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EFFECT OF DELAYED NITROGEN FERTILIZATION ON MAIZE (*ZEA MAYS* L.) GRAIN YIELDS AND NITROGEN USE EFFICIENCY

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□ *Maize grain yield potential can be estimated mid-season using NDVI at the V8 growth stage, thus affording delayed sidedress nitrogen (N) application. Several combinations of preplant and sidedress N at various growth stages were evaluated. Maize grain yields were maximized with 90 kg N ha-1 preplant followed by 90 kg N ha-1 sidedress at V6 or V10 (8 of 9 site-years). Delaying N application until V10 growth stage when preplant N was applied did not result in lower yields. Mid-season N supplies fertilizer at the time when crop need and N uptake are at a maximum, and thus facilitates more efficient N use. Lowest nitrogen use efficiencies (NUE) were observed with higher N rates and when all N was applied preplant. Highest NUE's were achieved with 45 kg N ha-1 preplant followed by 45 kg N ha-1 sidedress applied at V6 growth stage (8 of 9 site-years) and at V10 (6 of 9 site-years).*

Keywords: nitrogen, fruit crops, fertilizers

INTRODUCTION

The typical world-wide nitrogen use efficiency (NUE) reported by Raun and Johnson (1999) for most cereal crops including maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), sorghum (*Sorghum bicolor* L.), rye (*Secale cereale* L.), and millet (*Pennisetum glaucum* L.), is approximately 33% with estimated averages of 29% and 42% for the developing and the developed countries, respectively. Such a low NUE reflects ineffective nitrogen (N) management in agriculture and causes both great economic loss to producers and negative impact on the environment. On a global scale, the question of whether NUE

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can be increased above the average 33% becomes crucial considering the continuous pressure on agricultural producers to meet the demands of a rapidly growing population worldwide.

Because of the need for continuous nutrient inputs to the soil, simply reducing the rates of N fertilizer used in agriculture would obviously prevent crop producers from achieving their major goal: higher yields (Evans, 1998). Therefore, creating an effective N management system, improving N recommendations, and increasing NUE are critical issues; which should be addressed to maintain and increase the sustainability of crop production in the future. Highly intensive crop production worldwide results in large amounts of N being removed with the harvested grain, and therefore, results in natural nutrient depletion year after year. On the other hand, one of the most harmful ecological problems known to be caused by accelerated agriculture is run-off from croplands. This results in deterioration of water quality and declining sea-life. One of the most difficult challenges researchers and crop producers face today is to sustain global food security, and minimize the negative impact of intense agriculture on the environment.

Traditional approaches for fertilizing maize in the fall, prior to spring planting, is still considered to be more advantageous by many crop producers because it enables them to better distribute their time and labor (Randall et al., 2003) and benefit from better soil conditions and lower fertilizer N prices (Bundy, 1986; Randall and Schmitt, 1998). However, it is necessary to evaluate the risks imposed by fall post-harvest application versus spring application and split N fertilization (40% at planting followed by 60% mid-season). Aldrich (1984), Olson and Kurtz (1982), Russelle et al. (1981), Stanley and Rhoads (1977), and Welch et al. (1971) all agree that the best practice in managing maize is the application of N fertilizer at the time (or near the time) when both the need for N and N uptake are maximum for maize plants because it promotes higher NUE by reducing denitrification, N immobilization and leaching. Miller et al. (1975) and Olson et al. (1986) evaluated the efficiency of in-season N application and concluded that both NUE and grain yields can be increased by delaying N fertilization for maize. Results of a seven-year study on timing of N application in maize and soybean production, conducted by Randall et al. (2003), demonstrated lowest grain yields were achieved with fall N application compared to highest grain yields with split N fertilization.

Using chlorophyll meter readings, Varvel et al. (1997) calculated a SI (sufficiency index) to determine the appropriate timing for in-season N fertilization for maize. Nitrogen was applied when index values were below 95%. They further reported that maximum yields for maize could not be achieved by late in-season fertilization if sufficiency index values at the 8 leaf vegetative sage (V8) were below 90%. Therefore, the suggestion was made that N fertilization before V8 growth stage was critical for maize. Scharf et al. (2002) found N fertilization even as late as the 11-leaf vegetative stage (V11) did not result in irreversible yield loss for maize showing very significant N stress. Delaying N application until growth stages V12 and V16 (12 and 16 leaf growth stages, respectively) caused a loss of just 3% in grain yield. Scharf et al. (2002) concluded benefits of delayed N fertilization in maize outweigh the risk of grain yield loss. Teal et al. (2006) showed maize grain yield potential can be accurately estimated mid-season using NDVI at the V8 growth stage. As such, there is a need to investigate whether sidedress N fertilization in maize can be delayed until mid-season without leading to irreversible grain yield loss. Blackmer et al. (1989) found delaying N fertilization until mid-season allows for more accurate determination of crop need for N, and further suggested in-season soil tests to avoid over application, thus minimizing N loss. Schmidt et al. (2002) evaluated maize grain yield response to N fertilizer applied at various rates and times; they recommended sidedress application of N fertilizer during the growing season as a means to improve NUE.

One of the problems associated with the application of N later in the growing season is the suppression of maize grain yield due to N deficiency. Understanding the effects imposed on maize by delayed N application is extremely important for improvement of fertilizer recommendations because the effectiveness of delayed N application to maize is strongly dependent on the degree of N deficiency at that time (Binder et al., 2000).

To improve fertilizer recommendations, it is necessary to determine the effects of delayed N applications and how long it is possible to delay N applications for maize without compromising maximum grain yields. The following hypotheses were tested in this study: (i) NUE can be increased by delaying fertilizer N application until later in the season to maize without compromising grain yield; (ii) supplying all N to the established crop at V6 will enable maize to overcome stress caused by N deficiency earlier in the season when no preplant fertilizer is applied; (iii) it is possible to achieve high yield with the minimum amount of preplant fertilizer followed by N application delayed until the V10 growth stage; and (iv) maize will fail to recover if no preplant fertilizer is applied and all of the N is supplied to the crop at the V10 growth stage.

Specific objectives of this study were to evaluate the effects of delayed N fertilization on maize grain yields, identify the minimum preplant N needed to achieve maximum yields if sidedress N fertilizer is applied later in-season, and to determine how late in the growing season fertilizer N can be applied without decreasing maize grain yields.

MATERIALS AND METHODS

This study was conducted at three locations in 2005, 2006 and 2007: Stillwater Research Station near Lake Carl Blackwell (irrigated), Oklahoma, Efaw Research Farm (rainfed) near Stillwater, Oklahoma, and at the Eastern

TABLE 1 Treatment structure for experiments conducted at Efaw, Lake Carl Blackwell, and Haskell, OK, 2005–2007

Treatment	Preplant N fertilizer application† N rate (kg ha^{-1})	Sidedress N fertilizer application‡ N rate (kg ha^{-1})	Growth stage
1	0	0	—
2	90	0	—
3	180	0	—
4	0	90	V6
5	0	180	V6
6	0	90	V10
7	0	180	V10
8	0	90	VT
9	0	180	VT
10	90	90	V6
11	90	90	V10
12	90	90	VT
13	45	45	V10
14	45	45	V6

†Preplant N applied as ammonium nitrate (34-0-0) in 2005, as urea (46-0-0) in 2006, and as urea ammonium nitrate (28-0-0) in 2007.

‡Sidedress N applied as urea ammonium nitrate (28-0-0).

Oklahoma Research Station (rainfed) near Haskell, Oklahoma. A completely randomized block design with three replications was used to evaluate 14 treatments at all sites. Various combinations of preplant and sidedress N fertilizer applications at several growth stages (V6, V10, and VT) were evaluated to determine the optimum nutrient management strategy for maize production. Treatment structure is shown in Table 1. At all sites the size of the individual plots was 3.1 × 6.2 m with 3.1 m alleys. Initial surface (0–15cm) soil chemical characteristics and classification are reported in Table 2.

Field activities including planting dates, seeding rates, hybrids, preplant soil sampling dates, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil

TABLE 2 Initial surface (0–15 cm) soil chemical characteristics and classification at Efaw, Lake Carl Blackwell, and Haskell, OK, 2005

Location	pH	NH_4-N	NO_3-N	P	K	Total N	Organic C
		mg kg^{-1}				g kg^{-1}	
Efaw	5.87	13.86	3.74	20.14	89.50	0.65	10.24
Lake Carl Blackwell	5.63	28.40	4.35	45.10	144.00	0.76	9.87
Haskell	6.11	22.85	2.17	25.33	61.00	0.75	8.93

†pH – 1:1 soil: water; K and P – Mehlich III; NH_4-N and NO_3-N – 2 M KCl, total N and organic C – dry combustion.

TABLE 3 Field activities including planting dates, seeding rates, hybrids, preplant soil sampling dates, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Efaw, Lake Carl Blackwell, and Haskell, OK, 2005

Field activity	Efaw	Lake Carl Blackwell	Haskell
Planting date	March 30	April 12	April 4
Cultivar	Pioneer 33B51	Pioneer 33B51	Triumph 1416Bt
Seeding rate (plants ha^{-1})	59,280	74,100	59,280
Preplant soil sampling date	March 30	March 28	April 4
Preplant N fertilization date†	March 30	March 28	April 4
Herbicide application date‡	April 8	May 12	April 6
Sidedress N fertilization at V6§	May 19	May 19	May 24
Sidedress N fertilization at V10§	June 2	June 2	June 9
Sidedress N fertilization at VT§	June 14	June 21	June 20
Harvest date	August 27	September 7	August 29
Rainfall (mm)¶	509	581	449
Average air temperatures (C°)¶	23	23	23
Average soil temperatures (C°)¶	25	27	24

†Preplant N fertilizer was applied as ammonium nitrate (34-0-0).
‡Herbicide – Bicep II Magnum was applied at 930 ml ha^{-1}.
§Sidedress N fertilizer was applied as urea ammonium nitrate (UAN) (28-0-0).
¶Rainfall, average air and average soil temperatures for the period from planting through harvest.

temperatures for Efaw, Lake Carl Blackwell, and Haskell, Oklahoma, for 2005, 2006, and 2007 are summarized in Tables 3, 4, and 5, respectively. In 2005, Pioneer 33B51 was planted at Efaw and Lake Carl Blackwell, and Triumph 1416Bt at Haskell. In 2006, Pioneer 33B51 was planted at all sites. In

TABLE 4 Field activities including planting dates, seeding rates, hybrids, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Efaw, Lake Carl Blackwell, and Haskell, OK, 2006

Field activity	Efaw	Lake Carl Blackwell	Haskell
Planting date	March 30	March 31	April 13
Cultivar	Pioneer 33B51	Pioneer 33B51	Pioneer 33B51
Seeding rate (plants ha^{-1})	61,750	79,040	54,340
Preplant N fertilization date†	March 30	March 31	April 13
Herbicide application date‡	March 30	March 31	April 13
Sidedress N fertilization at V6§	May 19	May 16	May 23
Sidedress N fertilization at V10§	June 2	May 29	June 8
Sidedress N fertilization at VT§	June19	June 12	June 21
Harvest date	September 1	August 18	August 31
Rainfall (mm)¶	415	414	412
Average air temperatures (C°)¶	25	24	27
Average soil temperatures (C°)¶	26	27	26

†Preplant N fertilizer was applied as ammonium nitrate (34-0-0).
‡Herbicide – Bicep II Magnum was applied at 930 ml ha^{-1}.
§Sidedress N fertilizer was applied as urea ammonium nitrate (UAN) (28-0-0).
¶Rainfall, average air and average soil temperatures for the period from planting through harvest.

TABLE 5 Field activities including planting dates, seeding rates, hybrids, preplant N fertilizer application dates, sidedress N fertilizer application dates, herbicide application dates and harvest dates, climatic data including rainfall, average air temperatures, and average soil temperatures for Efaw, Lake Carl Blackwell, and Haskell, OK, 2007

Field activity	Efaw	Lake Carl Blackwell	Haskell
Planting date	March 21	April 6	April 12
Cultivar	Dekalb DKC 50-20	Dekalb DKC 66-23	Pioneer 33B54
Seeding rate (plants ha^{-1})	54,340	79,040	59,280
Preplant N fertilization date†	March 21	March 19	April 12
Herbicide application date‡	March 21	April 6	April 16
Sidedress N fertilization at V6§	May 26	May 28	May 29
Sidedress N fertilization at V10§	June 11	June 6	June 13
Sidedress N fertilization at VT§	June 21	June 19	July 5
Harvest date	August 29	August 23	September 19
Rainfall (mm)¶	1139	906	795
Average air temperatures (C°)¶	21	21	21
Average soil temperatures (C°)¶	20	21	21

†Preplant N fertilizer was applied as ammonium nitrate (34-0-0).
‡Herbicide – Bicep II Magnum was applied at 930 ml ha^{-1}.
§Sidedress N fertilizer was applied as urea ammonium nitrate (UAN) (28-0-0).
¶Rainfall, average air and average soil temperatures for the period from planting through harvest.

2007, the varieties were DeKalb DKC 50-20, DeKalb DKC 66-23, and Pioneer 33B54 for Efaw, Lake Carl Blackwell, and Haskell, respectively. The seeding rates were 59,280 plants ha^{-1} for Efaw and Haskell, and 74,100 plants ha^{-1} for Lake Carl Blackwell in 2005. In 2006, seeding rates were 54,340 plants ha^{-1} at Efaw, 79,040 plants ha^{-1} at Lake Carl Blackwell, and 61,750 plants ha^{-1} at Haskell. In 2007, seeding rates were 54,340 plants ha^{-1} at Efaw, 79,040 plants ha^{-1} at Lake Carl Blackwell and 59,280 plants ha^{-1} at Haskell.

Preplant N fertilizer as ammonium nitrate (34% N), urea (46%N), and urea ammonium nitrate (UAN) (28% N) were broadcast manually and incorporated into the soil at planting in 2005, 2006, and 2007, respectively. Sidedress fertilizer N was applied mid-season as UAN (28-0-0). Sidedress N was applied along each row at the base of the plants in a continuous stream using 50–200 ml syringes.

The center 2 rows from each 4-row plot were harvested with a Massey Ferguson 8XP (Massey Ferguson, Duluth, GA, USA) self-propelled combine. Grain sub-samples were collected, oven-dried at 72°C for 72 hours and processed to pass a 106 μm (140 mesh screen) and analyzed for total N content using a Carlo Erba NA 1500 dry combustion analyzer (Carlo Erba, Milan, Italy) (Schepers et al., 1989). Total N uptake (kg ha^{-1}) was determined by multiplying grain yield (kg ha^{-1}) by grain percent N. Nitrogen use efficiency was determined using the difference method (Varvel and Peterson, 1991).

Statistical analysis was performed using SAS for Windows (SAS, Cary, NC, USA). Analysis of variance (ANOVA) was used to evaluate the effect of treatments on grain yield and NUE. Multiple comparisons of treatment means were also evaluated. Linear and quadratic polynomial orthogonal contrasts were used to assess trends in grain yield to N fertilizer rates.

RESULTS

Grain Yield - 2005

In general, the highest grain yields at Efaw were obtained with split fertilization and higher total N application (Table 6). There were no statistically significant differences in grain yield associated with timing of sidedress fertilizer applications.

At Lake Carl Blackwell, at the fertilizer N rates evaluated, grain yields for treatments with sidedress applications at V6 were significantly higher ($P < 0.05$) compared to those with delayed fertilization at the VT growth stage (Treatments 4, 5, 10, 14 vs 8, 9, 12) (Table 7). Overall, treatments where fertilizer N was applied earlier in the growing season (V6 growth stage) yielded more than treatments where sidedress N was delayed until tasseling (VT growth stage) (Figure 1).

At Haskell, with the 180 kg N ha^{-1}, treatment that received 90 kg N ha^{-1} preplant and 90 kg N ha^{-1} at V6, yields were 4742 kg ha^{-1} and significantly superior ($P < 0.05$) to applying all N at V6 (Treatments 10 and 5) (Table 8). Grain yields gradually decreased from 4641 kg ha^{-1} (plots receiving all N preplant) to 4107 kg ha^{-1} (sidedress fertilizer applied at V6) to 3852 kg ha^{-1}

TABLE 6 Treatment, preplant N, sidedress N, and mean grain yields and SED's for Efaw, OK, 2005–2007

Treatment	Preplant N kg ha^{-1}		Sidedress N growth stage	Mean grain yield kg ha^{-1} 2005	2006	2007
1	0	0	—	6187	3799	1966
2	90	0	—	8181	6343	1977
3	180	0	—	8546	6913	2171
4	0	90	V6	7570	5754	2405
5	0	180	V6	9049	6577	3231
6	0	90	V10	7691	5467	2927
7	0	180	V10	7970	6370	2241
8	0	90	VT	8175	5829	2647
9	0	180	VT	8433	6713	2533
10	90	90	V6	9104	7116	2892
11	90	90	V10	9144	6600	2879
12	90	90	VT	9056	6153	2443
13	45	45	V10	8543	6835	2558
14	45	45	V6	8272	6813	2667
SED†				679	660	485

†SED – Standard error of the difference between two equally replicated means.

TABLE 7 Treatment, preplant N, sidedress N, and mean grain yields and SED's for Lake Carl Blackwell, OK, 2005–2007

Treatment	Preplant N kg ha^{-1}		Sidedress N growth stage	Mean grain yield kg ha^{-1}		
				2005	2006	2007
1	0	0	—	8842	3001	6119
2	90	0	—	12862	6586	6496
3	180	0	—	13814	6405	7285
4	0	90	V6	14210	7482	7679
5	0	180	V6	13563	3141	8362
6	0	90	V10	12852	4141	7900
7	0	180	V10	13927	7468	7163
8	0	90	VT	12571	6158	7476
9	0	180	VT	11454	4868	7367
10	90	90	V6	14228	7971	6830
11	90	90	V10	14345	9073	6598
12	90	90	VT	14502	8127	6270
13	45	45	V10	13405	5579	6852
14	45	45	V6	13683	6094	7007
SED†				759	1983	3338

†SED – Standard error of the difference between two equally replicated means.

(sidedress application at V10) to 3535 kg ha^{-1} (sidedress at VT) (Figure 2). Delaying fertilizer N application until the VT growth stage resulted in a significant reduction in grain yields compared to treatments that were fertilized at V6 growth stage (Figure 2) independent of the fertilizer rate.

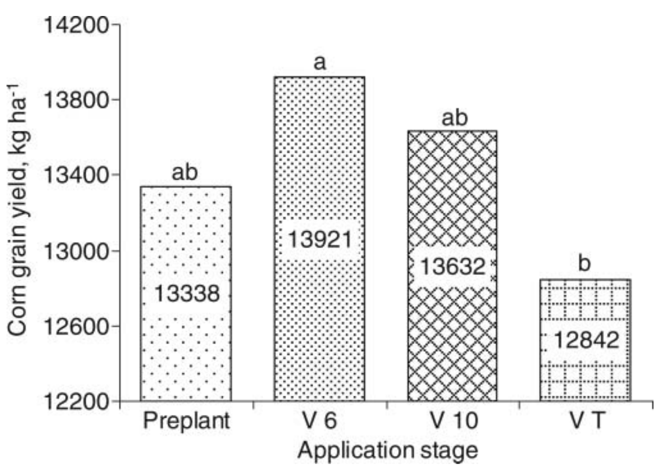

FIGURE 1 Maize grain yield as affected by time of fertilizer N application at Lake Carl Blackwell, 2005 averaged over N rates. Bars followed by the same letter were not significantly different at $P < 0.05$ using Least Significant Difference (LSD) mean separation procedure.

TABLE 8 Treatment, preplant N, sidedress N, and mean grain yields and SED's for Haskell, OK, 2005–2007

Treatment	Preplant N kg ha^{-1}		Sidedress N growth stage	Mean grain yield kg ha^{-1} 2005	2006	2007
1	0	0	—	3029	3726	4644
2	90	0	—	4562	3079	10067
3	180	0	—	4720	2732	12776
4	0	90	V6	3889	2970	9843
5	0	180	V6	3279	3153	11025
6	0	90	V10	3537	3116	9487
7	0	180	V10	4168	3708	9807
8	0	90	VT	3483	3474	7897
9	0	180	VT	3401	3397	10121
10	90	90	V6	4742	3938	11332
11	90	90	V10	3730	3013	10572
12	90	90	VT	3720	2782	10646
13	45	45	V10	3973	3000	11127
14	45	45	V6	4519	3793	10559
SED†				476	463	1128

†SED – Standard error of the difference between two equally replicated means.

Nitrogen Use Efficiency - 2005

At Efaw, the highest fertilizer N use efficiency of 48% was obtained at Efaw with 90 kg N ha^{-1} split applied (preplant plus sidedress at V10) (Treatment 13) (Table 9). The lowest NUE's were achieved for treatments that received no N preplant and where high rates of sidedress N were delayed until late mid-season (V10-VT growth stages) (Treatments 7 and 9) (Table 9). Since

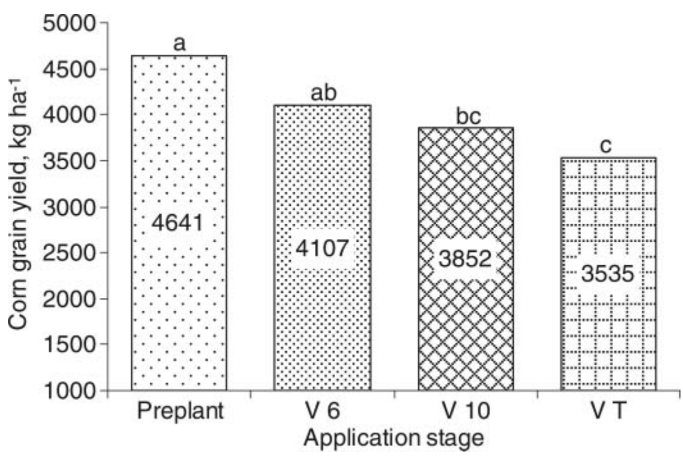

FIGURE 2 Grain yield as affected by time of fertilizer N application at Haskell, 2005. Bars followed by the same letter are not significantly different at $P < 0.05$ using Least Significant Difference (LSD) mean separation procedure.

TABLE 9 Treatment, grain N uptake, and NUE for Efaw, OK, 2005–2007

				2005		2006		2007	
Treatment	Preplant N kg ha^{-1}		Sidedress N growth stage	Grain N uptake, kg ha^{-1}	NUE, %	Grain N uptake, kg ha^{-1}	NUE, %	Grain N uptake, kg ha^{-1}	NUE, %
1	0	0	—	78	.	44	.	19	.
2	90	0	—	113	37	83	42	26	7
3	180	0	—	129	28	95	28	31	5
4	0	90	V6	110	35	78	37	31	13
5	0	180	V6	143	36	97	29	50	12
6	0	90	V10	111	35	79	38	42	20
7	0	180	V10	119	22	96	28	36	5
8	0	90	VT	113	37	86	46	41	17
9	0	180	VT	128	27	100	30	41	8
10	90	90	V6	143	35	105	34	40	10
11	90	90	V10	142	35	99	30	44	10
12	90	90	VT	139	33	95	28	38	7
13	45	45	V10	123	48	92	53	35	15
14	45	45	V6	116	41	90	51	37	17
SED†				12	9	10	8	7	5

†SED – Standard error of the difference between two equally replicated means.

the need for fertilizer during crop establishment and rapid development was not satisfied earlier in the growing season, even the application of large amounts of N later on did not allow the crop to "catch up" and achieve maximum yields.

Increased NUE was generally observed with split fertilizer application compared to treatments that received all fertilizer N at one time (Treatments 13 vs 6, and 14 vs 4) (Table 9).

At Lake Carl Blackwell, the highest NUE of 96% was achieved for the treatment that received no N preplant and N applied early in the growing season, which allowed the crop to "catch up" and produce near maximum grain yields (Treatment 4) (Table 10). In general, split fertilizer applications resulted in greater NUE's compared to treatments with no N preplant, and all fertilizer N applied mid-season. Consequently, NUEs for treatments with the total N rate of 90 kg ha^{-1} were 82% (no preplant) compared to 94% obtained with preplant followed by sidedress at the V10 growth stage (Treatments 6 and 13) (Table 10). When a total of 180 kg ha^{-1} fertilizer N was applied, 62% NUE was achieved with split fertilizer application, while only 39% NUE was observed when no N was applied preplant and all fertilizer was applied at VT (Treatments 12 and 9) (Table 10).

At Haskell, greater NUEs were achieved when all fertilizer was supplied as preplant (27%) and with the split application when sidedress N was applied early in the growing season (V6 growth stage) (29%) (Treatments 2 and 14) (Table 11). However, since the application of higher N rates later in the season did not improve yields, the fertilizer N use efficiency was lower. The

TABLE 10 Treatment, grain N uptake, and NUE for Lake Carl Blackwell, OK, 2005–2007

Treatment	Preplant N kg ha^{-1}		Sidedress N growth stage	2005 Grain N uptake, kg ha^{-1}	2005 NUE, %	2006 Grain N uptake, kg ha^{-1}	2006 NUE, %	2007 Grain N uptake, kg ha^{-1}	2007 NUE, %
1	0	0	—	106	.	40	.	50	.
2	90	0	—	181	81	84	49	101	35
3	180	0	—	201	53	98	33	130	29
4	0	90	V6	201	96	102	68	202	89
5	0	180	V6	207	56	53	11	263	65
6	0	90	V10	181	82	65	33	196	96
7	0	180	V10	210	58	112	38	100	16
8	0	90	VT	181	82	94	59	182	83
9	0	180	VT	176	39	78	20	254	57
10	90	90	V6	218	62	125	48	186	56
11	90	90	V10	222	64	132	50	131	30
12	90	90	VT	217	62	113	40	102	20
13	45	45	V10	195	94	85	48	194	98
14	45	45	V6	190	87	84	47	147	61
SED†				16	11	26	22	82	37

†SED – Standard error of the difference between two equally replicated means.

NUEs tended to gradually decrease with delayed N application, averaged over N rates (Figure 3).

Omitting preplant N and applying 90 kg N ha^{-1} sidedress at V10 resulted in significantly lower ($P < 0.05$) NUE (11%) compared to treatments with split application (18%) (Treatments 6 and 13) (Table 11).

TABLE 11 Treatment, grain N uptake, and NUE for Haskell, OK, 2005–2007

Treatment	Preplant N kg ha^{-1}		Sidedress N growth stage	2005 Grain N uptake, kg ha^{-1}	2005 NUE, %	2006 Grain N uptake, kg ha^{-1}	2006 NUE, %	2007 Grain N uptake, kg ha^{-1}	2007 NUE, %
1	0	0	—	39	.	55	.	51	.
2	90	0	—	63	27	48	3	118	75
3	180	0	—	63	14	44	0	174	56
4	0	90	V6	56	20	46	0	124	72
5	0	180	V6	48	6	51	1	149	44
6	0	90	V10	48	11	48	0	132	67
7	0	180	V10	61	12	59	3	140	36
8	0	90	VT	47	10	53	2	110	45
9	0	180	VT	52	7	54	2	157	38
10	90	90	V6	69	17	61	5	153	46
11	90	90	V10	55	9	49	0	142	41
12	90	90	VT	54	8	46	1	155	42
13	45	45	V10	55	18	47	2	142	90
14	45	45	V6	65	29	58	6	134	82
SED†				7	6	7	3	20	15

†SED – Standard error of the difference between two equally replicated means.

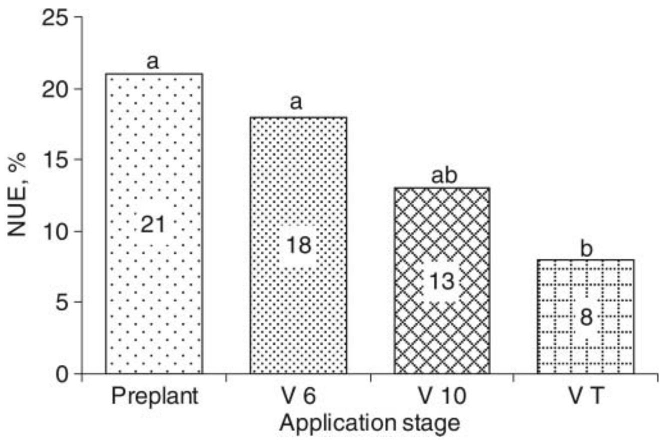

FIGURE 3 Fertilizer N use efficiency as affected by time of fertilizer N application at Haskell, 2005. Bars followed by the same letter are not significantly different at $P < 0.05$ using Least Significant Difference (LSD) mean separation procedure.

Grain Yield – 2006

At Efaw, when a total of 90 kg N ha^{-1} was applied, significantly greater ($P < 0.05$) grain yields (6835 kg ha^{-1}) were obtained by splitting N applications compared to only 5467 kg ha^{-1} for the treatment with no preplant N (Treatments 13 and 6) (Table 6). Statistical analysis indicated a quadratic relationship between N fertilizer rate and grain yield at Lake Carl Blackwell. A significant ($p < 0.05$) reduction in grain yield was observed when fertilizer N was doubled. The magnitude of grain yield loss, however, was much larger in 2006, since plots that received 90 kg N ha^{-1} yielded more than twice as much (7482 kg ha^{-1}) than plots with 180 kg N ha^{-1} (3141 kg ha^{-1}) (Treatments 4 and 5) (Table 7). Likewise, split fertilization resulted in significantly greater ($P < 0.05$) grain yield compared to treatments that did not receive any N preplant, and all fertilizer was applied at V6 growth stage (Treatments 5 and 10) (Table 7). At Haskell, no statistically significant differences in grain yields were observed regardless of N fertilizer rates and/or timing of sidedress application in 2006. Also, yields were generally lower in 2006 compared to the yields achieved in the previous growing season, largely due to drought conditions (Table 7).

Nitrogen Use Efficiency - 2006

At Efaw, greater NUEs were obtained at Efaw in 2006 via split fertilization (53%) of 90 kg N ha^{-1} compared to one time mid-season application at V10 (38%) (Treatments 13 and 6) (Table 9). A similar trend was apparent when fertilizer N was applied at 180 kg N ha^{-1}. Overall, sidedress application timing did not contribute significantly to differences in fertilizer N use efficiency at Efaw.

At lake Carl Blackwell, unlike 2005, method (split versus one time fertilization) of fertilizer application did not affect NUE (Table 10). The NUE's for treatments with no preplant N and high sidedress N (180 kg ha^{-1}) at V6 were only 11% (Treatment 5) (Table 10). This significantly lower ($P <$ 0.05) fertilizer N use efficiency is explained by the fact that much lower grain yields (3141 kg ha^{-1}) were obtained with 180 kg N ha^{-1} than with 90 kg N ha^{-1} (7482 kg ha^{-1}) (Treatments 5 and 4) (Table 8).

At Haskell, fertilizer N use efficiencies were extremely low in 2006 due to very low grain yields even for treatments with higher fertilizer N rates. In general NUEs at this site were low, since grain N uptake in the check plot was high, thus limiting what could be interpreted from subtle treatment differences. Low NUE's can be explained by lack of crop's response to fertilizer N at this location in 2006.

Grain Yield – 2007

At Efaw, independent of fertilizer N rate applied, significantly lower ($P <$ 0.05) maize grain yields were obtained when all N was applied preplant (2074 kg ha^{-1}), compared to grain yield for the treatments for which sidedress was delayed until V6 (2799 kg ha^{-1}), V10 (2799 kg ha^{-1}) or VT (2541 kg ha^{-1}) growth stages compared to grain yield of 2799 kg ha^{-1} with sidedress fertilization at V6. No significant differences associated with the time of sidedress N application time (V6, V10, and tasseling) were observed (Figure 4).

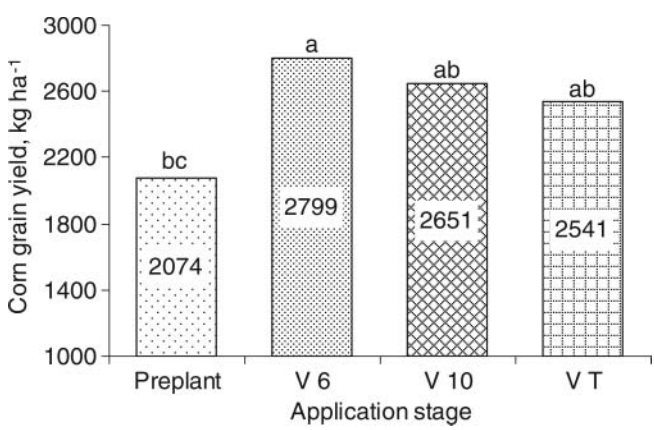

FIGURE 4 Corn grain yield as affected by time of fertilizer N application at Efaw, 2007 averaged over N rates. Bars followed by the same letter were not significantly different at $P < 0.05$ using Least Significant Difference (LSD) mean separation procedure.

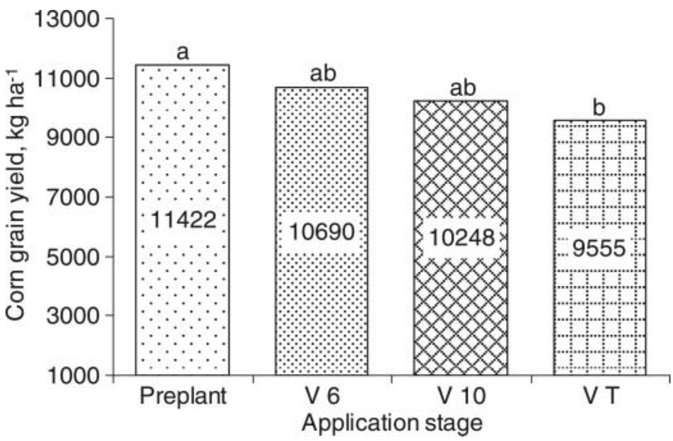

FIGURE 5 Corn grain yield as affected by time of fertilizer N application at Haskell, 2007 averaged over N rates. Bars followed by the same letter were not significantly different at $P < 0.05$ using Least Significant Difference (LSD) mean separation procedure.

At Lake Carl Blackwell, with no preplant N, delaying 180 kg N ha^{-1} sidedress from V6 to V10 application caused a decrease in grain yield of 990 kg ha^{-1}. On the other hand, when sidedress N was delayed until V10 and VT growth stages, similar grain yields were obtained independent of N rate applied (Table 7). Unlike at Lake Carl Blackwell, in 2007 at Haskell, significantly higher ($P < 0.05$) maize grain yields were obtained when all N was applied preplant (11422 kg ha^{-1}) compared to treatments that received sidedress N at tasseling (9555kg ha^{-1}). However, there was no statistically significant difference in mean maize grain yields between treatments that were sidedressed at V6, V10, or even tasseling (Figure 5).

Nitrogen Use Efficiency – 2007

In general, very low fertilizer NUEs (ranging from 5% to 20%) were observed at Efaw in 2007 (Table 9). This could be explained by lack of response to fertilizer N and low maize grain yields. Overall, higher NUEs were obtained with lower N rates. For example, Treatment 6 (no preplant, 90 kg N ha^{-1} applied at V10 growth) had NUE of 20%, whereas Treatment 7 (no preplant, 180 kg N ha^{-1} applied at V10 growth) had NUE of only 5%.

In general, when no preplant N was applied, sidedress N fertilizer application affected NUE to a greater extent than time of fertilization. When a total of 180 kg N ha^{-1} was split applied, NUEs were the same (10%) whether sidedress N was applied at V6 growth stage (Treatment 10) or delayed until V10 (Treatment 11). However, delaying sidedress N until tasseling (Treatment 12) led to a 3% decrease in NUE (from 10% to 7%). Neither N fertilizer application rate nor N application time significantly affect NUEs.

The highest NUEs (up to 98%) were achieved at Lake Carl Blackwell in 2007 compared to any other site-year. As at Efaw, greater NUE's were obtained with lower N rates applied. For example, Treatment 2 (90 kg N ha^{-1} applied all preplant) had NUE of 35% compared to 28% for Treatment 3 (180 kg N ha^{-1} applied all preplant) (Table 8).

At Haskell in 2007, relatively high N fertilizer use efficiency was achieved. NUEs ranged from 36% to 90% (Table 11). The greatest NUE was recorded for Treatment 13 (90 kg N ha^{-1} total split between preplant and sidedress at V10), whereas Treatment 7 (180 kg N ha^{-1} all applied at V10). With no preplant N, and 90 kg N ha^{-1} applied sidedress at V6, V10, and VT (Treatments 4, 6, and 8, respectively) higher NUEs of 72%, 67%, and 45% were observed compared to NUE's of 44%, 36%, and 38% for treatments that received 180 kg N ha^{-1} (Treatments 5, 7, and 9) (Table 11). There were no significant differences among NUE treatment means associated with the time of sidedress N application. The fertilizer N rate affected the NUEs to a greater extent than the timing of fertilizer application. On the other hand, when fertilizer N was split applied, this trend was not observed. For example, Treatment 14 (90 kg N ha^{-1} rate split applied at V6) had NUE of 82%; when sidedress N was delayed until V10 growth stage (Treatment 13) a greater NUE of 90% was achieved. Also, with 180 kg N ha^{-1} rate split applied (Treatments 10, 11, and 12) (sidedress at V6, V10, and VT, respectively), comparable NUEs (46%, 41%, and 42%) were observed (Table 11).

DISCUSSION

Grain Yield

Higher maize grain yields were generally achieved in the 2005 season compared to 2006 (Table 6). Beneficial climatic conditions such as more abundant rainfall (509mm, 590mm, and 577mm for Efaw, Lake Carl Blackwell, and Haskell, respectively in 2005) compared to only 417mm, 380mm, and 412mm in 2006 for Efaw, Lake Carl Blackwell, and Haskell, respectively contributed to higher grain yields in 2005 cropping year, especially at the rainfed sites (Tables 3 and 4). Low levels of soil moisture at all sites (especially in 2006) both pre-season and during the growing season resulted in moisture stress, which may have decreased N uptake. Higher soil and air temperatures also decreased grain yields in 2006 (Tables 3 and 4). Maize pollen is known to be sensitive to high temperatures (Hopf et al., 1992). Thus, heat stress present during most of the 2006 cropping year may have affected pollination and grain development. 2007 was an extremely wet year with several periods of continuous rainfall and numerous floods (32 floods reported for the period of March to July). The month of June was the wettest month for the state of Oklahoma (record since 1985) with 20 days of continuous rain from June 13 to July 2 (Arndt, 2007). All 3 experimental sites received much greater rainfall compared to the other crop years (1139mm, 906mm, and 795 mm) for Lake Carl Blackwell, Efaw, and Haskell, respectively (Tables 3, 4, and 5).

Statistical analysis of three years of data showed both year and site location significantly affected grain yields at all three sites ($P < 0.05$). No year-by-treatment or site-by-treatment interaction was found at any of the site-years (averages over site and year not reported). Overall, grain yields responded to 90 kg N ha^{-1}. Split fertilizer applications generally resulted in higher grain yields at most sites. The increase in N fertilizer rate from 0 to 180 kg N ha^{-1} almost always led to greater grain yields (Table 6).

Even though the obvious response to N fertilizer was observed comparing the 0-N check treatment, a significant decrease in yield was observed when N was increased from 90 to 180 kg N ha^{-1} at some sites. For instance, in both 2005 and 2006 cropping years, treatment 4 (no N preplant, sidedress N at 90 kg ha^{-1} applied at V6 growth stage) produced significantly higher ($P <$ 0.05) grain yields versus treatment 5 (no N preplant, sidedress at 180 kg N ha^{-1} at the V6 growth stage) (Table 6). Likewise, comparing treatments 8 and 9 at Lake Carl Blackwell in 2005, when sidedress application was delayed until VT, application of higher N fertilizer rates resulted in decreased grain yields (Table 6).

Nitrogen Use Efficiency

Statistical analysis showed no year-by-treatment or site-by-treatment interaction associated with fertilizer N use efficiency for any crop year. Higher NUEs were achieved in 2005 and in 2007 compared to the 2006 cropping year (Tables 9, 10, and 11). The Lake Carl Blackwell site generally had higher NUE's than Efaw and Haskell in all years (Tables 9, 10, and 11). Greater than average worldwide estimated NUEs were achieved for 6 of 9 site-years. The lowest N use efficiencies were observed at Haskell 2005 and 2006, with extremely low NUEs in 2006 due to the low grain yield produced at this location regardless of the fertilizer N applied (Table 8). Similar results were observed at Efaw in 2007, where extremely low maize grain yields coupled with no pronounced response to fertilizer N resulted in very low NUEs. Overall, N use efficiencies increased with mid-season fertilizer N applications and with preplant applications followed by sidedress N at or before the V10 growth stage.

Positive response to preplant fertilizer apparent for the majority of site-years is exemplified in higher NUEs achieved with split N fertilizer applications compared to treatments that received no preplant and a one-time fertilizer application mid-season. Overall, higher NUE's were achieved with mid-season (growth stages V6-V10) N fertilizer applications. Decreased NUE's were observed when sidedress N was delayed until tasseling and higher fertilizer N rates.

Application of preplant N followed by a mid-season sidedress fertilizer N application at or before the V10 growth stage is recommended for maize. Delaying N fertilization until mid- season supplies N at the time when the crop's need for N and N uptake are at maximum, and thus facilitates more efficient N fertilizer use.

CONCLUSIONS

Generally, maize grain yields were maximized with 90 kg N ha^{-1} preplant followed by 90 kg N ha^{-1} sidedress at V6 or V10 (8 of 9 site-years). Therefore, when no preplant fertilizer N was applied, supplying sidedress N early in the growing season allowed for crop recovery. Analysis of data from 9 site-years demonstrated no significant decrease in grain yield associated with delaying sidedress N application until V10 growth stage and tasseling when preplant N was applied. Application of preplant N provides essential nutrients for crop emergence and establishment.

However, delaying N fertilizer applications until later growth stages (V10-VT) generally resulted in decreased grain yields (6 site-years of 9) when no preplant N was applied, meaning the crop failed to recover from N stress and failed to "catch-up" and produce maximum grain yields. Lower maize grain yields were observed for treatments receiving all fertilizer N preplant (3 site-years of 9). This could be due to N loss from the soil via leaching, erosion, and denitrification processes that are active during the fall-winter periods.

Nitrogen use efficiency was generally improved with mid-season N application at lower N rates. Highest NUEs were achieved with 45 kg N ha^{-1} preplant followed by 45 kg N ha^{-1} sidedress applied at V6 growth stage (8 of 9 site-years) and at V10 (6 of 9 site-years). Lowest NUEs were observed with higher N fertilizer rates and when all N was applied preplant.

Delaying sidedress N applications until V8 to V10 growth stages allows for in-season plant nutrient evaluation and for the determination of fertilizer N needed to be applied to achieve maximum grain yields based on the crop's yield potential. The results of this study suggest optimum fertilizer recommendation in maize may be formulated as following: apply 90 kg N ha^{-1} preplant followed by 90 kg N ha^{-1} sidedress at or before V10 growth stage.

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