21	79	32	75
Hennessey	2009	5.3	1.0	7.6	21	101	35	160
Lake Carl Blackwell	2009	5.9	1.0	3.2	na*	11	22	138
Lake Carl Blackwell	2010	6.1	0.8	3.8	4	2	6	105
Efaw	2010	6.3	1.0	5.2	2	2	25	120

PH: 1:1 soil:water; K and P – Mehlich-3; NH_4-N and NO_3^--N M KCL, total N and organic C-dry combustion.
*Data were not determined.

Throughout, a randomized complete block design with three replications was used. Each plot size was 20 m long and four rows wide with row spacing of 76 cm. Depending on the maize variety used, planting rate varied for each site as indicated in Table 3. Treatments for each plot for all locations and years were administered according to

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

the treatment structure (Table 2). Planting was done using a John Deere Maxemerge 2, four-row vacuum planter. Experiments were rain-fed but experiments at the LCB site were irrigated (15 cm depth of water twice a week) when needed to supplement rainfall. Additional information about the experiments is presented in Table 3.

Table 2. Treatment structure and description of the trials conducted at Haskell, Hennessey, Lake Carl Blackwell and Efaw, Oklahoma, 2009–2010.

		Side dress N application	
Treatment	Prep-plant N (kg ha^{-1})	N rate (kg N ha^{-1})*	Placement distance (cm)†
1	0	0	0
2	0	45	0
3	0	45	10
4	0	45	20
5	0	45	30
6	45	45	0
7	45	45	10
8	45	45	20
9	45	45	30
10	45	90	0
11	45	90	10
12	45	90	20
13	45	90	30
14	45	134	0
15	45	134	10
16	45	134	20
17	45	134	30

*Midseason N was applied between V8 and V10 maize growth stages.
†A stream of urea ammonium nitrate (UAN) was applied at varying distances away from the maize row.

Table 3. Field trial information for all the sites, 2009–2010.

				Dates		
Site	Year	Variety	Planting rate (plants ha^{-1})	Planting	Side dress application	Harvest
Haskell	2009	DeKalb DKC 52–59	62,000	28 May 2009	9 July 2009	21 October 2009
Hennessey	2009	DeKalb DKC 52–59	62,000	22 April 2009	18 June 2009	26 August 2009
Lake Carl Blackwell	2009	DeKalb DKC 52–59	86,000	20 May 2009	8 July 2009	15 October 2009
Lake Carl Blackwell	2010	DeKalb DKC 52–59	86,000	28 April 2010	24 June 2010	7 September 2010
Efaw	2010	DeKalb DKC 52–59	62,000	28 April 2010	24 June 2010	24 August 2010

At planting, treatments 2 through 5 did not receive any prep-plant N (Table 2). The objective of these four treatments was to establish how varying placement distance of side dress N away from the maize row was going to affect grain yields and NUE, only at low N rate (45 kg N ha^{-1}) and with 0 kg N ha^{-1} prep-plant. Past researches have established that split application of N fertilizer leads to increased NUE (Martin *et al.*, 1994; Ritter *et al.*, 1993; Westermann and Crothers, 1993). Therefore, treatments 6 through 17 received pre-plant UAN (28% N) fertilizer at 45 kg N ha^{-1} and liquid

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

UAN side dress N fertilizer applied to the soil surface in a continuous stream at rates of 45, 90 and 134 kg N ha^{-1} at 0, 10, 20 and 30 cm placement distance away from the maize row.

At maturity, the two middle rows of each plot were harvested using a Massey Ferguson 8XP self-propelled, which was equipped with an automated weighing system (HarvestMaster Inc, 1994). Grain yields for all the treatments were calculated and expressed at 15.5% moisture levels.

Data management and analysis

Grain yield data obtained from all locations and years were separately analysed using the GLM procedure using SAS version 9.1 (SAS Institute, 2003) to determine treatment effects. Means were separated using Fishers-protected LSD and non-orthogonal, single-degree-of-freedom contrasts. NUE of the applied nutrients was calculated using the difference method (Varvel and Peterson, 1990) described below:

Percentage NUE (% NUE) = ((NF) – (NC)/R) × 100,

where

NF = total N uptake in maize grain yield from N fertilized plots;
NC = total N uptake in maize grain yield from unfertilized plots;
R = rate of fertilizer N applied.

RESULTS

Grain Yield

Grain yields were obtained for LCB in 2009 and 2010. In 2009 results indicated that N rate, application distance away from maize row (with or without prep-plant) and interaction between the two factors did not significantly ($p < 0.05$) affect maize grain yield (Table 4). In addition, treatments with 0 kg N ha^{-1} prep-plant and 45 kg N ha^{-1} side dress N did not record significantly ($p < 0.05$) different maize grain yields from those that received 45 kg N ha^{-1} prep-plant and 45, 90 or 134 kg N ha^{-1} side dress N. However, better maize grain yield was obtained when 45 kg N ha^{-1} prep-plant and 90 or 134 kg N ha^{-1} side dress was applied. Varying side dress N application distance of low side dress N rate (45 kg N ha^{-1}) showed inconsistent results with prep-plant N (45 kg N ha^{-1}) applied (Figure 3). Applying 90 and 134 kg N ha^{-1} side dress N at 0 and 10 cm away from the row resulted to high maize grain yield ranging from 1816 to 2265 kg ha^{-1} (Figure 3 and Table 4). Further increase of the application distance away from the maize row led to a decline in maize grain yield.

In 2010, there was a significant ($p < 0.0001$) effect of treatment on maize grain yield (Table 4). Treatments 2 through 17 resulted to higher maize grain yield, compared with that of the control (treatment 1). Treatments that received 0 kg N ha^{-1} prep-plant and 45 kg N ha^{-1} side dress N resulted to low maize grain yield, compared with those that received prep-plant N (45 kg N ha^{-1}). At 0 kg N ha^{-1} prep-plant and 45 kg N ha^{-1} side dress N, maize grain yields consistently reduced with increase in side dress N

Table 4. Grain yield means as affected by placement distance away from the maize row of side dress N application in 2009 and 2010 at Haskell, Hennessey, Efaw and Lake Carl Blackwell, Oklahoma.

				Mean grain yield (kg ha^{-1})				
				2009			2010	
Treatment	Prep-plant N (kg ha^{-1})	Side dress N (kg N ha^{-1})	Side dress N placement distance (cm)	Haskell	Hennessey	LCB	Efaw	LCB
1.	0	0	0	6247	516	1575	3761	2032
2.	0	45	0	6137	1362	2138	5413	4872
3.	0	45	10	5580	1117	1472	6960	3211
4.	0	45	20	5258	122	1451	6634	3226
5.	0	45	30	6138	1194	1836	5316	2554
6.	45	45	0	6429	1435	1562	7498	4552
7.	45	45	10	6603	1637	1440	6655	5960
8.	45	45	20	6441	1077	937	7446	6217
9.	45	45	30	4705	611	1803	6620	5450
10.	45	90	0	5589	1031	1816	8014	7086
11.	45	90	10	5033	668	1917	8086	8221
12.	45	90	20	4753	1217	1792	7203	6272
13.	45	90	30	6703	880	1635	6409	7796
14.	45	134	0	4590	1232	2265	8145	7871
15.	45	134	10	5114	928	2098	7114	8038
16.	45	134	20	7106	914	1589	7556	7193
17.	45	134	30	5599	1531	1570	7402	7302
SED§				**1130**	**374**	**407**	**899**	**855**
Contrast								
1 vs (2, 3, 4, 5)				ns	ns	ns	*	ns
1 vs (6, 7, 8, 9)				ns	†	ns	***	***
1 vs (10, 11, 12, 13)				ns	ns	ns	***	***
1 vs (14, 15, 16, 17)				ns	†	ns	***	***
(2, 3, 4, 5) vs (6, 7, 8, 9)				ns	ns	ns	*	***
(2, 3, 4, 5) vs (10, 11, 12, 13)				ns	ns	ns	**	***
(2, 3, 4, 5) vs (14, 15, 16, 17)				ns	ns	ns	***	***
(6, 7, 8, 9) vs (10, 11, 12, 13)				ns	ns	†	ns	***
(6, 7, 8, 9) vs (14, 15, 16, 17)				ns	ns	†	ns	***
(10, 11, 12, 13) vs (14, 15, 16, 17)				ns	ns	ns	ns	ns

†, *, **, ***: Significant at the 0.1, 0.05, 0.01 and 0.001 probability levels respectively.
§SED: Standard error of the difference between two equally replicated means.

application distance away from the maize row (Table 4). The maize grain yield ranged from 4872 kg ha^{-1} (0 cm application distance) to 2554 kg ha^{-1}(30 cm application distance). Treatments that received 45 kg N ha^{-1} prep-plant showed an overall linear increase in maize grain yields with applied side dress N (Figure 4). Application of 45 kg N ha^{-1} prep-plant followed by 90 or 134 kg N ha^{-1} side dress N, applied 10 cm away from the maize row, gave the highest maize grain yields of 8221 kg ha^{-1} and 8038 kg ha^{-1} respectively (Table 4). But generally, varying the application distance did not contribute to any significant differences in maize grain yields ($p < 0.05$) regardless of side dress N rate applied. The interaction between the two factors was also not significant ($p > 0.05$).

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

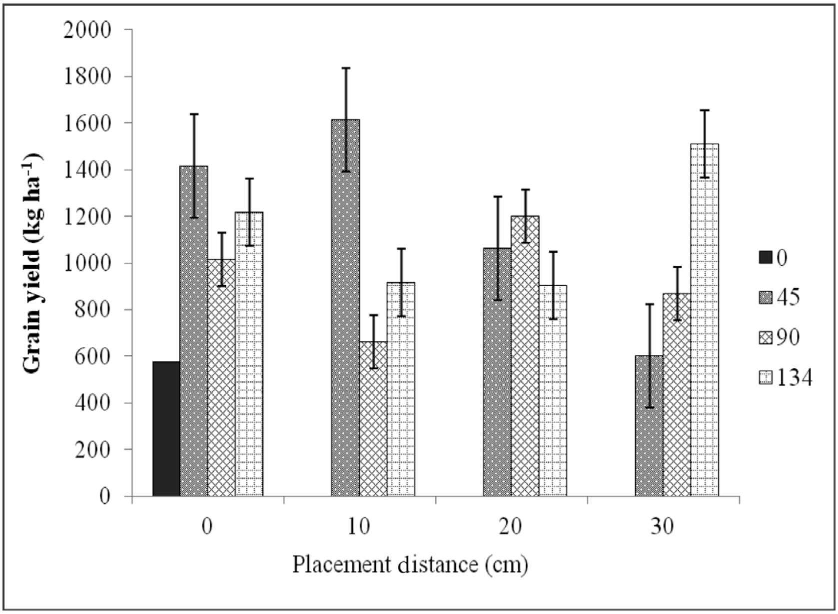

Figure 3. Grain yield as affected by side dress N at 0, 45, 90 and 134 kg N ha^{-1} applied at 0, 10, 20 and 30 cm away from the maize row, LCB, Oklahoma, 2009.

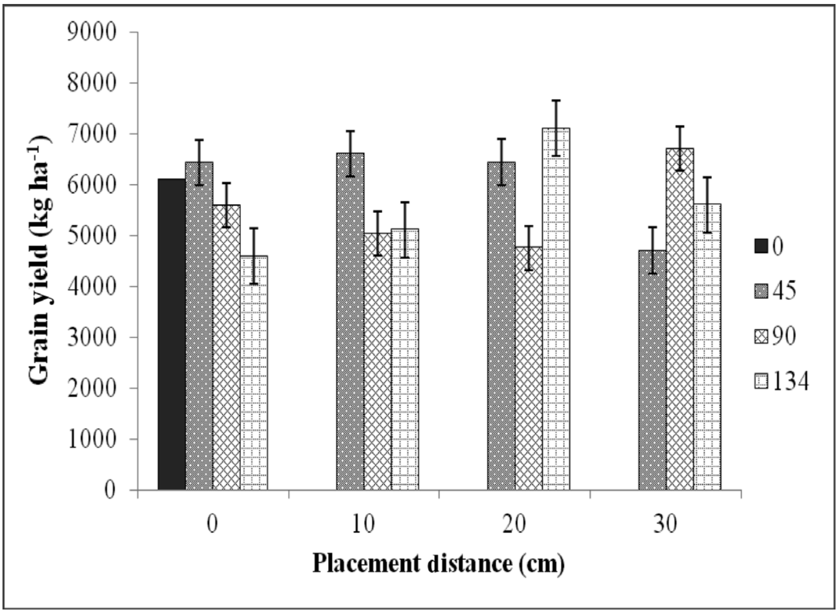

Figure 4. Grain yield as affected by side dress N at 0, 45, 90 and 134 kg N ha^{-1} applied at 0, 10, 20 and 30 cm away from the maize row, LCB, Oklahoma, 2010.

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

At Haskell, in 2009, the results obtained indicated that there was no significant effect of treatment on maize grain yield (Table 4). Treatments with 0 kg N ha^{-1} prep-plant and 45 kg N ha^{-1} side dress N did not significantly differ from the rest of the treatments. Overall poor N response was recorded. Application of side dress N, application distance away from the maize raw and interaction between the two factors did not contribute to any significant ($p < 0.05$) maize grain yield differences among treatments. However, it was apparent that at low N rate (45 kg N ha^{-1}) maize grain yield increased with close application of side dress N (Figure 5). Maize grain yield declined to as low as 4705 kg ha^{-1} when side dress N was applied 30 cm away from the maize row (Table 4). At high N rates side dress N, application distance away from the maize row showed inconsistent trend in maize grain yields (Figure 5).

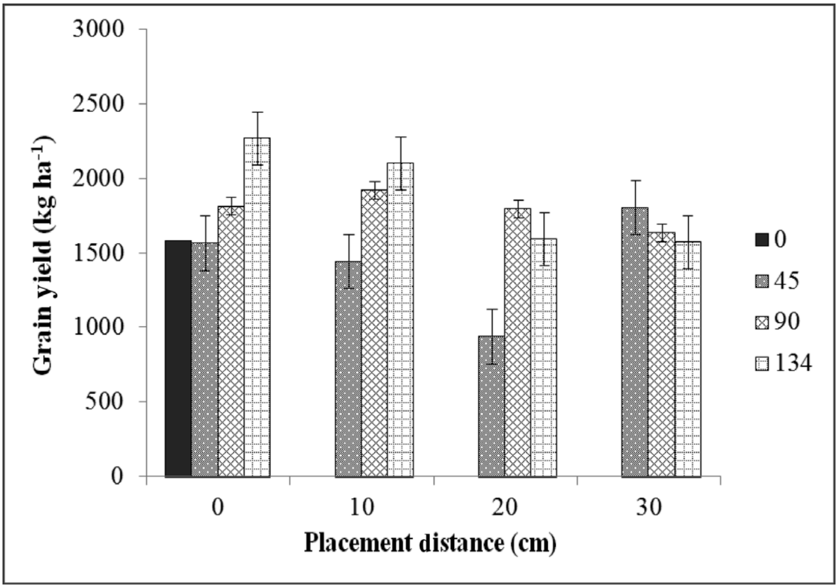

Figure 5. Grain yield as affected by side dress N at 0, 45, 90 and 134 kg N ha^{-1} applied at 0, 10, 20 and 30 cm away from the maize row, Haskell, Oklahoma, 2009.

The experiment at Hennessey in 2009 gave the lowest maize grain yields compared with all the cropping seasons and locations. Overall, treatments were not significant ($p < 0.05$) (Table 4) and poor response to side dress N application was recorded (Figure 6). Maize grain yields obtained from treatments that received prep-plant N and those that did not were not significantly ($p < 0.05$) different from each other. Varying the application distance away from the maize row did not significantly ($p < 0.05$) influence maize grain yields even for the treatments that did not receive prep-plant N (treatments 2 through 5). However, at low side dress N rate (45 kg N ha^{-1}), maize grain yield reduced with increase in the application distance when prep-plant N was applied (treatments 6 through 9). Applying side dress N at 0 and 10 cm away from the maize row resulted to better maize grain yield (Figure 6). At low side dress N, 1435 kg ha^{-1} and 1637 kg ha^{-1} was recorded when side dress

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

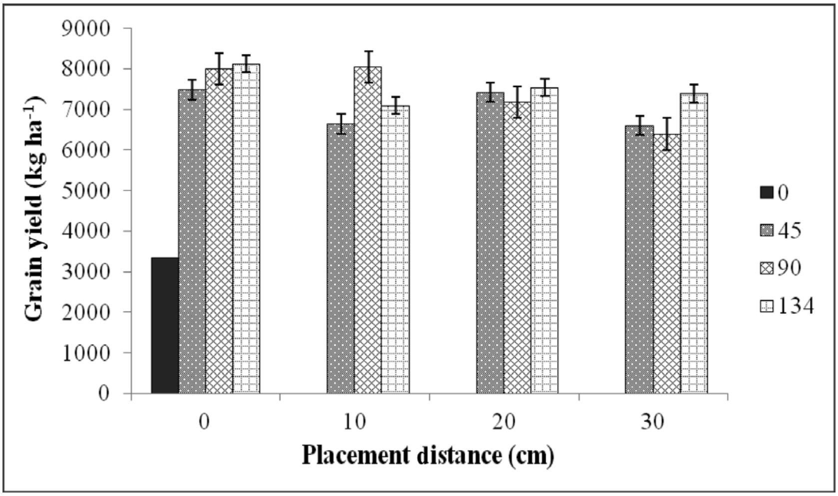

Figure 6. Grain yield as affected by side dress N at 0, 45, 90 and 134 kg N ha^{-1} applied at 0, 10, 20 and 30 cm away from the maize row, Hennessey, Oklahoma, 2009.

N was applied 0 and 10 cm away from the maize row respectively (Table 4). High N rates (90 and 134 kg N ha^{-1}) led to inconsistent results regardless of how far the side dress N was applied from the maize row.

At Efaw, treatments significantly ($p < 0.01$) affected maize grain yield, contributing to higher maize grain yields compared with that of the control. Treatments that received prep-plant N gave significantly higher yields, compared with treatments 2 through 5 (no prep-plant N applied). A positive response to side dress N application was recorded (Figure 7). However, distance the side dress N was applied away from

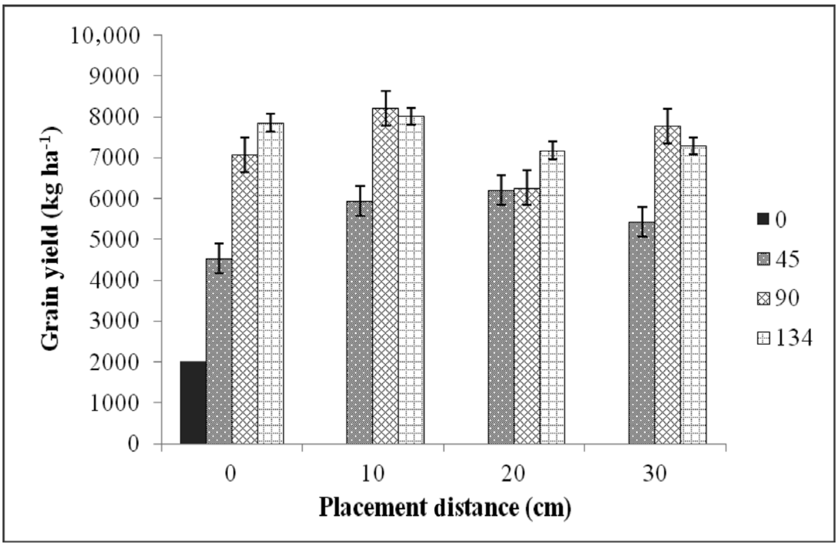

Figure 7. Grain yield as affected by side dress N at 0, 45, 90 and 134 kg N ha^{-1} applied at 0, 10, 20 and 30 cm away from the maize row, Efaw, Oklahoma, 2010.

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

the maize row did not significantly ($p < 0.05$) affect maize grain yields even when low side dress N was applied with no prep-plant application. Higher N rates (90 and 134 kg N ha^{-1}) gave better results when side dress N was applied closer to maize row. Maize grain yield was the highest when side dress N was placed 0 to 10 cm for 90 kg N ha^{-1} and 0 cm for 134 kg N ha^{-1} side dress N application (Table 4).

Nitrogen Use Efficiency

Nitrogen use efficiency results for LCB, Hennessey and Efaw are presented in Tables 5 and 6 for 2009 and 2010 respectively. At LCB in 2009, application of 0 kg N ha^{-1} prep-plant plus 45 kg N ha^{-1} side dress N overall contributed to high NUE compared with the rest of the treatments regardless of the side dress N application distance. Lack of prep-plant N application led to a better response to application distance. The highest NUE (35%) was recorded when 45 kg N ha^{-1} side dress N was applied 0 cm away from the maize row with zero prep-plant. Treatments with prep-plant N applied indicated that NUE decreased with side dress N rate to as low as 7% (45 kg N ha^{-1} prep-plant + 134 kg N ha^{-1} side dress N). Application distance and the interaction between the two had no significant effect on NUE and no consistent trend was recorded.

In 2010, 0 kg N ha^{-1} prep-plant N plus 45 kg N ha^{-1} side dress N contributed to significantly ($p < 0.05$) lower NUE. Application of prep-plant lead to an increase in NUE, which ranged from 44 to 99% across side dress N rates applied. Increasing N rates significantly ($p < 0.01$) lead to a decline in NUE. Application distance and interaction between N rate and application distance did not significantly ($p < 0.05$) affect NUE regardless of whether prep-plant was applied or not. Generally, the highest NUE of up to 99% was obtained with 45 kg N ha^{-1} pre-plant and 45 kg N ha^{-1} side dress N, applied 10 or 20 cm away from the maize row.

At Hennessey in 2009, results of application of zero prep-plant and 45 kg N ha^{-1} side dress (low N rate) did not significantly ($p < 0.05$) influence NUE. However, with zero prep-plant, applying side dress N at the base of the maize row gave the highest NUE (23%). The factorial treatments (6 through 17) showed that side dress N, application distance and the interaction between the two factors did not significantly ($p < 0.05$) affect NUE with or without prep-plant. Nonetheless, NUE consistently declined with increasing side dress N rate. Overall, NUE increased when low side dress N rate (45 kg N ha^{-1}) was applied closer to the maize row.

At Efaw, application of 0 kg N ha^{-1} prep-plant and 45 kg N ha^{-1} side dress N did not significantly ($p < 0.05$) affect NUE. Overall, with prep-plant applied was followed by side dress N, NUE reduced with an increase in side dress N rate. Application distance and the interaction term were not significant ($p < 0.05$) whether prep-plant was applied or not. However, application of side dress N at the base (0 cm) of the maize row consistently gave the highest NUE across all the side dress N rates applied. Applying 45 kg N ha^{-1} prep-plant followed by 45 kg N ha^{-1} side dress N contributed to the highest NUE of 80% when side dress N was applied 0 cm away from the maize row.

Table 5. Grain nitrogen uptake means and percentage NUE as affected by placement distance away from the maize row of side dress N application in 2009 at Hennessey, and Lake Carl Blackwell, Oklahoma.

Treatment	Prep-plant N (kg ha^{-1})	Side dress N (kg N ha^{-1})	Side dress N placement distance (cm)	N uptake (kg N ha^{-1})		% NUE	
				Hennessey	LCB	Hennessey	LCB
1.	0	0	0	8	16	–	–
2.	0	45	0	18	32	23	35
3.	0	45	10	12	20	8	19
4.	0	45	20	9	22	1	14
5.	0	45	30	16	27	17	26
6.	45	45	0	21	22	28	14
7.	45	45	10	16	21	17	21
8.	45	45	20	13	13	9	19
9.	45	45	30	10	27	11	25
10.	45	90	0	16	28	8	13
11.	45	90	10	9	29	2	15
12.	45	90	20	17	26	10	11
13.	45	90	30	12	24	5	14
14.	45	134	0	12	36	1	13
15.	45	134	10	14	31	3	11
16.	45	134	20	13	23	4	10
17.	45	134	30	21	22	8	7
SED§				**6**	**5**	**11**	**5**
Contrast							
1 vs (2, 3, 4, 5)				ns	†	na	na
1 vs (6, 7, 8, 9)				ns	ns	na	na
1 vs (10, 11, 12, 13)				ns	**	na	na
1 vs (14, 15, 16, 17)				ns	**	na	na
(2, 3, 4, 5) vs (6, 7, 8, 9)				ns	ns	ns	ns
(2, 3, 4, 5) vs (10, 11, 12, 13)				ns	ns	ns	***
(2, 3, 4, 5) vs (14, 15, 16, 17)				ns	ns	ns	***
(6, 7, 8, 9) vs (10, 11, 12, 13)				ns	*	†	*
(6, 7, 8, 9) vs (14, 15, 16, 17)				ns	*	ns	**
(10, 11, 12, 13) vs (14, 15, 16, 17)				ns	ns	ns	ns

†, *, **, ***: Significant at the 0.1, 0.05, 0.01 and 0.001 probability levels respectively.
§SED: Standard error of the difference between two equally replicated means.
Na: Not applicable.

DISCUSSION

The findings presented in this experiment varied with location and cropping season. This outcome was mainly attributed to spatial and temporal variability that exists in any particular study location (Solie *et al.*, 1999). Soil moisture directly relates to the rainfall distribution of a given location. In N fertilizer management, it is already known that soil moisture is crucial in N mobility, especially NO_3^--N, and plays a great role in uptake of N by the crops, and overall NUE (NaNagara *et al.*, 1975). This is because N in the soil moves mainly through mass flow and diffusion to plant roots (Barber, 1995). Temperature as well directly influences soil moisture loss and nutrients uptake through evapotranspiration process (Pregitzer and King, 2005). In

Table 6. Grain nitrogen uptake means and percentage NUE as affected by placement distance away from the maize row of side dress N application in 2010 at Efaw, and Lake Carl Blackwell, Oklahoma.

Treatment	Prep-plant N (kg ha^{-1})	Side dress N (kg N ha^{-1})	Side dress N placement distance (cm)	N uptake (kg N ha^{-1})		% NUE	
				Efaw	LCB	Efaw	LCB
1.	0	0	0	59	24	–	–
2.	0	45	0	64	55	13	69
3.	0	45	10	96	33	83	19
4.	0	45	20	86	52	60	62
5.	0	45	30	66	40	17	37
6.	45	45	0	95	48	80	53
7.	45	45	10	75	69	42	99
8.	45	45	20	91	69	71	99
9.	45	45	30	87	61	64	81
10.	45	90	0	108	86	54	68
11.	45	90	10	108	102	55	87
12.	45	90	20	103	69	49	50
13.	45	90	30	78	95	21	79
14.	45	134	0	114	103	41	52
15.	45	134	10	93	100	26	56
16.	45	134	20	110	92	39	51
17.	45	134	30	101	82	32	44
SED[§]				**15**	**14**	**28**	**23**
Contrast							
1 vs (2, 3, 4, 5)				ns	†	na	na
1 vs (6, 7, 8, 9)				**	***	na	na
1 vs (10, 11, 12, 13)				***	***	na	na
1 vs (14, 15, 16, 17)				***	***	na	na
(2, 3, 4, 5) vs (6, 7, 8, 9)				***	*	ns	**
(2, 3, 4, 5) vs (10, 11, 12, 13)				ns	***	ns	*
(2, 3, 4, 5) vs (14, 15, 16, 17)				**	***	ns	ns
(6, 7, 8, 9) vs (10, 11, 12, 13)				***	***	ns	ns
(6, 7, 8, 9) vs (14, 15, 16, 17)				ns	***	†	**
(10, 11, 12, 13) vs (14, 15, 16, 17)				*	ns	ns	†

†, *, **, ***: Significant at the 0.1, 0.05, 0.01 and 0.001 probability levels respectively.
[§]SED: Standard error of the difference between two equally replicated means.
na: Not applicable.

this study, according to the Oklahoma Mesonet weather station (www.mesonet.org), mean monthly air temperatures were the highest for all sites in June and July, 2009 and 2010 (Figure 1 and 2). The rainfall distribution for Haskell, Hennessey and LCB in 2009 was low for these two months excluding LCB in July (Figure 1). In 2010, Efaw and LCB recorded high mean rainfall distribution for June and July (Figure 2). This indicated that soil moisture could have been a problem in Haskell and Hennessey, but not Efaw and LCB experimental sites. It is also important to remember that LCB experiments were irrigated whenever it was necessary.

Side dress N was applied between June and July for all seasons and sites (Table 3), which corresponded to V8 to V10 maize development stage. At V8 to V10 demand for nutrients and water by maize is relatively high. Moisture and nutrients deficiency at

https://doi.org/10.1017/S0014479712000981 Published online by Cambridge University Press

these stages leads to poor growth and development of the ears and eventually reduced maize grain yields.

High temperatures and low rainfall distribution at Haskell and Hennessey could have resulted to low soil moisture and generally recorded poor N response. At both sites, varying side dress N application distance away from the maize row did not significantly affect maize grain yield regardless of whether prep-plant N was applied or not. But at lower N rates (45 kg N ha^{-1}), maize grain yield was high when side dress N was placed 0 to 20 cm and 0 cm away from the maize row for Haskell and Hennessey respectively. The same thing applied for NUE at Hennessey, where NUE only increased when side dress was applied at base (0 cm) of maize row.

Since N is taken up by plants through mass flow and diffusion (Barber, 1995), inadequate soil moisture could have contributed to further applied side dress N failing to reach plant roots on time before it was lost through ammonia volatilization. High losses of N through ammonium volatilization have been reported to occur when N fertilizer is applied to soils with low soil moisture and high air temperature (>50 °F) (Sommer *et al.*, 1991). The decline in NUE with increased side dress N rate emphasized the important of avoiding excess N fertilizer application in maize production.

Availability of adequate moisture at Efaw and LCB (except in 2009) could have contributed to the positive N response recorded. Although application distance of side dress N away from the maize row did not significantly affect maize grain yield regardless of whether prep-plant was applied or not, slightly higher maize grain yield was obtained when side dress N was applied 0 to 10 cm away from the maize row at high N rates (90 and 134 kg N ha^{-1}). For the two sites, high NUE was recorded when side dress was placed 0 to 20 cm away from the maize row. The decrease in root densities as the distance from the maize row increased and high concentration of maize root mass at 0 to 10 cm soil layer, located directly under the plant (Mengel and Barber, 1974), could have contributed to the increase in NUE and maize grain yield when side dress N was applied closer to the maize row. At both sites, NUE declined with increased side dress N, mainly due to over application. The increased NUE with zero prep-plant at LCB in 2009 emphasized how results can vary in the same site from one year to another due to spatial and temporal field visibilities, especially when dealing with N fertilizer.

CONCLUSIONS

Soil moisture plays a crucial role in N mobility, especially NO_3^--N and uptake of N by the maize. Therefore, poor N response, low maize grain yield and NUE were recorded when side dress N was applied at locations with high temperature and low rainfall distribution. Adequate soil moisture contributed to positive N response, high maize grain yields and enhanced NUE. Across sites and seasons, side dress N application distance away from the maize row did not influence maize grain yield and NUE substantially even in cases where no prep-plant was applied. However, in moisture limiting environments (Haskell and Hennessey) high maize grain yields and NUE were achieved when side dress N was applied 0 to 20 cm away from the maize row especially at low N rates (45 kg N ha^{-1}). Environments with adequate rainfall distribution (Efaw and LCB) generally had better maize grain yields and slightly higher NUE when high side dress N rates (90 and 134 kg N ha^{-1}) were applied between 0 cm and 20 cm away from the maize row. Irrespective of how far the side dress N was applied, increasing side dress N to 134 kg N ha^{-1} lead to a general decline in mean NUE to as low as 4%, 26%, 45%, 43% at Hennessey, Efaw, LCB (2009), and LCB (2010) respectively.

REFERENCES

Barber, S. A. (1995). *Soil Nutrient Bioavailability: A Mechanistic Approach*, 2nd edn. New York: John Wiley.

Davidson, E. A. (1992). Sources of nitric oxide and nitrous following wetting of dry soil. *Soil Science Society of America Journal* 56:95–102.

De Klein, C. A. and Van Logtestijn, R. S. (1994). Denitrification in the top soil of managed grassland in the Netherlands in relation to soil and fertilizers level. *Plant and Soil* 163:33–44.

Edmonds, D. E. (2007). *Corn grain yield response to variable row nitrogen fertilizer*. MS thesis, Oklahoma State University, Stillwater, OK.

Fageria, N. K. and Baligar, V. C. (2003). Fertility management of tropical acid soils for sustainable crop production. In *Handbook of Soil Acidity*, 359–385. (Ed Z. Rengel). New York: Marcel Dekker.

Fageria, N. K., Baligar, V. C. and Jones, C. A. (1997). *Growth and Nutrition of Field Crops*, 3rd edn. New York: Marcel Dekker, 85 pp.

Follett, R. F. (2001). Innovative ^{15}N microplot research techniques to study nitrogen use efficiency under different ecosystem. *Communications in Soil Science and Plant Analysis* 32:951–979.

Foth, H. D. and Ellis, B. G. (1988). *Soil Fertility*. New York: John Wiley.

Gregory, P. J. (2006). *Plant Roots: Growth, Activity and Interaction with Soils*. Oxford: Blackwell Publishing.

Harper, L. A. and Sharp, R. R. (1995). Nitrogen dynamics in irrigation corn: soil-plant nitrogen and atmospheric ammonia transport. *Agronomy Journal* 87:669–675.

HarvestMaster Inc (1994). *HM-1/HM-2 Field Book: User Manual*. Logan UT: HarvestMaster Inc.

Kanampiu, F. K., Raun, W. R. and Johnson, G. V. (1997). Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. *Journal of Plant Nutrition* 20(2 & 3):389–404.

Kuangfei, L., Yaling, X., Xuefeng, L. and Pastore, G. (1999). Loss of nitrogen, phosphorus, and potassium through crop harvests in agroecosystems of Qianjiang, Hubei province, PR China. *Critical Reviews in Plant Sciences* 18(3):393–401.

Martin, E. C., Loudon, T. L., Ritchie, J. T. and Werner, A. (1994). Use of drainage lysimeter to evaluate nitrogen and irrigation management strategies to minimize nitrate leaching in maize production. *Transactions of the American Society of Agricultural Engineers* 37:79–83.

McNeal, B. L. and Pratt, P. F. (1978). Leaching of nitrates from soils. In *Management of Nitrogen in Irrigated Agriculture*, 195–230 (Ed. P. F. Pratt). Riverside, CA: University of California.

Mengel, D. B. and Barber, S. A. (1974). Development and distribution of the corn root system under field conditions. *Agronomy Journal* 66:341–344.

NaNagara, T., Philips, R. E. and Leggett, J. E. (1975). Diffusion and mass flow of nitrate-nitrogen into corn roots grown under field conditions. *Agronomy Journal* 68:67–72.

Pregitzer, K. S. and King, J. S. (2005). Effects of soil temperature on nutrient uptake. In *Nutrient Acquisition by Plants an Ecological Perspective; Ecological Studies*, Vol. 181 (Ed. H. BassiriRad). Berlin, Germany: Springer-Verlag.

Reidenbach, G. and Horst, W. (1997). Nitrate-uptake capacity of different root zones of *Zea mays* (L.) in vitro and in situ. *Plant Soil* 196:295–300.

Ritter, W. F., Scarborough, R. W. and Chirnside, A. E. M. (1993). Nitrate leaching under irrigated corn. *Journal of Irrigation and Drainage Engineering* 119:544–553.

SAS Institute (2003). *SAS/STAT User Guide: Release 9.1*. Cary, NC: SAS Inst.

Sawyer, J., Nafziger, E., Randall, G., Bundy, L., Rehm, G. and Joern, B. (2006). *Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn*. Iowa City, IA: Iowa State University.

Shoup, D. and Janssen, K. (2009). Diagnosing uneven corn height problems. *Agronomy e-update* 191 (Kansas State Ext. Pub. Manhattan, KS).

Solie, J. B., Raun, W. R. and Stone, M. L. (1999). Submeter spatial variability of selected soil and plant variables. *Soil Science Society of America Journal* 63:1724–1733.

Sommer, S. G., Olesen, J. E. and Christensen, B. T. (1991). Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry. *Journal of Agricultural Science* 117:91–100.

Varney, G. T. and Canny, M. J. (1993). Rates of water uptake into the mature root system of maize plants. *New Phytologist* 123:775–786.

Varvel, G. E. and Peterson, T. A. (1990). Nitrogen fertilizer recovery by corn in monoculture and rotation systems. *Agronomy Journal* 82:935–938.

Vyn, T. J. and West, T. D. (2008). Efficient fluid fertilizer management for corn producers with automatic guidance systems. Year 3 results. In *Fluid Forum Proceedings CD Volume 25*. Manhattan, KS: Fluid Fertilizer Foundation.

Westermann, D. T. and Crothers, S. E. (1993). Nitrogen fertilization of wheat no-till planted in alfalfa stubble. *Journal of Production Agriculture* 6:404–408.

Xing, G. X. and Zhu, Z. L. (2000). An assessment of N loss from agricultural fields to the environment in China. *Nutrient Cycling in Agroecosystems* 57:67–73.

Yu-Hua, T., Bin, Y., Lin-Zhang, Y., Shi-Xue, Y. and Zhao-Liang, Z. (2007). Nitrogen runoff and leaching losses during rice-wheat rotations in Taihu Lake Region, China. *Pedosphere* 17(4):445–456.