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Irrigated and rain-fed maize response to different nitrogen fertilizer application methods

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ABSTRACT

With the demand for maize increasing, production has spread into more water limited regions. Couple this with increasing resource costs and environmental concerns and the need for efficient nutrient and water management practices has increased. The objective of this trial was to evaluate the effects of different nitrogen (N) fertilizer application methods and timings on maize grain yield, N use efficiency (NUE), and water use efficiency (WUE) under irrigated and rain-fed conditions. Four site-years of data were collected. Fertilizer treatments consisted of all N applied preplant, split surface applied, and split foliarly applied. Irrigation applied prior to and during reproductive growth increased grain yield, NUE, and WUE compared to rain-fed treatments for all site-years. Split surface applied N fertilizer applications typically increased NUE, but not always grain yield compared to preplant applications. The use of split foliar N fertilizer applications was only beneficial in the site-years when leaf burn was not as severe.

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Maize; nitrogen; sidedress; foliar; irrigation

Introduction

According to the U.S. Department of Commerce (2012), the world population is over 7 billion people and will be nearing 8 billion people by the year 2025. This increase in population raises the concern for the need of an abundant food supply. Cereal grains are a staple for feeding the world. Nearly 2.5 billion metric tons of cereal grains were produced in the world in 2009 (FAO, 2012). One way to meet the growing demand for grain is for cultivated agriculture to spread into drier, more semi-arid environments. However, in areas where irrigation is available, water is becoming less available for food production and instead is being utilized for human and industrial consumption (Hokam et al., 2011), thus the need for more water efficient agricultural production practices are needed.

Research has shown that maize hybrid selection based upon improved Nitrogen use efficiency (NUE) does not appear to be influenced by amount of water supplied and often parallels selection based upon water use efficiency (WUE) (Eghball and Maranville, 1991). Without question, irrigation increases maize grain yield; however, several researchers have reported that WUE, based upon yield, decreases as the amount of water supplied by irrigation increases (Stone et al., 1987, 1993; Hergert et al., 1993). Typically, increases in water added to the maize crop result in greater yield response to nitrogen (N) fertilization as well as fertilizer N uptake by the plant (Eck, 1984; Martin et al., 1982).

Several researchers have investigated the interactive effect of N fertilization and water use in maize production. Russelle et al. (1981) investigated the effects of time and rate of N fertilizer application and the frequency of irrigation on maize grain yield, N uptake, and fertilizer use efficiency. They reported that grain yield and N uptake were not influenced by time of N application, and yields were maximized

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with light frequent irrigation events. The highest NUE was obtained with low N rates applied midseason during vegetative growth, and with light frequent irrigation events. Martin et al. (1982) evaluated maize production management practices using irrigation water high in nitrate. They concluded that N uptake was strongly influenced by the rate of N fertilizer applied and irrigation water applied. Eck (1984) studied maize grain yield response in the Southern High Plains to different N fertilizer rates as well as different N fertilizer application timings and amounts of water stress. He reported significant grain yield losses for each day of water stress during the grain filling period, but he found that adequate N only slightly increased grain yield under stress and greatly increased yield when water was adequately applied. He also stated that excess N did not reduce grain yield with water stress, thus he reported no reason to reduce N rates to reduce crop water stress. Weinhold et al. (1995) researched the interaction of different N fertilizer application rates with supplemental irrigation rates applied according to differing levels of maize evapotranspiration (ET). They reported that supplemental irrigation is a viable technology for increasing maize grain yields, as long as excess water wasn't added that could lead to N losses via leaching and/or denitrification. Norwood (2000) investigated water use and grain yield of maize grown under limited irrigation or dryland conditions for both conventional tillage and no-till systems. He concluded that no-till increased grain yield and WUE and that maize grown under limited irrigation can produce adequate yields with proper fertility and plant populations. Al-Kaisi and Yin (2003) attempted to establish an accurate irrigation and N management system for maize grown in the Great Plains. They reported plant N uptake typically responded positively to irrigation, N rate, and plant population. They also observed that irrigation supplied at 80 percent of the estimated ET losses yielded higher WUE values regardless of N rate. Di Paolo and Rinaldi (2008) investigated the interaction of irrigation and N fertilization on maize yield in the Mediterranean region. Their results showed that at certain irrigation levels crop N response and NUE improved, but there was a valid compromise between N rates and irrigation if the goal was productivity and resource use efficiency. Mansouri-Far et al. (2010) researched the effect of water deficiency and N fertilizer rate on maize grain yield. The authors observed grain yield was less affected when water deficits occurred in early growth stages, but there were substantial grain yield losses when water was deficient during reproductive stages. They also noted the addition of N fertilizer applied increased yield and WUE when water deficit occurred earlier in the growing season.

The timing of N fertilizer applications has been shown to be critical in improving NUE. Historically, in the Midwestern United States' maize-belt the most common N fertilizer application was a single preplant rate applied in the fall (Randall et al., 1997). This practice was attributed to lower fertilizer N prices, better soil conditions for incorporation, and it allowed maize producers to better distribute their time and labor (Randall and Schmitt, 1998; Randall et al., 2003). However, because of potential soil loss mechanisms and the uncertainty of weather conditions between fall harvest and spring planting, researchers have reported this practice to be an inefficient use of N fertilizer when compared to spring preplant and in-season application timings (Stevenson and Baldwin, 1969; Welch et al., 1971; Vetsch and Randall, 2004; Freeman et al., 2007). Several researchers have reported the best practice for optimizing NUE of applied N fertilizer in maize is to supply the N fertilizer as close to the time of need and the maximum N uptake (Welch et al., 1971; Russelle et al., 1981; Olson and Kurtz, 1982; Aldrich, 1984; Walsh et al., 2012). This has led to researchers evaluating the effects of preplant versus in-season N fertilizer application timings on NUE and maize grain yield. Stevenson and Baldwin (1969) investigated the effects spring preplant and sidedress N fertilizer application in maize and reported that averaged over various research locations, grain yields were 80 to 100 kg ha^{-1} higher for sidedress treatments compared to spring preplant treatments. Olson et al. (1986) compared urea ammonium nitrate (UAN) applied preplant to a sidedress application in maize over 15 growing seasons. Grain yield increases averaged five percent more with the sidedress application treatments when compared to the preplant application treatments. Walsh et al. (2012) evaluated several combinations of preplant and sidedress N application rates at different growth stages. They reported grain yields were maximized when 90 kg N ha^{-1} were applied preplant followed by 90 kg N ha^{-1} at V6 or V10 growth stage, and NUE values were lowest when higher rates of N were applied and also when all N fertilizer was applied preplant.

Over the last half century, foliar applications of nutrients have grown in popularity and according to Raun and Johnson (1999) foliar applications of N can potentially increase NUE. Fertilizer nutrients that are soluble in water can be applied to a growing crop in season using equipment customarily used for spraying pesticides. Much of the yield increases and nutrient use efficiencies of foliar fertilizer applications have been observed in the application of micronutrients. However, the major drawback in supplying adequate amounts highly demanded nutrients, such as N, phosphorus (P), potassium (K), in foliar applications is that over application can potentially lead to leaf burn and to avoid leaf burn multiple applications would need to be made (Tisdale et al., 1993).

Researchers have proposed that there may potentially be a foliar fertilizer by moisture stress interaction that is likely due to the fact that as the soil becomes drier plant roots grow deeper into less fertile soil seeking water, thus supplying nutrients via the leaves may allow the plant to function at a productive level (Harder et al., 1982a; Marschner, 2012). Harder et al. (1982a, 1982b) evaluated the effect of foliar fertilization during grain fill under different moisture stress levels on maize grain yield, N response, and leaf photosynthetic rate. They observed that foliar fertilization resulted in significant grain yield decreases and there was no evidence of an interaction effect of moisture stress and foliar fertilizer application. However, grain N values were increased in treatments receiving foliar N applications compared to the control. They also reported that leaf photosynthetic rates did decrease immediately after foliar fertilizer application, but recovered by the second day and that there were no significant differences in the seasonal trends of photosynthetic rates between control and foliar fertilizer treatments. Below et al. (1984a, 1984b) examined the effects of foliar nutrient applications before and after anthesis on maize grain yield and grain N content as well as the physiological responses. They hypothesized that foliar N applications could potentially delay the remobilization of leaf N and leaf senescence, thus maintaining photosynthesis and sustaining productivity. They reported that foliar N applications did not affect grain yields, but did increase grain N concentrations. They noted adverse effects of stalk lodging and foliar N applications did not delay the remobilization of N from the leaves likely because it did not increase the N concentration of the leaves and it decreased the accumulation of carbohydrates by the stalks. Foliar applications also appeared to interfere with indigenous N metabolism leading to the ineffectiveness of foliar N applications to increase grain yield. Sawyer and Barker (1999) evaluated the impact of foliar N fertilizer applied at several growth stages on maize grain yield and grain components. They reported there was no significant yield response to foliar N application, regardless of timing, and also that there was no significant effects on the grain yield components and thus they did not recommend foliar N applications for maize production. Ling and Silberbush (2002) compared N foliar fertilizer products and a mixture of urea with soil applied N and how it could affect maize leaf area, chlorophyll, and N content. They concluded that the effectiveness of foliar fertilizers may be limited to the leaf surface area for the liquid fertilizer and that foliar applications could only partially compensate for insufficient plant uptake, but must have adequate leaf area to be effective.

With an increased demand for maize production in water limited areas of the United States' Southern Great Plains, we wanted to further investigate maize response to different N application timings and methods to provide sound agronomic recommendations for maize producers in the Southern Great Plains. The objectives of this study were to evaluate the interactive effects of N fertilizer application timing, application method, and irrigation on maize grain yield, NUE, and WUE.

Materials and methods

The study was conducted at two locations (Stillwater, OK and Lake Carl Blackwell, OK) during the 2012 and 2013 growing seasons for a total of four site-years. Site soil descriptions and basic soil nutrient testing results are provided in Table 1. To ensure N was the only limiting nutrient, sites were fertilized prior to planting to 100 percent sufficient levels based upon soil test P and K results and the regional fertilizer recommendations described in Zhang and Raun (2006).

A split-block experiment in a randomized complete block design with three replications per site-year was utilized in this trial. Irrigated or rain-fed treatments served as the main plot, while six N fertilizer treatments served as the sub-plot. Various combinations of application timings, application

Table 1. Preplant surface (0–15 cm) chemical characteristics and soil classification of sites utilized in this study.

Location[a]	Year	Soil mapping unit	Major component soil taxonomic classification	pH[b]	NH_4-N[c]	NO_3-N[c]	P[d]	K[d]	Total N[e]	Organic C[e]
					mg kg^{-1}				g kg^{-1}	
STW	2012	Easpur loam, 0 to 1 percent slopes, occasionally flooded	Easpur: Fine-loamy, mixed, superactive, thermic Fluventic Haplustolls	6.2	11	4	30	119	0.8	9.4
LCB	2012	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: Fine-silty, mixed, superactive, thermic Cumulic Haplustolls Oscar: Fine-silty, mixed, superactive, thermic Typic Nastrustalfs	5.6	8	3	22	111	0.6	7.8
STW	2013	Norge loam, 3 to 5 percent slopes	Norge: Fine-silty, mixed, active, thermic Udic Paleustolls	5.0	16	11	87	117	1.2	10.5
LCB	2013	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: Fine-silty, mixed, superactive, thermic Cumulic Haplustolls Oscar: Fine-silty, mixed, superactive, thermic Typic Nastrustalfs	6.1	6	5	24	139	1.1	9.5

[a]STW, Oklahoma State University Agriculture Experiment Station near Stillwater, OK; LCB, Oklahoma State University Agriculture Experiment Station near Lake Carl Blackwell, OK.
[b]1:1 water.
[c]2 M KCl extract (Mulvaney, 1996).
[d]Mehlich III extract (Mehlich, 1984).
[e]Dry combustion (Nelson and Sommers, 1996).

methods, and fertilizer rates were evaluated to determine best management practices for N fertilization in irrigated or rain-fed maize grown in the Southern Great Plains (Table 2). Plots receiving preplant N were fertilized with UAN (28-0-0) in which the fertilizer was broadcast applied and mechanically incorporated prior to planting. For some treatments, fertilizer was applied at two mid-season timings. The first timing (V8-V10) included a surface application of UAN and foliar applied treatments. The second timing (V10-V12) included only the foliar applied treatments. The mid-season surface application N source was UAN. The surface applied fertilizer was applied mid-row with streamer nozzles. Nitamin (Koch Agronomic Services, LLC, Wichita, KS, USA) (30-0-0), a low salt N source derived from urea triazone, methylene urea, and urea, was utilized for the foliar application treatments. All maize growth stages reported according to Abendroth et al. (2011).

For all site-years, the plot size was 3.1 m wide by 6.2 m long. Four rows spaced at 76 cm apart were planted per plot and all measured observations were collected on the middle two rows. Field activities including planting dates, hybrids, seeding rates, N fertilizer application dates, and harvest dates are provided in Table 3. Planting took place in the spring using different maize hybrids that are known to have a higher drought tolerance. Seeding rates were based on best agronomic practices. The type of irrigation used was surface drip irrigation. Two strips of drip tape were placed through each plot between the first and second rows and between the third and fourth rows. The amount of irrigation water

Table 2. Nitrogen fertilizer treatment structure applied to both irrigated and rain-fed plots in this study.

Treatment no.	Preplant N rate kg N ha^{-1}	Midseason N rate kg N ha^{-1}	Midseason application method[a]	Total N applied kg N ha^{-1}
1	0	0	—	0
2	90	0	—	90
3	45	45	Foliar	90
4	180	0	—	180
5	90	90	Foliar	180
6	90	90	Surface	180

[a]Foliar treatments applied as low-salt, foliar N source split 50/50 at growth stage V8 and V10; Surface treatment applied as UAN in a stream between rows at growth stage V8.

Table 3. Field activities for the four site-years utilized in this study.

Field activity	2012 STW[a]	2012 LCB[a]	2013 STW	2013 LCB
Preplant N fertilization date	April 2	April 5	March 18	March 18
Planting date	April 9	April 10	March 20	March 20
Cultivar	Pioneer P1498HR	Pioneer P0876HR	Pioneer P1498HR	Dekalb 63–55
Seeding rate (seeds ha^{-1})	49,000	49,000	54,000	54,000
Start of irrigation	May 16	May 17	June 13	June 14
Cease irrigation	July 11	July 9	July 9	July 9
Amount of irrigation (mm)	173	89	55	27
Amount of rainfall (mm)	233	201	621	834
Mid-season N fertilization date #1	May 25	May 25	June 3	May 29
Mid-season N fertilization date #2	June 1	June 3	June 14	June 8
Harvest date	August 6	July 26	September 9	September 4

[a]STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

(mm) distributed over each plot was determined by measuring the liters of water applied over the given area.

To evaluate the severity of leaf burn of foliar treatments, visual ratings of the estimated percent leaf area damaged in the upper most leaves was recorded. To obtain an objective estimate of leaf burn, normalized difference vegetative index values (NDVI) were collected prior to the foliar applications and after foliar applications. The NDVI measurements were collected with a Greenseeker (Trimble, Sunnyvale, CA, USA) active optical crop sensor. Because of the impact certain climatic conditions (temperature, relative humidity, and wind speed) may have on potential leaf burn, these parameters were collected from adjacent climate-monitoring sites (Oklahoma Mesonet, 2014) for the time period after foliar fertilizer application (Table 4).

Grain yield was determined by harvesting the center two rows of the four row plots with a Massey Ferguson 8XP self-propelled plot combine (Massey Ferguson, Duluth, GA, USA). Plot grain yields were adjusted to a standard moisture content of 155 g kg^{-1}. Oven-dried and processed to pass 140

Table 4. Days until measurable rainfall and average temperature, relative humidity, and wind speed for the first four hours after foliar N fertilizer applications (Oklahoma Mesonet, 2014).

Location	First application	Second application
STW[a] 2012 (May 25/June 1)		
Temperature (°C)	24.2	14.7
Relative humidity (%)	78.0	64.8
Wind speed (m s^{-1})	2.4	2.9
Days until rainfall (d)	3	1
LCB[a] 2012 (May 25/June 3)		
Temperature (°C)	25.3	20.8
Relative humidity (%)	76.0	89.0
Wind speed (m s^{-1})	3.0	0.6
Days until rainfall (d)	4	<1 [b]
STW 2013 (June 3/June 14)		
Temperature (°C)	16.7	26.6
Relative humidity (%)	84.0	74.5
Wind speed (m s^{-1})	1.2	1.1
Days until rainfall (d)	1	1
LCB 2013 (May 29/June 8)		
Temperature (°C)	22.8	20.6
Relative humidity (%)	81.8	70.0
Wind speed (m s^{-1})	6.2	2.1
Days until rainfall (d)	<1 [b]	<1 [b]

[a]STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.
[b] Rainfall occurred less than 24 hours after, but more than 8 hours after foliar application.

mesh screen grain-subsamples were analyzed for total N content using a dry combustion analyzer. Total grain N uptake was calculated by multiplying the total grain yield (kg ha^{-1}) by the percent N in the grain sample. Nitrogen use efficiency was then calculated by employing the difference method described by Varvel and Peterson (1991).

The WUE (kg ha^{-1} mm^{-1}) was calculated for both the Stillwater and Lake Carl Blackwell sites for only the 2013 growing season. It was calculated as the ratio of grain yield (kg ha^{-1}) to the seasonal water use/ET. The ET was estimated using a modified water balance proposed by Heerman (1985) detailed in the following equation:

$$ET = \pm \Delta SWC + R + I$$

where ΔSWC is the change in soil profile (0 to 80 cm) volumetric soil water content from planting to harvest, R the rainfall, and I the irrigation. It was assumed that water losses due to deep percolation/leaching or surface runoff were negligible and not included in the water balance. The ΔSWC was determined by collecting volumetric soil water samples from each plot with a 5 cm diameter probe long enough to encompass the 80 cm depth. The samples were collected using a hydraulic push probe (Giddings Machine Company, Windsor, CO, USA). Daily rainfall was measured from the adjacent Oklahoma Mesonet (Oklahoma Mesonet, 2014) climate-monitoring station.

To understand the impact the climate and added irrigation could have on the parameters being evaluated, daily water balances were created (Figures 1 and 2). These balances were based upon the daily potential ET (PET) for the trial area, as well as the measured rainfall and added irrigation. The PET values were determined from the ASCE Standardized Reference Evapotranspiration Equation described by Walter et al. (2002). Data collected to determine PET and rainfall was downloaded from the adjacent Oklahoma Mesonet (Oklahoma Mesonet, 2014) climate-monitoring site.

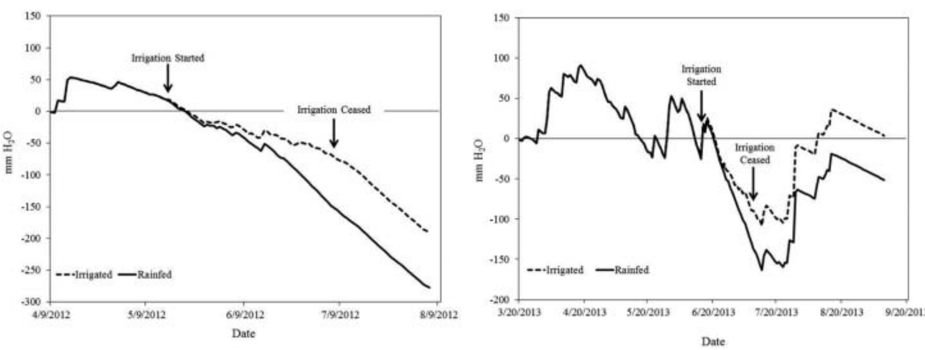

Figure 1. Stillwater, OK daily water balance for the 2012 (left) and 2013 (right) growing seasons. Potential evapotranspiration estimated from adjacent weather monitoring station (Oklahoma Mesonet, 2014).

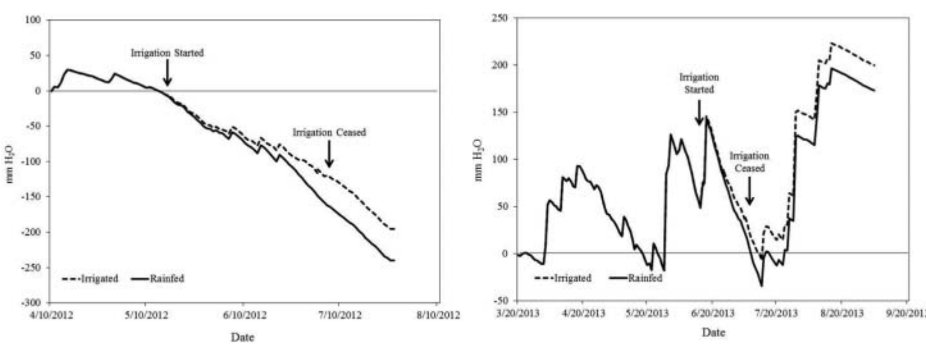

Figure 2. Lake Carl Blackwell, OK daily water balance for the 2012 (left) and 2013 (right) growing seasons. Potential evapotranspiration estimated from adjacent weather monitoring station (Oklahoma Mesonet, 2014).

Analysis of variance techniques were employed to detect significant differences for the main and interactive effects of treatments on grain yield, NUE, and WUE. Single degree-of-freedom contrasts were used to partition statistical differences in treatment grouping means. Because visual leaf burn ratings are subjective, only the treatment means were reported, however, statistical differences in NDVI values were determined using analysis of variance along with Fisher's Protected least significant difference (LSD). Because of varying climatic conditions and soil types for each site-year, all site-years were analyzed separately and thus results reported separately. For all analysis, an alpha level of 0.10 was used to determine statistical significance.

Results

Stillwater, OK (2012)

Water balance

Irrigation was started at Stillwater, OK shortly before the time the water balance fell below zero (Figure 1). This coincided with the V6 maize growth stage. Early irrigation was applied at rates of approximately 40 percent PET. Irrigation rates increased throughout the reproductive growth stages and irrigation was ceased at growth stage R6.

Grain yield

Irrigated and rain-fed grain yield values ranged from 5494 to 10675 kg ha^{-1} and 2611 to 6153 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 5). On average, irrigated plots yielded about 4000 kg ha^{-1} more than rain-fed plots (Table 6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effects were observed (Table 5). Single degree-of-freedom contrasts did reveal some differences in treatment groupings. Regardless of plots being irrigated or rain-fed, plots receiving 180 kg N ha^{-1} had increased yields when the rate was split either foliarly or surface applied compared to all 180 kg N ha^{-1} being applied preplant (Table 7). Irrigated treatments that were fertilized did not display any significant differences in yield; however, the 90 kg N ha^{-1} preplant application did yield 1300 kg ha^{-1} more than the split foliar application (Table 7). Rain-fed consistently yielded more when the N application was split compared to preplant only applications, especially for the split surface applications. The split foliar application did yield about 1400 kg ha^{-1} more than the preplant only treatments for both the 90 and

Table 5. P value results from analysis of variance for the main and interactive effects of irrigation (Irr.) and fertilizer treatment (Tmt.) on grain yield, N use efficiency (NUE), and water use efficiency (WUE).

Source	Grain yield	NUE	WUE
STW[a] 2012			
Irrigation	0.0145	0.0604	—
Treatment	0.6510	0.5189	—
Irr. X tmt.	0.1104	0.3773	—
LCB[a] 2012			
Irrigation	0.0131	0.7628	—
Treatment	0.2634	0.0124	—
Irr. X tmt.	0.9341	0.3206	—
STW 2013			
Irrigation	0.0085	0.0810	0.0023
Treatment	0.0028	0.2609	0.0180
Irr. X tmt.	0.0013	0.1624	0.0013
LCB 2013			
Irrigation	0.0043	0.1007	0.0021
Treatment	0.0031	0.0186	0.0029
Irr. X tmt.	0.4462	0.8306	0.3732

[a]STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

Table 6. Irrigated and rain-fed treatment means for grain yield, N use efficiency (NUE), and water use efficiency (WUE).

Source	Grain yield kg ha^{-1}	NUE %	WUE kg ha^{-1} mm^{-1}
STW[a] 2012			
Irrigated	8055	19.9	—
rain-fed	4240	7.3	—
P value	0.0145	0.0604	—
LCB[a] 2012			
Irrigated	5769	15.6	—
rain-fed	4435	12.0	—
P value	0.0131	0.7628	—
STW 2013			
Irrigated	9061	38.0	15.3
rain-fed	2918	16.8	5.4
P value	0.0085	0.081	0.0023
LCB 2013			
Irrigated	9691	68.0	12.4
rain-fed	4075	39.0	5.3
P value	0.0043	0.1007	0.0021

[a]STW, Stillwater, OK; LCB, Lake Carl Blackwell, OK.

180 kg N ha^{-1} rates, however, foliar N applications were not as effective as the split surface applied treatments at improving grain yield for rain-fed conditions.

NUE

Irrigated and rain-fed NUE values ranged from 13.1 to 58.1 percent and nearly zero to 19.2 percent, respectively. Analysis of variance determined the effect of irrigation to be significant on NUE (Table 5). NUE values on average increased more than 10 percent for plots that received irrigation (Table 6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effect on NUE was observed (Table 5). Single degree-of-freedom contrasts did reveal treatment grouping differences. For the 90 kg N ha^{-1} treatments no increase in NUE was observed when foliar applications were compared to the preplant only application, in fact the irrigated plots had significantly higher NUE values (Table 7). When evaluating the plots that received a total of 180 kg N ha^{-1}, slight increases in NUE were observed regardless of irrigation or rain-fed conditions. No differences were observed for the irrigated plots, but there was consistently an increase in NUE for the rain-fed plots that received a split application compared to the preplant only application (Table 7).

Table 7. Single degree-of-freedom contrast results for differences in treatment groupings for grain yield, N use efficiency (NUE), and water use efficiency (WUE) for Stillwater, OK (STW) in 2012 and 2013. Values reported are the difference in mean values for the group after the 'vs.' subtracted from the mean value of the group before the 'vs.'. Values listed below the 'Main' title are treatments pooled across irrigated and rain-fed plots.

Contrast	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed
	Grain yield (kg ha^{-1})			NUE (%)			WUE (kg ha^{-1} mm^{-1})		
STW 2012									
90 Pre vs. split foliar	10	1363	−1341	6.9	17.2*	−3.3	—	—	—
180 Pre vs. split foliar	−396	655	−1448	−1.3	2.8	−5.5	—	—	—
180 Pre vs. split surface	−1040	45	−2126*	−6.4	−0.7	−12.0	—	—	—
180 Foliar vs. surface	−644	−610	−678	−5.1	−3.5	−6.6	—	—	—
180 Pre vs. split	−718	350	−1787*	−3.8	1.1	−8.8	—	—	—
STW 2013									
90 Pre vs. split foliar	−6	350	−362	−16.6*	−19.6*	−13.6	−0.1	0.5	−0.7
180 Pre vs. split foliar	910*	2949*	−1128	−6.7	−6.9	−20.3*	1.6*	5.4*	−2.2*
180 Pre vs. split surface	557	2110*	−997	−12.7	−6.7	−18.7	0.8	3.5	−1.8*
180 Foliar vs. surface	−354	−839	131	−6.0	−13.5	1.6	−0.8	−1.9*	0.4
180 pre vs. split	734*	2530*	−1062*	−9.7	0.1	−19.5*	1.2*	4.5*	−2.0*

*Denotes differences significant at least at the 0.10 alpha level.

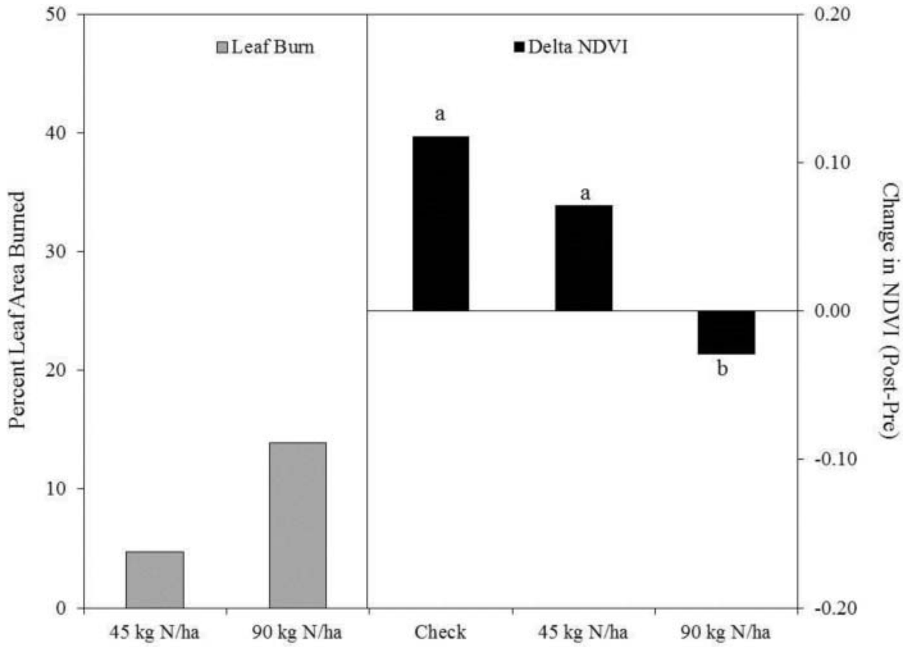

Figure 3. Stillwater, OK (2012) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. Bars with different letters are significantly different at the 0.10 alpha level.

Foliar leaf burn

No difference was observed in visual leaf burn ratings between irrigated and rain-fed treatments. The majority of the leaf burn for this site-year occurred after the first application with minimal additional burn after the second application. Plots that received a total of 90 kg N ha^{-1} applied foliarly, displayed overall higher burn ratings than the plots receiving 45 kg N ha^{-1} (Figure 3). This was reflected in the change in NDVI values taken prior to foliar applications and after foliar applications. Decreased changes in NDVI were observed for the 45 kg N ha^{-1} treatments compared to the check. The 90 kg N ha^{-1} foliar treatments actually reported lower NDVI values post application time compared to pre application and thus a statistically lower change in NDVI compared to the check and 45 kg N ha^{-1} treatments (Figure 3).

Lake Carl Blackwell, OK (2012)

Water balance

Irrigation was started at Lake Carl Blackwell, OK shortly after the time the water balance fell below zero (Figure 2). This coincided with the V6 maize growth stage. Early irrigation was applied at rates of less than 25 percent PET. Irrigation rates were increased through the reproductive growth stages and irrigation was ceased at growth stage R6.

Grain yield

Irrigated and rain-fed grain yield values ranged from 4490 to 7351 kg ha^{-1} and 1322 to 5914 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 5). On average, irrigated plots yielded about 1300 kg ha^{-1} more than rain-fed plots (Table 6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effect was observed (Table 5). Single degree-of-freedom contrasts did not reveal any statistically different treatment groupings. Preplant applications had higher grain yields compared to split foliar applications for both N rates, regardless if irrigated and rain-fed (Table 8). Though not statistically significant, an

Table 8. Single degree-of-freedom contrast results for differences in treatment groupings for grain yield, N use efficiency (NUE), and water use efficiency (WUE) for Lake Carl Blackwell, OK (LCB) in 2012 and 2013. Values reported are the difference in mean values for the group after the 'vs.' subtracted from the mean value of the group before the 'vs.'. Values listed below the 'Main' title are treatments pooled across irrigated and rain-fed plots.

	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed	Main	Irrigated	Rain-fed
Contrast	Grain yield (kg ha^{-1})			NUE (%)			WUE (kg ha^{-1} mm^{-1})		
LCB 2012									
90 Pre vs. split foliar	894	1228	561	11.2*	19.7*	2.7	—	—	—
180 Pre vs. split foliar	563	791	336	5.8	6.1	5.5	—	—	—
180 Pre vs. split Surface	−90	−437	255	0.3	−2.7	3.3	—	—	—
180 Foliar vs. surface	−653	−1228	−79	−5.4	−8.7	−2.2	—	—	—
180 Pre vs. split	236	177	296	3.1	1.7	4.4	—	—	—
LCB 2013									
90 Pre vs. split foliar	−729	−873	−584	−27.1*	−26.9	−27.3	−1.0	−1.3	−0.8
180 Pre vs. split foliar	−1436	−2369*	−503	−41.7*	−55.8*	−27.7	−1.9	−3.4*	−0.4
180 Pre vs. split Surface	60	−716	835	−27.9*	−39.4*	−16.7	0.1	−1.0	1.1
180 Foliar vs. surface	1496	1653	1338	13.9	16.7	11	2.0	2.4	1.5
180 Pre vs. split	−688	−1542	167	−34.8*	−47.4*	−22.2	−0.9	−8.2*	0.4

*Denotes differences significant at least at the 0.10 alpha level.

increase of about 400 kg ha^{-1} in grain yield were observed for split surface applications compared to preplant only applications on irrigated treatments (Table 8).

NUE

Irrigated and rain-fed NUE values ranged from 4.2 to 44.2 percent and nearly zero to 44.0 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE (Table 5). On average, NUE values increased no more than three percent for plots that received irrigation (Table 6). No significant interaction effect of irrigation and fertilizer treatment was observed, but the main effect of fertilizer treatment was significant and was explained with the single degree-of-freedom contrasts. The only statistically significant contrasts were the increased NUE values of all the 90 kg N ha^{-1} preplant treatments compared to the foliar applied treatments of the irrigated plots and plots grouped across irrigated and rain-fed treatments (Table 8). For rain-fed treatments, plots receiving 90 or 180 kg N ha^{-1} preplant had increases in NUE compared to either split applications. Even though the split applications did not compare well with the preplant applications, when the foliar application was compared to the surface applied method, the surface applied had increased NUE values in both the irrigated and rain-fed treatments.

Foliar leaf burn

No difference was observed in visual leaf burn ratings between irrigated and rain-fed treatments. The majority of the leaf burn for this site-year occurred after the first application with minimal additional burn after the second application. Visual leaf burn ratings were greater than 40 percent of the leaf area burned for plots that received a total of 90 kg N ha^{-1} applied foliarly and greater than 25 percent for plots receiving 45 kg N ha^{-1} (Figure 4). This was reflected in the change in NDVI values taken prior to foliar applications and after foliar applications. Statistically significant, reduced changes in NDVI were observed for both the 45 and 90 kg N ha^{-1} foliar treatments (Figure 4).

Stillwater, OK (2013)

Water balance

Irrigation was initiated at Stillwater, OK shortly before the time the water balance fell below zero for a significant period of time (Figure 1). This coincided with the V10 growth stage. Irrigation was applied

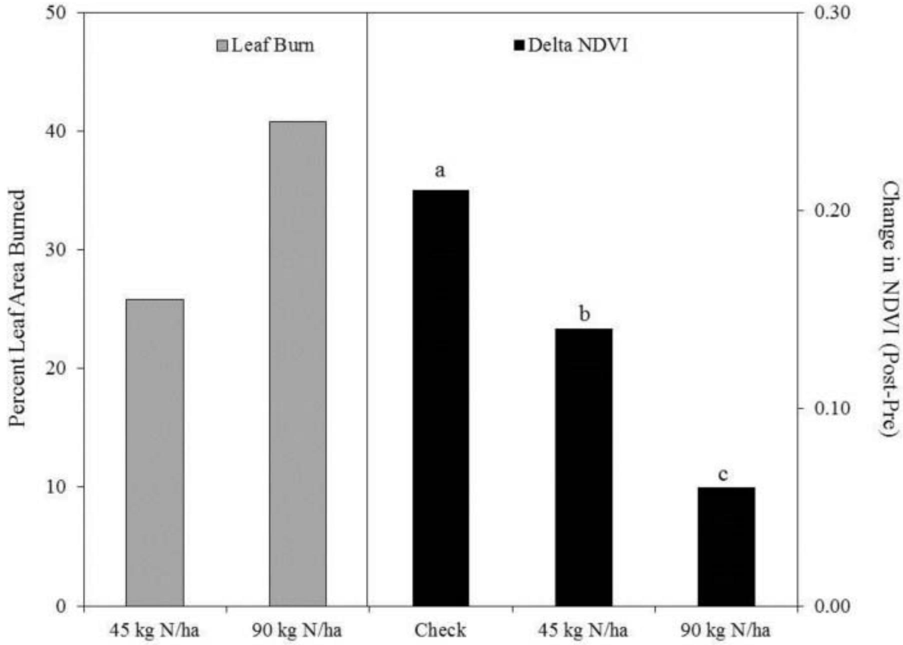

Figure 4. Lake Carl Blackwell, OK (2012) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. Bars with different letters are significantly different at the 0.10 alpha level.

at rates of approximately 30 percent PET. Irrigation was ceased at approximately the R3 maize growth stage as substantial, unseasonable moisture fell in the middle to late July.

Grain yield

Irrigated and rain-fed grain yield values ranged from 6224 to 11583 kg ha^{-1} and 1425 to 3856 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 5). On average, irrigated plots yielded about 6000 kg ha^{-1} more than rain-fed plots (Table 6). The interactive effect of irrigation and fertilizer treatment, as well as the main effect of fertilizer treatment were also significant and were interpreted with the single degree-of-freedom contrasts. Grain yields as affected by treatment groupings were conflicting between irrigated and rain-fed treatments. For the irrigated treatments preplant applications outperformed both methods of split applications (Table 7). However, in the rain-fed treatments split applications consistently increased grain yields compared to all N fertilizer being applied preplant (Table 7).

NUE

Irrigated and rain-fed NUE values ranged from 1.2 to 83.7 percent and nearly zero to 60.1 percent, respectively. Analysis of variance determined the effect of irrigation to be significant on NUE (Table 5). NUE values on average increased more than 20 percent for plots that received irrigation (Table 6). No significant fertilizer treatment effect or interaction of irrigation and fertilizer treatment effect on NUE was observed (Table 5). Single degree-of-freedom contrasts did reveal treatment grouping differences. Regardless of N application rate or mid-season application method, split applications improved NUE values (Table 7). When comparing the two split application methods, the surface applied method increased NUE compared to foliar application methods for irrigated treatments, but there was no difference observed in the rain-fed treatments (Table 7).

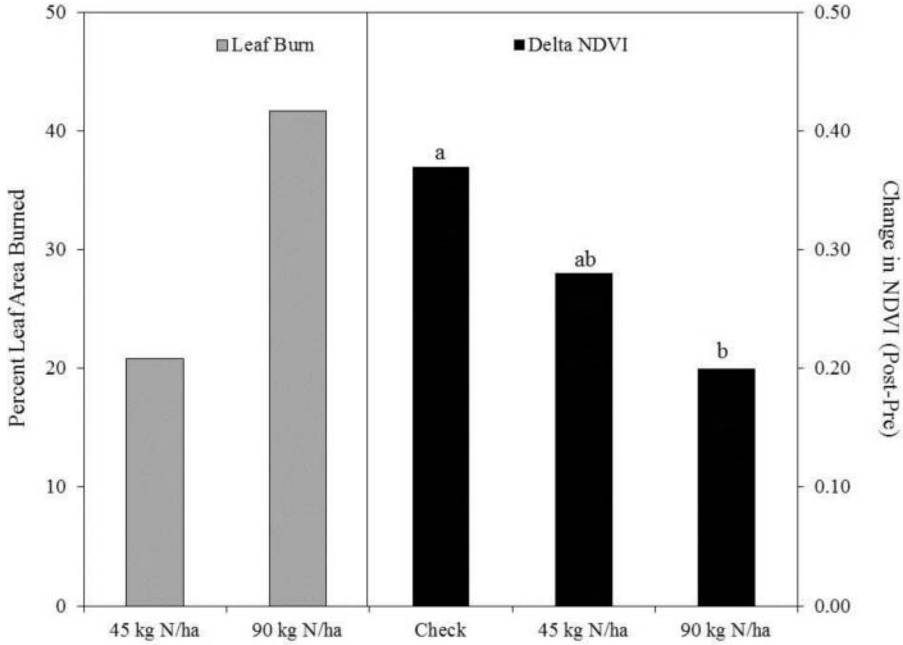

Figure 5. Stillwater, OK (2013) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. Bars with different letters are significantly different at the 0.10 alpha level.

Foliar leaf burn

Minimal differences were observed in visual leaf burn ratings between irrigated and rain-fed treatments. However, they were not significantly different at the 0.10 level. Very little leaf burn was observed after the first foliar fertilizer application while the majority of the leaf burn occurred as a result of the second application. Visual leaf burn ratings were greater than 20 percent of the leaf area burned for plots that received a total of 45 kg N ha^{-1} applied foliarly and almost double the burned area for the 90 kg N ha^{-1} (Figure 5). This was supported by the change in NDVI values taken prior to foliar applications and after foliar applications. Though there was no statistical difference between the changes in NDVI between the two fertilized treatments, the 45 kg N ha^{-1} treatment had a higher change in NDVI compared to the 90 kg N ha^{-1} treatment (Figure 5).

WUE. Irrigated and rain-fed WUE values ranged from 10.5 to 19.3 kg ha^{-1} mm^{-1} and 2.7 to 7.5 kg ha^{-1} mm^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on WUE (Table 5). On average, irrigated plots resulted in about 10 kg ha^{-1} mm^{-1} more than rain-fed plots (Table 6). The interactive effect of irrigation and fertilizer treatment, as well as the main effect of fertilizer treatment on WUE values were also significant and were explained with the single degree-of-freedom contrasts. Conflicting results were observed between the irrigated and rain-fed WUE values. For the irrigated plots, the preplant only fertilizer treatments increased WUE values compared to the two split applications (Table 7). The opposite was observed for the rain-fed treatments, in which the two split application methods performed similarly at increasing the WUE values compared to the all preplant treatments (Table 7).

Lake Carl Blackwell, OK (2013)

Water balance

Irrigation was started at Lake Carl Blackwell, OK at approximately the V12 growth stage (Figure 2). Very little irrigation water was applied (27 mm) during the late vegetative and early reproductive stages. Irrigation was ceased at approximately the R2 maize growth stage as substantial, unseasonable moisture fell in the middle to late July. According to the PET reported from the adjacent climate-monitoring site, the rain-fed site water balance only fell below zero for approximately one week during the early reproductive growth stages (Figure 2).

Grain yield

Irrigated and rain-fed grain yield values ranged from 4675 to 12871 kg ha^{-1} and 1326 to 7173 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 5). On average, irrigated plots yielded about 5500 kg ha^{-1} more than rain-fed plots (Table 6). The interactive effect of irrigation and fertilizer treatments was not significant; however, the main effect of fertilizer treatment was significant and was explained with the single degree-of-freedom contrasts. Regardless if plots were irrigated or rain-fed, increases in grain yield were observed for plots receiving a split foliar application compared to a preplant only fertilizer application (Table 8). This was particularly true for the irrigated, 180 kg N ha^{-1} treatment, in which yields increased more than 2000 kg ha^{-1} (Table 8). Surface applied split applications improved yields for the irrigated treatments, but not for the rain-fed treatment and overall didn't perform as well as the foliar fertilized plots (Table 8).

NUE

Irrigated and rain-fed NUE values ranged from 6.4 to close to 100 percent and 2.3 to 72.3 percent, respectively. Analysis of variance revealed the effect of irrigation to be insignificant on NUE (Table 5). NUE values on average increased almost 30 percent for plots that received irrigation (Table 6). The main effect of fertilizer treatment was significant; however, the irrigation by fertilizer treatment interaction effect did not statistically affect NUE. Single degree-of-freedom contrasts did reveal several treatment grouping differences. Regardless of plots being irrigated or rain-fed, both methods of split applications increased NUE values (Table 8). The increase was more prominent and statistically significant for the irrigated treatments (Table 8). Though not

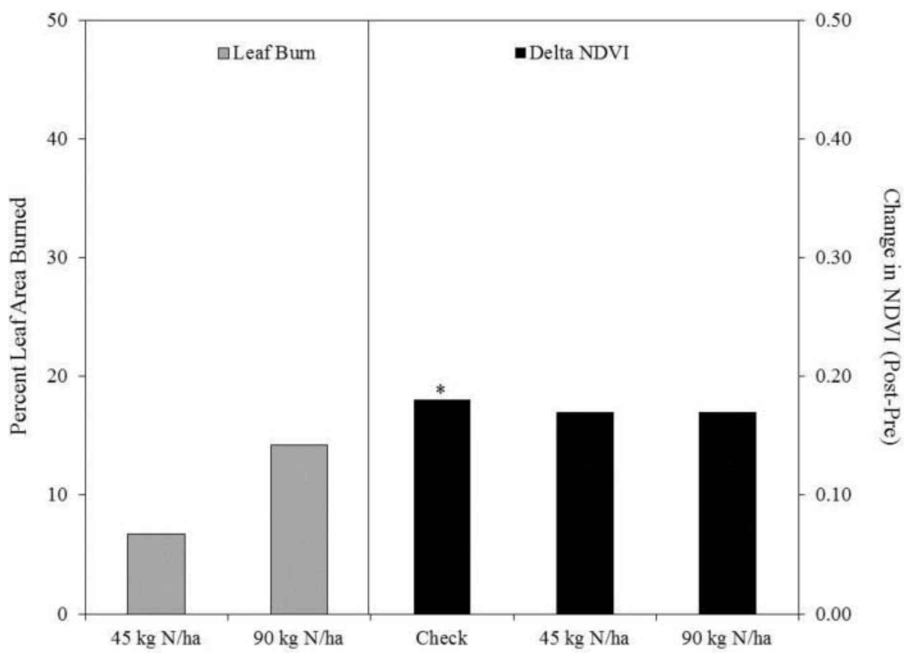

Figure 6. Lake Carl Blackwell (2013) percent leaf area burned and change in normalized difference vegetative index (NDVI) pre and post fertilizer application for plots receiving foliar fertilizer compared to a check. (*) Denotes treatments were not significantly different at the 0.10 alpha level.

statistically significant, foliar applied treatments increased NUE by at least 11 percent compared to surface applied split applications (Table 8).

Foliar leaf burn

Less than 10 and 15 percent of the leaf area displayed foliar fertilizer burn symptoms for the 45 and 90 kg N ha^{-1} treatments, respectively (Figure 6). No significant differences in changes in NDVI were observed for either treatment, supporting the lack of reduced growth from leaf burn (Figure 6).

WUE

Irrigated and rain-fed WUE values ranged from 5.5 to 17.0 kg ha^{-1} mm^{-1} and 1.7 to 8.5 kg ha^{-1} mm^{-1}, respectively. Analysis of variance determined the effect of irrigation was significant on WUE (Table 5). On average, irrigated plots resulted in about 7 kg ha^{-1} mm^{-1} more than rain-fed plots (Table 6). The interactive effect of irrigation and fertilizer treatment was not observed to be significant; however, the main effect of fertilizer treatment on WUE values was significant and was explained with the single degree-of-freedom contrasts. Regardless of being irrigated or rain-fed, plots that received foliar fertilizer applications had increased WUE values compared to preplant only treatments (Table 8). No significant difference was observed between surface applied treatments and preplant only treatments; however, the surface applied treatments did not perform as well as the foliar treatments (Table 8).

Discussion

Even though the amount of irrigation water was applied at less than 40 percent of the PET demand for all four site-years, significant differences in grain yield were observed. Research studies have reported that for maize, irrigation during moisture sensitive periods, such as reproductive growth stages, can still produce an optimum grain yield and maximize water use efficiency (Shaozhong et al, 2000). This type of deficit irrigation management is effective at reducing water consumption while not greatly impacting grain yield (Pandey et al., 2000). The most critical maize growth stage at which water stress begins to affect grain yield is typically the two weeks prior to and following silking (Singh and Singh, 1995). For all four site-years, irrigation was started in the vegetative growth stages and continued until reproductive maturity had been reached or ample rainfall was present. The increases in NUE and WUE efficiency when the maize crop was irrigated were to be expected. Improvements in NUE and WUE are likely due to greater N uptake and grain yield response, similarly to what has been reported by other researchers (Martin et al., 1982; Eck, 1984; Al-Kaisi and Yin, 2003; Di Paolo and Rinaldi, 2008).

The variability in grain yield response to mid-season N fertilizer applications between site-years and irrigated or rain-fed treatments is not unexpected. Though some researchers have reported improvement in maize grain yields with mid-season N applications (Stevenson and Baldwin, 1969; Walsh et al., 2012), others have also reported extreme variability in the response to mid-season N applications from year to year (Welch et al., 1971). It is widely accepted that to optimize NUE of applied N fertilizer, the N should be applied at the time of maximum N uptake (Aldrich, 1984; Olson and Kurtz, 1982; Russelle et al., 1981; Welch et al., 1971; Walsh et al., 2012). For rain-fed conditions the NUE was improved for three of the four site-years when a mid-season N application was made. The only rain-fed site-year in which NUE was not increased was at Lake Carl Blackwell, OK (2012). This was likely due to the extreme amount of leaf burn observed in the foliar treatments along with a fairly early water deficit that made water a more limiting factor than N. For all four irrigated site-years the NUE was increased with mid-season surface applications for the 180 kg N ha^{-1} fertilizer rates. In irrigated site-years where foliar leaf burn was substantial, such as Stillwater, OK (2012) and Lake Carl Blackwell (2012), no improvement was observed in in NUE; however, the opposite was observed for the other two site years in which leaf burn was minimized. At the Lake Carl Blackwell site in 2013 observed improvements in grain yield and NUE from split applications may have been due to some of the preplant N being lost to denitrification and/or leaching losses. The uncharacteristic wet late-spring and summer at this site, left the surface water-logged for extended periods of time. These detrimental effects of water-logging on N fertility in maize have been well documented (Meyer et al., 1987). Foliar applications at this site outperformed the surface applications. Saturated surface conditions likely decreased or did not facilitate root growth (Lizaso and Ritchie, 1997), which then would not have allowed for greater acquisition of surface applied N fertilizer.

Because lower grain yields decrease the demand of N nutrition for maize grown in a more semi-arid environment, it was hypothesized that low fertilizer rates supplemented foliarly could have potential to improve grain yield and NUE, as long as leaf burn was minimized. The rapid drying of the foliar N fertilizer spray on the leaf is what leads to leaf burn. This drying is affected by temperature, relative humidity, and wind speed (Marschner, 2012). When leaf burn was significant, reductions in grain yield and sometimes NUE were typically observed. For the site-years where significant leaf burn was observed, one common trend was that when temperatures were above 24°C the four hours after application and when no measureable rainfall occurred for three days following foliar applications, like at both sites in 2012 (Table 4). Lack of water in the top soil can lead to reduced nutrient availability and thus be crop growth limiting and not allow roots to obtain water at deeper depths (Marschner, 2012). Foliar fertilization has the potential to alleviate this. For three of the four rain-fed site years, increases in grain yield, NUE, and WUE were observed for foliar applications compared to preplant only applications. The only site-year this trend was not observed was Lake Carl Blackwell (2012), which was the site that exhibited the most damage from leaf burn.

The WUE values reported for both irrigated site-years analyzed fall within the range 2.2 to 39.9 kg ha^{-1} mm^{-1} of what has been reported for maize (Zwart and Bastiaanssen, 2004). The WUE values for the rain-fed treatments were obviously at the lower end of this range for maize and even had values lower than 2.2 kg ha^{-1} mm^{-1} (Zwart and Bastiaanssen, 2004). One trend observed for the WUE values for both site-years analyzed was that the treatment differences coincided with grain yield differences. This is due to the methodology in which WUE was calculated. The calculation is the ratio of actual grain yield to ET. In determining actual ET, the change in soil profile moisture was derived from measurements at the beginning of the growing season and after harvest. It could likely be assumed that much of the water in the soil profile was lost to evaporation and some transpiration during the grain dry-down period after irrigation had been ceased. Because of this, there was no fertilizer treatment differences observed in the quantity of soil moisture between fertilizer treatments (data not reported). If no differences were observed in ET, then differences in WUE based on N fertilizer treatment would be dictated by the differences in grain yield.

Conclusions

With four site-years reporting four differing sets of results that likely came about from differences in weather, one could conclude why managing N in the Southern Great Plains can be difficult. Managing irrigation with deficit irrigation applications can be beneficial to grain yield, as long as the irrigation is applied at the most water stress sensitive time (the weeks prior and post silking). Split fertilizer applications typically increased NUE for both irrigated and rain-fed treatments; however, the predictability of when it would increase grain yield was difficult to determine. Split fertilizer applications allow for mid-season adjustment, if enough N has potentially been lost that could be a detriment to final grain yield. The use of foliar N fertilizer showed the potential to increase grain yield and NUE, in an environment in which N demand isn't as elevated as the high maize producing regions, like the Midwestern United States. However, caution needs to be taken to avoid potential grain yield reducing leaf burn.

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The mention of any trademarked products or equipment utilized in this experiment was for research purposes only and does not act as an endorsement by Oklahoma State University. The authors and Oklahoma State University have no

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