Hindawi Publishing Corporation
International Journal of Agronomy
Volume 2014, Article ID 247835, 10 pages
http://dx.doi.org/10.1155/2014/247835

Research Article

Effect of Irrigation and Preplant Nitrogen Fertilizer Source on Maize in the Southern Great Plains

Jacob T. Bushong, Eric C. Miller, Jeremiah L. Mullock, D. Brian Arnall, and William R. Raun

Department of Plant and Soil Sciences, Oklahoma State University, 368 Agricultural Hall, Stillwater, OK 74078, USA

Correspondence should be addressed to Jacob T. Bushong; jacob.bushong@okstate.edu

Received 16 June 2014; Revised 26 November 2014; Accepted 26 November 2014; Published 17 December 2014

Academic Editor: Othmane Merah

With the demand for maize increasing, production has spread into more water limited, semiarid regions. Couple this with the increasing nitrogen (N) fertilizer costs and environmental concerns and the need for proper management practices has increased. A trial was established to evaluate the effects of different preplant N fertilizer sources on maize cultivated under deficit irrigation or rain-fed conditions on grain yield, N use efficiency (NUE), and water use efficiency (WUE). Two fertilizer sources, ammonium sulfate (AS) and urea ammonium nitrate (UAN), applied at two rates, 90 and 180 kg N ha^{-1}, were evaluated across four site-years. Deficit irrigation improved grain yield, WUE, and NUE compared to rain-fed conditions. The preplant application of a pure ammoniacal source of N fertilizer, such as AS, had a tendency to increase grain yields and NUE for rain-fed treatments. Under irrigated conditions, the use of UAN as a preplant N fertilizer source performed just as well or better at improving grain yield compared to AS, as long as the potential N loss mechanisms were minimized. Producers applying N preplant as a single application should adjust rates based on a reasonable yield goal and production practice.

1. Introduction

Over the last two decades, the number of maize hectares planted and harvested in the Southern Great Plains of the United States has increased. While the number of irrigated hectares has remained fairly constant over this time span, the increase in rain-fed hectares has more than doubled [1]. This rise in area cultivated to maize is due to increased demand for maize for livestock feed exports and maize-based ethanol production [2]. With this increased production and an ever-growing concern for environmental implications, sustainable production practices that maximize the use of resources are being sought.

In some portions of the Southern Great Plains, groundwater is available for irrigation of maize production. However, in areas, such as the Ogallala Aquifer, the amount of water extracted from the aquifer has been much greater than the amount recharged leading to drastic declines in the water table which can exceed 50 percent of the saturated thickness [3]. One method utilized to better maximize maize grain yield and water use efficiency (WUE) has been deficit irrigation. Deficit irrigation is a management practice in which irrigation is applied below the evapotranspiration (ET) level at critical growth stages without significant reduction in grain yields [4]. The most critical growth stage at which moisture stress has been observed to be the most yield limiting in maize is the two weeks prior and the two weeks following silking [5]. Irrigation during the reproductive stages can still produce optimum grain yields and maximize WUE [6, 7].

The inefficient use of N fertilizer has been one of the major focal points for environmental contamination. A considerable factor affecting maize grain yield and N use efficiency (NUE) is the chemical make-up of the N fertilizer source. The source of the N fertilizer can impact the potential rate of loss and/or availability of the fertilizer [8]. According to Tsai et al. [9], utilizing ammoniacal-based N fertilizer sources may reduce potential losses via leaching and denitrification and may extend the availability of N in the soil for plant uptake throughout the growing season. Stevenson and Baldwin [10] compared the effects of ammonium nitrate,

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]	SO_4-S[d]	P[e]	K[e]	Total N[f]	Organic C[f]
					mg kg^{-1}					g kg^{-1}	
STW	2012	Easpur loam, 0 to 1 percent slopes, occasionally flooded	Easpur: fine-loamy, mixed, superactive, and thermic Fluventic Haplustolls	6.2	11	4	13	30	119	0.8	9.4
LCB	2012	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: fine-silty, mixed, superactive, and thermic Cumulic Haplustolls Oscar: fine-silty, mixed, superactive, and thermic Typic Nastrustalfs	5.6	8	3	8	22	111	0.6	7.8
STW	2013	Norge loam, 3 to 5 percent slopes	Norge: fine-silty, mixed, active, and thermic Udic Paleustolls	5.0	16	11	15	87	117	1.2	10.5
LCB	2013	Port-Oscar complex, 0 to 1 percent slopes, occasionally flooded	Port: fine-silty, mixed, superactive, and thermic Cumulic Haplustolls Oscar: fine-silty, mixed, superactive, and thermic Typic Nastrustalfs	6.1	6	5	8	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 [20].
[d]Calcium monophosphate extract [21].
[e]Mehlich III extract [22].
[f]Dry combustion [23].

urea, and anhydrous ammonia applied at different times in maize. Regardless of application time, anhydrous ammonia yielded 240 to 260 kg ha^{-1} more than both ammonium nitrate and urea. Power et al. [11] evaluated the effects of ammonium sulfate (AS), ammonium nitrate, calcium nitrate, and urea on maize grain yield and dry matter production. They reported that maize dry matter increased significantly with fertilization; however, grain yield differences among the different N sources were seldom significant. The ammoniacal sources typically displayed increased dry matter production with increasing N rates when compared to the calcium nitrate treatments while urea treatments were less than the other two ammoniacal sources. Olson et al. [12] compared anhydrous ammonia to urea ammonium nitrate (UAN) that was applied at planting or sidedress. They reported that anhydrous ammonia yielded more than the UAN treatment. They attributed the decreased yields in the UAN treatments to the nitrate component, which has the potential for being lost through leaching or denitrification, and the urea component, which has greater potential for N losses via ammonia volatilization. Freeman et al. [8] investigated the use of urea and anhydrous ammonia applied at different times with different soil incorporation procedures. They concluded that both grain yield and N uptake were improved when the N fertilizer source was urea, but only if the urea was applied and incorporated preplant or after harvest when residue incorporation is practiced.

The NUE and WUE of maize hybrids often coincide with one another [13] because of the greater response to N fertilizer with increases in added water [14, 15]. Because of this relationship, researchers have evaluated the effects of N fertilizer practices on WUE. For maize fields to be productive and resource-use efficient, numerous researchers have proposed a compromise of management practices that optimize grain yield and WUE. These practices include only applying N when water is adequate [15, 16], maintaining proper fertility based on tillage practices [16] and applying proper amounts of irrigation at critical growth stages [15, 17, 18].

The objectives of this study were to evaluate the interactive effects of two N fertilizer sources (UAN and AS), application rate, and deficit irrigation on maize early season vegetative growth, grain yield, NUE, and WUE. Our hypotheses for this trial are parallel to what previous researchers have documented in that the use of irrigation will increase not only the grain yield and NUE, but also the WUE. How efficient each fertilizer source will be for each system will be determined with the premise that the source that is more ammoniacally based will be more efficient regardless of system.

2. Materials and Methods

The experiment was conducted at two locations (Stillwater, OK, and Lake Carl Blackwell, OK) during the 2012 and 2013 growing seasons. Basic early spring preplant soil nutrient testing results (0–15 cm) and site soil mapping unit descriptions are provided in Table 1. If required, sites were fertilized prior

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

Treatment number	Preplant N rate kg N ha^{-1}	Preplant N source[a]
1	0	—
2	90	UAN
3	90	AS
4	180	UAN
5	180	AS

[a]UAN: urea ammonium nitrate (28-0-0); AS: ammonium sulfate (21-0-0); applied prior to planting and mechanically incorporated.

to planting to 100 percent sufficient levels based on soil test P and K results and the fertilizer recommendations described in Zhang and Raun [19]. This practice was conducted to ensure that N was the only limiting nutrient.

A split-block experimental design with three replications per site-year was employed to evaluate the effects of irrigation and N fertilizer source in this experiment. Irrigated or rain-fed treatments served as the main plot, while five N fertilizer treatments based upon N source and N rate served as the subplot. Ammonium sulfate (AS, 21-0-0) and urea ammonium nitrate (UAN, 28-0-0) N fertilizer sources were evaluated in this experiment. Both fertilizer sources were applied at N rates of 90 and 180 kg N ha^{-1}. Fertilizer was broadcast applied and mechanically incorporated prior to planting. A complete list of the five N fertilizer treatments, which includes an unfertilized check, implemented to both irrigated and rain-fed plots, is provided in Table 2. To ensure that the added sulfur associated with the AS fertilizer would not have an effect on treatments, preplant soil samples were analyzed for sulfate-sulfur content (Table 1). The sulfate-sulfur soil test values were above sufficient levels described by the regional recommendations of Zhang and Raun [19].

For all site-years, plot sizes were 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, irrigation totals, and harvest dates are provided in Table 3. Planting took place in the spring using maize hybrids that are known to express improved drought tolerance. Seeding rates were based on best agronomic practices for the region. The type of irrigation used was surface drip irrigation. Though this is not an economically viable option for irrigation in maize production, it was used strictly for research purposes. The use of drip irrigation allowed for the accurate measurement and placement of applied water. 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 (mm) distributed over each plot was determined by measuring the liters of water applied over the given area.

Potential differences in early vegetative growth/biomass accumulation were measured using the normalized difference vegetative index (NDVI) values collected with a Greenseeker (Trimble, Sunnyvale, CA, USA) ground based, optical sensor. Sensor readings were collected at the V6, V8, V10, and V12 growth stages [24] for all site-years.

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 for a standard moisture content of 155 g kg^{-1}. Grain subsamples were oven-dried and processed to pass a 140 mesh screen and were analyzed for total N content using a dry combustion analyzer. The NUE was then calculated by employing the difference method described by Varvel and Peterson [25] that utilizes the following equation:

$$\text{NUE} = \frac{(\text{Grain N uptake treated} - \text{Grain N uptake check})}{\text{N fertilizer added}}, \quad (1)$$

where grain N uptake for treated plots or the check plot was quantified by the percent N in the grain multiplied by the grain yield.

The WUE (kg ha^{-1} mm^{-1}) was measured for both site locations during the 2013 growing season. It was calculated as the ratio of dry grain yield (kg ha^{-1}) at 15.5 percent moisture to the seasonal water use expressed as ET. The ET was estimated using a modified water balance proposed by Heerman [26] detailed in the following equation:

$$\text{ET} = \pm\Delta\text{SWC} + R + I, \quad (2)$$

where ΔSWC is the change in soil profile (0 to 80 cm) volumetric soil water content from planting to harvest, R is the rainfall, I is the irrigation. It was assumed that water losses due to deep percolation or surface runoff were negligible. 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). Samples were collected the day prior to preplant fertilizer application and the day following grain harvest for each location. A moist weight was collected in the field and the samples were then oven-dried until no moisture was present in the sample. Daily rainfall was measured from the adjacent Oklahoma Mesonet [27] climate-monitoring station.

To understand the relationship of irrigation water applied to the daily potential ET (PET) for the trial area, daily PET values were determined. The PET values were derived from the American Society of Civil Engineers' Standardized Reference Evapotranspiration Equation described by Walter et al. [28]. Data collected as inputs for the equation to determine PET and rainfall were downloaded from the adjacent Oklahoma Mesonet [27] climate-monitoring site. The percent of irrigation water applied compared to PET losses for each site-year is described in Table 3.

Analysis of variance techniques was employed to detect significant differences for the main and interactive effects of treatments on early vegetative growth (NDVI), grain yield, NUE, and WUE. Single degree-of-freedom contrasts were used to partition statistical differences in treatment

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

Field activity	2012		2013	
	STW[a]	LCB[a]	STW	LCB
Preplant N fertilization date	April 2	April 5	March 18	March 18
Planting date	April 9	April 10	March 20	March 20
Maize hybrid	Pioneer P1498HR	Pioneer P0876HR	Pioneer P1498HR	Dekalb 63–55
Seeding rate (seeds ha^{-1})	49,000	49,000	54,000	54,000
Start irrigation	May 16	May 17	June 13	June 14
Cease irrigation	July 11	July 9	July 9	July 9
Irrigation percent of PET[b]	38	21	28	13
Number of irrigations	22	14	9	5
Amount of irrigation (mm)	173	89	55	27
Amount of rainfall (mm)	233	201	621	834
Harvest date	August 6	July 26	September 9	September 4

[a]STW: Stillwater, OK; LCB: Lake Carl Blackwell, OK.
[b]PET: potential evapotranspiration.

grouping means as well as detect any potential linear or quadratic trends based upon N fertilizer rate. All site-years were analyzed separately and thus the results are reported separately. For all analyses, an alpha level of 0.10 was used to determine statistical significance.

3. Results

3.1. Stillwater, OK (2012)

3.1.1. Vegetative Growth. No significant differences were observed in either the irrigated or rain-fed NDVI values for any of the growth stages evaluated (Figure 1). Regardless of treatment, the increase in NDVI appeared linear for the growth stages V6 through V10, and then plateaued between the V10 and V12 growth stages. One noticeable trend that was observed was that the 180 kg N ha^{-1} UAN irrigated treatments had the lowest NDVI values for the V6, V8, and V10 growth stages, but the opposite was observed for that specific treatment under rain-fed conditions (Figure 1).

3.1.2. Grain Yield. Irrigated and rain-fed grain yield values ranged from 6381 to 12265 kg ha^{-1} and 2565 to 5980 kg ha^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on grain yield (Table 4). On average, irrigated plots yielded about 4500 kg ha^{-1} more than rain-fed plots (Table 5). The interactive effect of irrigation and fertilizer treatment was significant; however, the main effect of fertilizer treatment was not significant. Regardless of the fertilizer treatments being irrigated or rain-fed, AS treatments had numerically higher grain yields compared to the UAN treatments. This trend was also true for the rain-fed plots, except for the difference that was statistically significant (Table 6). Both the irrigated UAN and AS treatments displayed statistically significant linear increases in grain yield (Table 6). For rain-fed treatments, a quadratic trend was the only statistically significant N response trend for AS.

Table 4: *P* value results from the analysis of variance for the main and interactive effects of irrigation (Irr.) and preplant fertilizer treatment (Tmt.) on grain yield, N use efficiency (NUE), and water use efficiency (WUE).

Source	Grain yield	NUE	WUE
STW[a] 2012			
Irrigation	0.0150	0.2258	—
Treatment	0.2241	0.6263	—
Irr. × Tmt.	0.0544	0.1089	—
LCB[a] 2012			
Irrigation	0.0118	0.9156	—
Treatment	0.1355	0.0145	—
Irr. × Tmt.	0.3038	0.0394	—
STW 2013			
Irrigation	0.0034	0.2243	0.0037
Treatment	0.0221	0.0381	0.0283
Irr. × Tmt.	0.1036	0.3306	0.1190
LCB 2013			
Irrigation	0.0440	0.0415	0.0498
Treatment	0.0370	0.2215	0.0319
Irr. × Tmt.	0.5533	0.7275	0.4957

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

3.1.3. NUE. Irrigated and rain-fed NUE values ranged from 5.6 to 60.7 percent and from nearly zero to 17.3 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE (Table 4). Though not statistically significant, irrigated plots improved NUE by more than 20 percent (Table 5). The analysis of variance did not detect significant differences for fertilizer treatment and the interaction of irrigation and fertilizer treatments. Single degree-of-freedom contrasts did not reveal any statistical differences in NUE between UAN and AS (Table 6). However, NUE values were numerically higher for the UAN irrigated treatments and NUE values were higher for the AS rain-fed treatments (Table 6). Because the check plots were used in

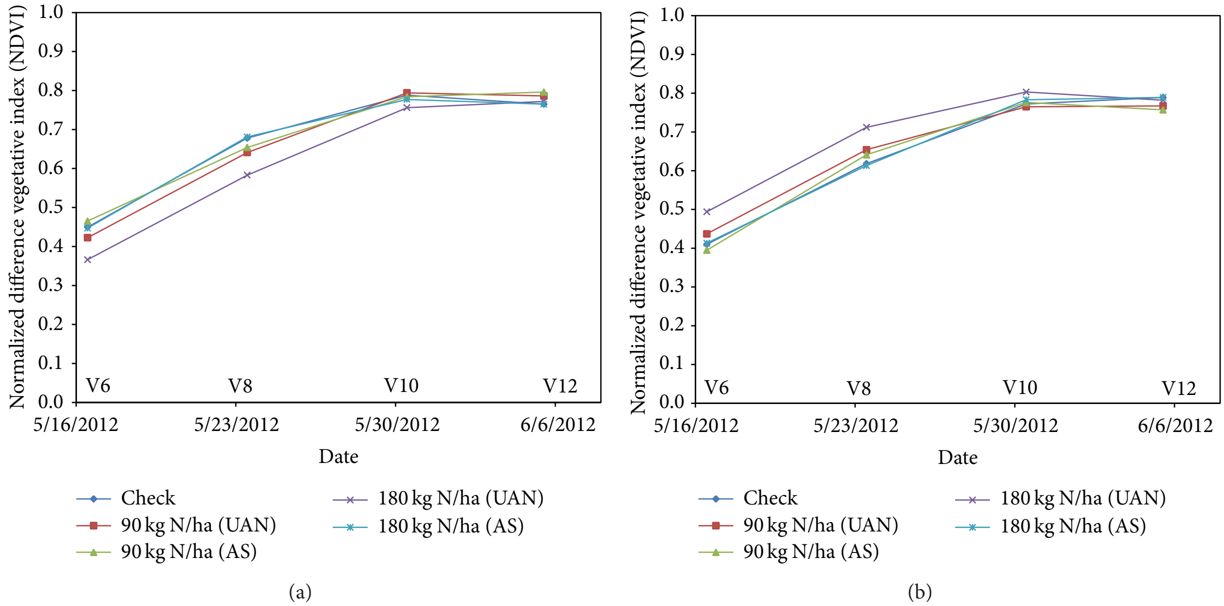

Figure 1: Normalized difference vegetative index (NDVI) values by maize growth stage for irrigated (a) and rain-fed (b) fertilizer treatments at Stillwater, OK (2012).

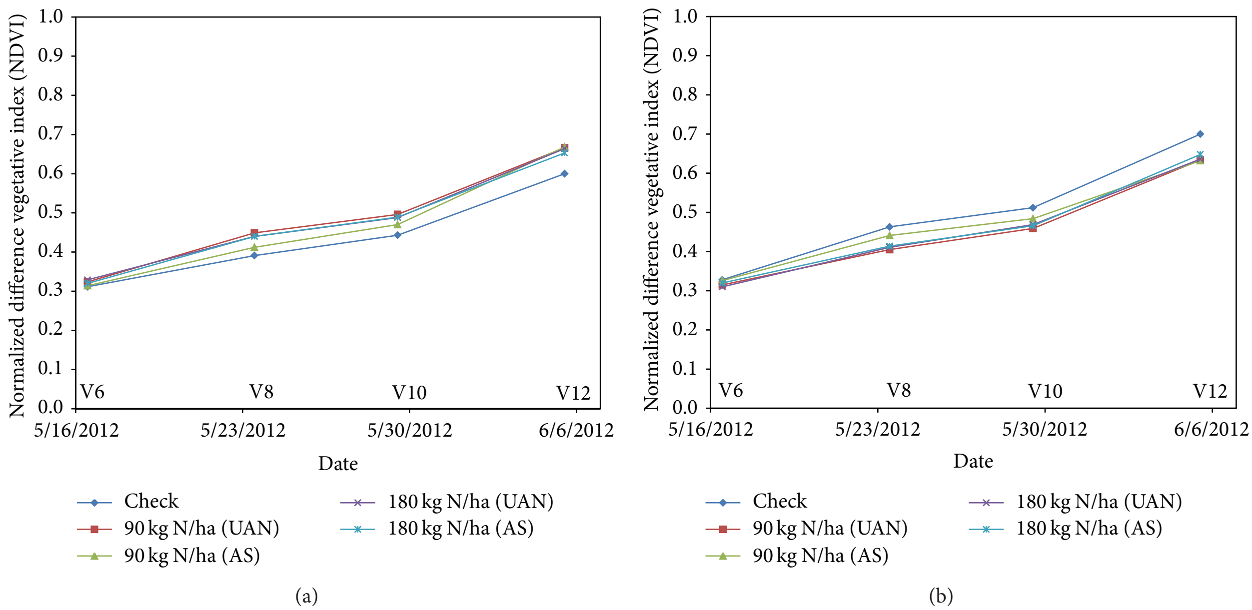

Figure 2: Normalized difference vegetative index (NDVI) values by maize growth stage for irrigated (a) and rain-fed (b) fertilizer treatments at Lake Carl Blackwell, OK (2012).

the calculation of determining NUE, only linear trends could be observed. A negative linear trend was the only observed statistically significant trend for the AS treatments in the irrigated plots (Table 6).

3.2. Lake Carl Blackwell, OK (2012)

3.2.1. Vegetative Growth. No significant differences were observed in either the irrigated or rain-fed NDVI values for any of the growth stages evaluated (Figure 2). Regardless of treatment, the increase in NDVI was linear for growth stages V6 through V10 and then increased linearly between V10 and V12. One noticeable trend was that the unfertilized check treatments had the lowest NDVI values for the V8, V10, and V12 growth stages, but the opposite was observed for that specific treatment when rain-fed (Figure 2).

3.2.2. Grain Yield. Irrigated and rain-fed grain yield values ranged from 4490 to 7351 kg ha^{-1} and from 1322 to

Table 5: 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	8598	29.0	—
Rain-fed	4017	6.4	—
P value	0.0150	0.2258	—
LCB[a] 2012			
Irrigated	6047	21.4	—
Rain-fed	4835	19.8	—
P value	0.0118	0.9156	—
STW 2013			
Irrigated	9120	31.1	15.6
Rain-fed	2361	6.2	4.4
P value	0.0034	0.2243	0.0037
LCB 2013			
Irrigated	8662	43.2	10.8
Rain-fed	4022	25.0	5.3
P value	0.0440	0.0415	0.0498

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

6461 $kg\,ha^{-1}$, respectively. Analysis of variance determined a significant effect of irrigation on grain yield (Table 4). On average, irrigated plots yielded 1000 $kg\,ha^{-1}$ more than rain-fed plots (Table 5). No statistically significant differences were observed for fertilizer treatments and the interaction of irrigation and fertilizer treatments (Table 4). Regardless of the fertilizer treatments being irrigated or rain-fed, AS treatments had numerically higher grain yields compared to the UAN treatments (Table 7). No significant trends were observed for the response to UAN fertilizer (Table 7). A significant linear response was observed for AS in the irrigated plots and a quadratic response was observed for the rain-fed plots (Table 7).

3.2.3. NUE. Irrigated and rain-fed NUE values ranged from 10.5 to 44.2 percent and from nearly zero to 78.3 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE (Table 4). When comparing irrigated versus rain-fed plots, no noticeable trend was observed in the differences between NUE values (Table 5). The analysis of variance did reveal significant differences for fertilizer treatment and the interaction of irrigation and fertilizer treatments. Regardless of the fertilizer treatments being irrigated or rain-fed, AS treatments displayed numerically higher NUE values (Table 7). This was especially true for the rain-fed plots in which the difference between UAN and AS was as much as 10 percent higher and was statistically significant (Table 7). Across irrigated and rain-fed treatments, significant, negatively linear responses were observed for both UAN and AS (Table 7). However, the linear response was only significant for UAN in the irrigated plots and AS in the rain-fed plots (Table 7).

3.3. Stillwater, OK (2013)

3.3.1. Vegetative Growth. Because irrigation did not commence until approximately the V12 or later growth stages, NDVI values were averaged across the irrigated and rain-fed treatments. No differences were observed for the V6, V10, and V12 growth stages; however, at the V8 growth stage, the NDVI value of the check treatment was significantly higher than the fertilized treatments (Figure 3). No distinct linear or quadratic trend was observed for the vegetative growth over time. The slopes of the lines between growth stages appeared to all be different, with the slope flattening out between the V10 and V12 growth stages (Figure 3).

3.3.2. Grain Yield. Irrigated and rain-fed grain yield values ranged from 6020 to 11583 $kg\,ha^{-1}$ and 1345 to 3651 $kg\,ha^{-1}$, respectively. Analysis of variance determined a significant effect of irrigation on grain yield (Table 4). On average, irrigated plots yielded 6000 $kg\,ha^{-1}$ more than rain-fed plots (Table 5). No significant difference was observed for irrigation by fertilizer treatments interaction, but the effect of fertilizer treatments was observed to be significant (Table 4). Regardless of the fertilizer treatments applied to irrigated or rain-fed conditions, single degree-of-freedom contrasts revealed the response to UAN to be a linear response, whereas the response to AS was a quadratic response (Table 6). Overall, the UAN treatments significantly yielded more compared to AS fertilizer treatments. This was also true when fertilizer treatments were partitioned by irrigated and rain-fed treatments in which the differences in means were statistically and numerically higher, respectively (Table 6).

3.3.3. NUE. Irrigated and rain-fed NUE values ranged from 6.5 to 83.7 percent and less than one to 25.4 percent, respectively. Analysis of variance determined the effect of irrigation to be insignificant on NUE, even though the average differences were greater than 20 percent (Table 4). The analysis of variance did reveal significant differences for fertilizer treatments, but not the interaction of irrigation and fertilizer treatments (Table 4). Single degree-of-freedom contrasts did not reveal any significant differences in NUE values between UAN and AS; however, the trend was that UAN gave numerically higher NUE values regardless of being irrigated or rain-fed (Table 6). No significant linear trend was observed for the UAN fertilizer treatments, but the AS treatments displayed a negative linear trend, especially for the irrigated treatments (Table 6).

3.3.4. WUE. Irrigated and rain-fed WUE values ranged from 10.5 to 19.7 $kg\,ha^{-1}\,mm^{-1}$ and 2.3 to 6.9 $kg\,ha^{-1}\,mm^{-1}$, respectively. Analysis of variance determined the effect of irrigation to be significant on WUE (Table 4). On average, irrigated plots yielded about 10 $kg\,ha^{-1}\,mm^{-1}$ more than rain-fed plots (Table 5). The interactive effect of irrigation and fertilizer treatments was insignificant; however, the main effect of fertilizer treatment on WUE values was significant (Table 4). Single degree-of-freedom contrasts revealed UAN fertilizer treatments to be higher than AS treatments, which

Table 6: 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. Results listed under the "Main" column heading are the results of data pooled across irrigated and rain-fed treatments. Values in parenthesis are the difference in mean values for the group after the "versus" subtracted from the mean value of the group before the "versus."

Contrast	Main	Irrigated Grain yield[a]	Rain-fed	Main	Irrigated NUE[a]	Rain-fed	Main	Irrigated WUE[a]	Rain-fed
STW 2012									
UAN versus AS (difference)	ns[b] (−792)	ns (−241)	(−1343)*[c]	ns (0.4)	ns (4.8)	ns (−5.7)	—	—	—
UAN linear	ns	**	ns	ns	ns	ns	—	—	—
UAN quadratic	ns	ns	ns	—	—	—	—	—	—
AS linear	**	**	ns	ns	*	ns	—	—	—
AS quadratic	ns	ns	*	—	—	—	—	—	—
STW 2013									
UAN versus AS (difference)	(924)*	(1463)**	ns (385)	ns (4.8)	ns (8.4)	ns (1.3)	(1.4)*	(2.1)*	ns (0.7)
UAN linear	**	***	ns	ns	ns	ns	**	***	ns
UAN quadratic	ns	ns	ns	—	—	—	ns	ns	ns
AS linear	ns	ns	ns	**	**	ns	ns	ns	ns
AS quadratic	**	**	ns	—	—	—	**	**	ns

[a]Units: grain yield: kg ha^{-1}; NUE: percent; WUE: kg ha^{-1} mm^{-1}.
[b]ns: not significant at the 0.10 level.
[c]*,**,*** Significant at the 0.10, 0.05, and 0.01 level, respectively.

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 Lake Carl Blackwell, OK (LCB), in 2012 and 2013. Results listed under the "Main" column heading are the results of data pooled across irrigated and rain-fed treatments. Values in parenthesis are the difference in mean values for the group after the "versus" subtracted from the mean value of the group before the "versus."

Contrast	Main	Irrigated Grain yield[a]	Rain-fed	Main	Irrigated NUE[a]	Rain-fed	Main	Irrigated WUE[a]	Rain-fed
LCB 2012									
UAN versus AS (difference)	ns[b] (−303)	ns (−767)	ns (−569)	ns (−4.5)	ns (1.0)	(−10.0)**	—	—	—
UAN linear	ns	ns	ns	**	**	ns	—	—	—
UAN quadratic	ns	ns	ns	—	—	—	—	—	—
AS linear	*[c]	*	ns	**	ns	***	—	—	—
AS quadratic	*	ns	**	—	—	—	—	—	—
LCB 2013									
UAN versus AS (difference)	ns (230)	ns (691)	ns (−232)	ns (2.2)	ns (6.0)	ns (−1.6)	ns (0.4)	ns (1.1)	ns (−0.4)
UAN linear	**	**	ns	*	ns	ns	**	**	ns
UAN quadratic	ns	*	ns	—	—	—	*	**	ns
AS linear	**	**	ns	ns	ns	ns	**	**	ns
AS quadratic	**	ns	ns	—	—	—	ns	ns	ns

[a]Units: grain yield: kg ha^{-1}; NUE: percent; WUE: kg ha^{-1} mm^{-1}.
[b]ns: not significant at the 0.10 level.
[c]*,**,*** Significant at the 0.10, 0.05, and 0.01 level, respectively.

was significant regardless of irrigation treatment and the irrigated treatments (Table 6). Overall, the response to UAN tended to follow a linear trend, but the response to AS was a quadratic trend (Table 6).

3.4. Lake Carl Blackwell, OK (2013)

3.4.1. Vegetative Growth. As previously stated, since irrigation did not commence until approximately the V12 or later growth stages, NDVI values were averaged across the irrigated and rain-fed treatments. No significant differences in NDVI were observed between fertilizer treatments at any of the growth stages. Regardless of fertilizer treatment, the NDVI values tended to follow a quadratic pattern over time. One noticeable trend observed was that the check fertilizer plot had the lowest NDVI values for the V8, V10, and V12 growth stages (Figure 3).

3.4.2. Grain Yield. Irrigated and rain-fed grain yield values ranged from 4675 to 12227 kg ha^{-1} and 1327 to 6440 kg ha^{-1},

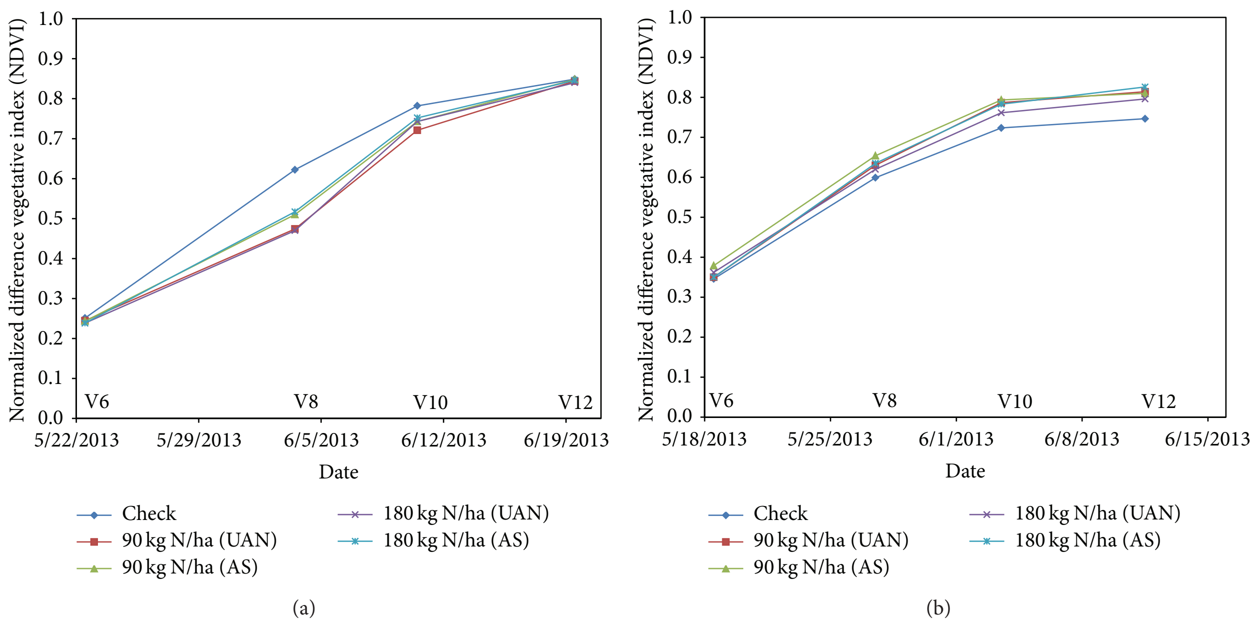

Figure 3: Normalized difference vegetative index (NDVI) values by maize growth stage, pooled across the main effect of irrigation, for Stillwater, OK (a) and Lake Carl Blackwell, OK (b) fertilizer treatments for the 2013 growing season.

respectively. Analysis of variance determined a significant effect of irrigation on grain yield (Table 4). On average, irrigated plots yielded 4500 kg ha^{-1} more than rain-fed plots (Table 5). No significant difference was observed for the irrigation by fertilizer treatments interaction, but the effect of fertilizer treatment was observed to be significant (Table 4). Even though it was not observed to be significant, AS treatments yielded higher than UAN treatments under rain-fed conditions with the opposite trend observed for the irrigated treatments (Table 7). A significant linear trend was observed for the UAN treatments regardless of being irrigated or rain-fed, but, for the AS treatments, significant linear and quadratic responses to fertilizer were observed (Table 7). Under irrigated conditions, the response of UAN treated plots was statically significant for both linear and quadratic trends, but only linear for the AS treatments (Table 7). No significant trends were observed for either N source under rain-fed conditions (Table 7).

3.4.3. NUE. Irrigated and rain-fed NUE values ranged from 6.4 to 79.7 percent and from 2.7 to 70.7 percent, respectively. Analysis of variance determined the effect of irrigation to be significant for NUE values (Table 4). On average, irrigated plots yielded 20 percent more than rain-fed plots (Table 5). The analysis of variance did not reveal significant differences for fertilizer treatment, as well as the interaction of irrigation and fertilizer treatment (Table 4). Single degree-of-freedom contrasts revealed no significant trends or differences between fertilizer sources. In irrigated treatments, UAN had slightly numerically higher NUE values compared to AS; however, the opposite was observed for rain-fed conditions (Table 7).

3.4.4. WUE. Irrigated and rain-fed WUE values ranged from 5.5 to 15.7 kg ha^{-1} mm^{-1} and 1.7 to 8.6 kg ha^{-1} mm^{-1}, respectively. Analysis of variance determined the effect of irrigation to be significant on WUE (Table 4). On average, irrigated plots yielded about 5 kg ha^{-1} mm^{-1} more than rain-fed plots (Table 5). The interactive effect of irrigation and fertilizer treatments was insignificant; however, the main effect of fertilizer treatment on WUE values was significant (Table 4). No trends or differences were observed for either fertilizer source in the rain-fed areas (Table 7). No difference was observed in the WUE values between the UAN and AS treatments for the irrigated plots (Table 7). A significant quadratic response was observed for the UAN treatments; however, the highest ordered significant response for the AS treatments was a linear trend (Table 7).

4. Discussion

Deficit irrigation applied in the later vegetative and reproductive maize growth stages significantly increased grain yield and WUE. These results are what were to be expected.

Irrigation at times that have been deemed critical for optimum grain yield [5] has aided in optimizing yield [6, 7]. Though it is only statistically significant for one of the four site-years, deficit irrigation also increased the NUE of the maize crop. Increases in NUE were likely due to greater N uptake and grain yield response to N fertilization. These results are similar to what has been observed by other researchers [14–17].

For three of the four site-years, rain-fed treatments had a greater yield response and increase in NUE for the AS treatments compared to the UAN treatments. This may be because of the more expansive root growth in the maize plant's attempt to acquire more soil moisture. The expansive root system would then have the ability to take up more of the immobile ammonium in the soil. Another desirable trait of ammoniacal N fertilizer sources in maize is that maize is able to take up ammonium during reproductive growth, whereas nitrate uptake is inhibited [9, 29]. Urea ammonium nitrate can be an effective N fertilizer source if the potential loss mechanisms (leaching, volatilization, and denitrification) are minimized [12]. The UAN treatments did outperform the AS treatments for the 2013 irrigated trials, but not the 2012 irrigated trials. This could be due to the fact that both 2013 sites had an above average rainfall for the region and, with adequate moisture early in the growing season, expansive root systems were not developed, which would have reduced ammonium acquisition from the soil. At Lake Carl Blackwell in 2013, the numerically lower yield response to UAN under irrigated conditions compared to the Stillwater site for that year and the lack of a numerical response to UAN for the rain-fed site could be due to potential N losses from the UAN. This site received the most rainfall of any site-year and we observed the topsoil to be saturated for a substantial amount of time prior to reproductive growth, thus leading to potential N losses via denitrification.

Little to no observable differences or trends in early season vegetative growth, as determined by collecting NDVI values, were present. However, with differences observed in grain yield and NUE between fertilizer treatments, there is the possibility that the inorganic N form (nitrate or ammonium) present in the soil later in the growing season affected grain yield and NUE.

To better optimize grain yield and NUE, the proper N fertilizer rate should be applied. The decrease in NUE values when the N fertilizer rate was increased from 90 to 180 kg N ha^{-1} is typical for maize production and has been observed by others [8, 30]. For irrigated treatments, linear relationships with grain yield and N fertilizer rate were usually observed for both UAN and AS. However, a few of the rain-fed and irrigated site-years displayed statistically significant quadratic trends. These trends in which there is either a decrease or no increase in grain yield with added N above 90 kg N ha^{-1} point towards excess N being applied and producers should adjust N application rates accordingly. With just two fertilizer rates plus a check treatment being employed, accurately determining an agronomic optimum preplant N fertilizer rate with the data from this trial would not be precise. However, producers should attempt to utilize some forms of a grain yield approach in making a preplant only N fertilizer rate recommendation or use regional N response trials from similar soil types under irrigation or rain-fed conditions.

Irrigated maize WUE values reportedly range from approximately 2 to 40 kg ha^{-1} mm^{-1} [31]. Irrigated WUE values observed in this experiment fell within this range. Variability in WUE values among treatments and growing seasons is to be expected. Zwart and Bastiaanssen [31] reported climate, water management, and soil fertility, all of which were evaluated in this trial and have the potential to give rise to the variability of WUE in maize. The main and interactive effects determined to be significant from the analysis of variance and single degree-of-freedom contrast results were similar for grain yield and WUE. This likely could be due to the manner in which WUE was calculated for this experiment, which involves the ratio of grain yield to the measured ET. One variable employed for deriving the ET was to measure the change in profile soil moisture prior to planting and immediately after harvest. Pre- and postharvest soil profile samples revealed no differences in the soil profile content between treatments (data not reported). The July and August months in the Southern Great Plains can be extremely hot and dry and likely much of the soil profile moisture was lost to evaporation and some transpiration during the grain dry-down period after irrigation had ceased. If no differences were observed in ET between fertilizer treatments within irrigated or rain-fed plots, then one can conclude that the differences in WUE would be dictated by the differences in grain yield.

5. Conclusions

In conclusion, deficit irrigation during late vegetative and reproductive growth stages increased grain yield, NUE, and WUE. With three of the four rain-fed site-years reporting increases in grain yield and NUE, we would recommend that a pure ammoniacal N fertilizer source be applied if a preplant only N fertilizer application is to be utilized. If irrigation water is available, the N source is not as critical. However, the producer should be cognizant of the potential N loss mechanisms (leaching, volatilization, and denitrification) of N fertilizer sources like UAN. Lastly, if producers are going to utilize a preplant only fertilizer N application for maize cultivated on the Southern Great Plains, they should accordingly adjust N fertilizer rates based on a reasonable irrigated or rain-fed yield goal or regional N response trials.

Abbreviations

AS:	Ammonium sulfate
ET:	Evapotranspiration
NUE:	Nitrogen use efficiency
NDVI:	Normalized difference vegetation index
PET:	Potential evapotranspiration
UAN:	Urea ammonium nitrate
WUE:	Water use efficiency.

Disclosure

The mention of any trademarked product or equipment utilized in this experiment was for research purposes only and does not act as an endorsement by Oklahoma State University.

Conflict of Interests

The authors and Oklahoma State University have no direct financial relation with any of the named manufacturers; thus, the authors declare there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would like to thank the Oklahoma Soil Fertility Research and Education Advisory Board for their funding of this research project and their continued financial support of soil fertility research at Oklahoma State University.

References

[1] U.S. Department of Agriculture, Quick Stats. USDA-NASS, 2014, http://www.nass.usda.gov/Quick_Stats/index.php.

[2] S. Wallander, R. Claassen, and C. Nickerson, "The ethanol decade: an expansion of U.S. corn production, 2000–2009," Tech. Rep. EIB-79, U.S. Department of Agriculture, Economic Research Service, 2011.

[3] M. Sophocleous, "Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA," *Hydrogeology Journal*, vol. 13, no. 2, pp. 351–365, 2005.

[4] FAO, "Deficit irrigation practices," Water Reports 22, Food and Agriculture Organization of the United Nations, Rome, Italy, 2002.

[5] B. R. Singh and D. P. Singh, "Agronomic and physiological responses of sorghum, maize, and pearl millet to irrigation," *Field Crops Research*, vol. 42, no. 2-3, pp. 57–67, 1995.

[6] R. K. Pandey, J. W. Maranville, and A. Admou, "Deficit irrigation and nitrogen effects on maize in a Sahelian environment I. Grain yield and yield components," *Agricultural Water Management*, vol. 46, no. 1, pp. 1–13, 2000.

[7] S. Kang, W. Shi, and J. Zhang, "An improved water-use efficiency for maize grown under regulated deficit irrigation," *Field Crops Research*, vol. 67, no. 3, pp. 207–214, 2000.

[8] K. W. Freeman, K. Girma, R. K. Teal et al., "Long-term effects of nitrogen management practices on grain yield, nitrogen uptake, and efficiency in irrigated corn," *Journal of Plant Nutrition*, vol. 30, no. 12, pp. 2021–2036, 2007.

[9] C. Y. Tsai, I. Dweikat, D. M. Huber, and H. L. Warren, "Interrelationship of nitrogen nutrition with maize (*Zea mays*) grain yield, nitrogen use efficiency and grain quality," *Journal of the Science of Food and Agriculture*, vol. 58, no. 1, pp. 1–8, 1992.

[10] C. K. Stevenson and C. S. Baldwin, "Effect of time and method of nitrogen application and source of nitrogen on the yield and nitrogen content of corn (*Zea mays* L.)," *Agronomy Journal*, vol. 61, pp. 381–384, 1969.

[11] J. F. Power, J. Alessi, G. A. Reichman, and D. L. Grunes, "Effect of nitrogen source on corn and bromegrass production, soil pH, and inorganic soil nitrogen," *Agronomy Journal*, vol. 64, pp. 341–344, 1972.

[12] R. A. Olson, W. R. Raun, Y. S. Chun, and J. Skopp, "Nitrogen management and interseeding effects on irrigated corn and sorghum and on soil strength," *Agronomy Journal*, vol. 78, no. 5, pp. 856–862, 1986.

[13] B. Eghball and J. W. Maranville, "Interactive effects of water and nitrogen stresses on nitrogen-utilization efficiency, leaf water status and yield of corn genotypes," *Communications in Soil Science and Plant Analysis*, vol. 22, pp. 1367–1382, 1991.

[14] D. L. Martin, D. G. Watts, L. N. Mielke, K. D. Frank, and D. E. Eisenhauer, "Evaluation of nitrogen and irrigation management for corn production using water high in nitrate," *Soil Science Society of America Journal*, vol. 46, pp. 1056–1062, 1982.

[15] H. V. Eck, "Irrigated corn yield response to nitrogen and water," *Agronomy Journal*, vol. 76, pp. 421–428, 1984.

[16] E. Di Paolo and M. Rinaldi, "Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment," *Field Crops Research*, vol. 105, no. 3, pp. 202–210, 2008.

[17] M. M. Al-Kaisi and X. Yin, "Effects of nitrogen rate, irrigation rate, and plant population on corn yield and water use efficiency," *Agronomy Journal*, vol. 95, no. 6, pp. 1475–1482, 2003.

[18] C. Mansouri-Far, S. A. M. M. Sanavy, and S. F. Saberali, "Maize yield response to deficit irrigation during low-sensitive growth stages and nitrogen rate under semi-arid climatic conditions," *Agricultural Water Management*, vol. 97, no. 1, pp. 12–22, 2010.

[19] H. Zhang and W. R. Raun, *Oklahoma Soil Fertility Handbook*, Oklahoma State University Press, Stillwater, Okla, USA, 6th edition, 2006.

[20] R. L. Mulvaney, "Nitrogen-inorganic forms," in *Methods of Soil Analysis. Part 3*, D. L. Sparks, A. L. Page, P. A. Helmke et al., Eds., Book Series 5, pp. 1123–1184, SSSA, Madison, Wis, USA, 1996.

[21] M. A. Tabatabai, "Sulfur," in *Methods of Soil Analysis. Part 3. Chemical Methods*, L. D. Sparks, Ed., SSSA Book Series 5, pp. 921–960, SSSA, Madison, Wis, USA, 1996.

[22] A. Mehlich, "Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant," *Communications in Soil Science & Plant Analysis*, vol. 15, no. 12, pp. 1409–1416, 1984.

[23] D. W. Nelson and L. E. Sommers, "Total carbon, organic carbon, and organic matter," in *Methods of Soil Analysis: Part 3*, D. L. Sparks, Soil Science Society of America, and American Society of Agronomy, Eds., SSSA Book Series 5, pp. 961–1010, SSSA, Madison, Wis, USA, 1996.

[24] L. J. Abendroth, R. W. Elmore, M. J. Boyer, and S. K. Marlay, *Corn Growth and Development*, PMR 1009, Iowa State University Extension, Ames, Iowa, USA, 2011.

[25] G. E. Varvel and T. A. Peterson, "Nitrogen fertilizer recovery by grain sorghum in monoculture and rotation systems," *Agronomy Journal*, vol. 83, pp. 617–622, 1991.

[26] D. F. Heerman, "ET in irrigation managements," in *Proceeding of the National Conference on Advances in Evapotranspiration*, pp. 323–334, ASAE, 1985.

[27] Mesonet, "Daily Data Retrieval," University of Oklahoma, 2014, http://www.mesonet.org/index.php/weather/category/past_data_files.

[28] I. A. Walter, R. G. Allen, R. Elliot et al., "The ASCE standardized reference evapotranspiration equation," Tech. Rep., American Society of Civil Engineers, Environmental and Water Resources Institute, 2002.

[29] W. L. Pan, E. J. Kamprath, R. H. Moll, and W. A. Jackson, "Prolificacy in corn: its effects on nitrate and ammonium uptake and utilization," *Soil Science Society of America Journal*, vol. 48, no. 5, pp. 1101–1106, 1984.

[30] O. Walsh, W. Raun, A. Klatt, and J. Solie, "Effect of delayed nitrogen fertilization on maize (*Zea mays* L.) grain yields and nitrogen use efficiency," *Journal of Plant Nutrition*, vol. 35, no. 4, pp. 538–555, 2012.

[31] S. J. Zwart and W. G. M. Bastiaanssen, "Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize," *Agricultural Water Management*, vol. 69, no. 2, pp. 115–133, 2004.