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IMPACT OF WATER AND NITROGEN MANAGEMENT STRATEGIES ON MAIZE YIELD AND WATER PRODUCTIVITY INDICES UNDER LINEAR-MOVE SPRINKLER IRRIGATION

D. R. Rudnick, S. Irmak

ABSTRACT. *With uncertainty in future irrigation water availability and regulations on nutrient application amounts, experimentally determined effects of “controllable” management strategies such as nitrogen (N), water, and their combination on crop water productivity (CWP, also known as crop water use efficiency) and actual evapotranspiration (ET_a) are essential. The effects of various N application rates (0, 84, 140, 196, and 252 kg ha⁻¹) under fully irrigated (FIT), limited irrigation (75% FIT), and rainfed conditions on maize (*Zea mays* L.) yield and various CWP indices were investigated in 2011 and 2012 growing seasons under linear-move sprinkler irrigation in south central Nebraska. CWP was presented as crop water use efficiency (CWUE), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE). The seasonal rainfall amounts in 2011 and 2012 were 371 mm and 296 mm, respectively, as compared with the long-term average of 469 mm. Two experimental seasons were contrasted with extreme warmer temperatures, greater solar radiation, and lower rainfall in 2012. Maximum grain yield of 12.68 metric tons ha⁻¹ and 14.42 tons ha⁻¹ was observed in 2011 and 2012, respectively, under the fully irrigated and 252 kg N ha⁻¹ treatment. Grain yield was linearly related to ET_a and curvilinearly related to N and irrigation application amounts. Lower N treatments were more susceptible to inter-annual effects on the grain yield response to irrigation water amount. CWUE ranged from 1.52 kg m⁻³ (FIT and 84 kg N ha⁻¹) to 2.58 kg m⁻³ (rainfed and 196 kg N ha⁻¹) with an average of 2.15 kg m⁻³ in 2011, and from 1.49 kg m⁻³ (FIT and 0 kg N ha⁻¹) to 2.72 kg m⁻³ (rainfed and 252 kg N ha⁻¹) with an average of 2.33 kg m⁻³ in 2012. CWUE had a positive quadratic relationship with N application amount and decreased with both the presence and amount of irrigation at a given N application amount. The maximum IWUE for 75% FIT and FIT in 2011 was 1.80 kg m⁻³ (252 kg N ha⁻¹) and 1.51 kg m⁻³ (252 kg N ha⁻¹), respectively, whereas in 2012 the maximum IWUE values were 1.40 kg m⁻³ (196 kg N ha⁻¹) and 1.78 kg m⁻³ (252 kg N ha⁻¹), respectively. A curvilinear relationship was observed between IWUE and N application amount. An optimal N application amount of 196 kg ha⁻¹ was identified for the pooled data to maximize the increase in grain yield above rainfed conditions per unit of applied irrigation water under limited irrigation management practices. In 2011, ETWUE ranged from 0.22 kg m⁻³ (140 kg N ha⁻¹) to 1.46 kg m⁻³ (196 kg N ha⁻¹) and from -0.21 kg m⁻³ (84 kg N ha⁻¹) to 3.74 kg m⁻³ (252 kg N ha⁻¹) for 75% FIT and FIT, respectively, whereas in 2012 ETWUE ranged from -0.07 kg m⁻³ (0 kg N ha⁻¹) to 1.87 kg m⁻³ (252 kg N ha⁻¹) and from -0.14 kg m⁻³ (0 kg N ha⁻¹) to 3.65 kg m⁻³ (196 kg N ha⁻¹) for 75% FIT and FIT, respectively. The results support that there is an optimal N level for each irrigation regime and, in general, lower N application amounts are required to reach maximum productivity (e.g., CWUE) under limited and rainfed conditions as compared with the FIT. In other words, there is an optimal N application amount to maximize the effectiveness of irrigation water on increasing grain yield above rainfed yields. The optimal N level for maximum productivity varied not only between the irrigation levels, but also exhibited interannual variability for the same irrigation level, indicating that these variables are impacted by the climatic conditions.*

Keywords. *Crop water productivity, Crop water use efficiency, Evapotranspiration, Evapotranspiration water use efficiency, Irrigation water use efficiency, Limited irrigation, Maize, Nitrogen.*

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Freshwater availability to sustain irrigated crop production has been receiving increasing global attention in the last decade. World collaborations through many organizations and institutions have been looking at effective ways to meet future food and fiber demands worldwide. Increasing competition for limited freshwater supplies is already apparent in major irrigated cropping systems of the U.S. and around the world (Irmak et al., 2012b). It is expected that further stress will be imposed on freshwater sources throughout the world due to a projected world population of over 9 billion by 2050, further expansion of biofuel technologies, and urban and industrial development. Additionally, geographical locations

that are dominated by agriculture are susceptible to variability in long-term trends and magnitude of changes in climatic variables, which can interact with and impact agroecosystem productivity and land surface-atmosphere interactions through various direct and indirect processes, further complicate the competition for water between different sectors, and pose further limitations on the availability of water for crop production (Irmak et al., 2012a).

Global irrigation accounts for approximately 90% of total water withdrawals (Döll and Siebert, 2002), and approximately 40% of global cereal production is obtained from irrigated settings (Feres and Connor, 2004). To address the increasing food and fiber demands for the world's rapidly increasing population, a combination of the following can be considered: further development of irrigated land (i.e., converting rainfed agriculture to irrigated agriculture), placing non-agricultural and/or marginally productive land into production, and/or increasing the efficiency of crop water use, all which can be accomplished through developing and implementing best technological and soil and crop management practices in irrigated and rainfed agriculture. With limitations on land availability for agricultural crop production and decreasing trends in water availability for increasing irrigated land area, much attention has been focused on increasing crop water productivity (CWP). One of the indices used in this research to measure CWP was crop water use efficiency (CWUE), which is the ratio of grain yield (Y) to crop water use expressed as seasonal actual evapotranspiration (ET_a):

$$CWUE = \frac{Y}{ET_a} \quad (1)$$

where CWUE, Y , and ET_a have units of kg m^{-3} , kg m^{-2} , and mm, respectively. Increasing CWUE can be accomplished by either increasing grain yield for the same given seasonal ET_a or by decreasing seasonal ET_a , without reducing yield. Evaluating CWP in terms of CWUE is especially vital when selecting agricultural crops for geographical areas where irrigation systems are not implemented or available. For instance, in an arid environment where water availability is usually limited, selecting a crop with a higher CWUE will result in greater yield output per unit of water used.

Water productivity is influenced by several factors, which results in values for a single crop type varying from field to field, from region to region, and between years for the same crop in the same region (Djaman and Irmak, 2012). The variability reported by researchers for CWP can be ascribed to the following: cropping type and rotations, climate, irrigation system and crop and soil management strategies, nutrient availability, soil physical and chemical properties, recurrent selection and gene transference, and farming practices (Kang et al., 2002; Wang et al., 2002; Cai et al., 2003; Deng et al., 2006; Liu et al., 2010). To help account for the irrigation component on CWP, Bos (1980, 1985) suggested two new indices, evapotranspiration water use efficiency (ETWUE) and irrigation water use efficiency (IWUE):

$$ETWUE = \frac{Y_i - Y_r}{ET_i - ET_r} \quad (2)$$

$$IWUE = \frac{Y_i - Y_r}{I_i} \quad (3)$$

where ETWUE and IWUE are expressed in units of kg m^{-3} , Y is treatment yield (kg m^{-2}), ET and I are treatment seasonal actual evapotranspiration and irrigation amounts (mm), respectively, and subscripts i and r represent irrigation level and rainfed, respectively. Both ETWUE and IWUE use a rainfed treatment as a reference point to account for the increase in yield associated with an amount of supplementary water (i.e., irrigation). ETWUE can be a more effective index than CWUE and IWUE when assessing the impact of irrigation on CWP because it accounts for the impact of crop yield produced (and its ET_a) under rainfed conditions in crop water productivity (Irmak, 2010; Djaman and Irmak, 2012).

Actual crop evapotranspiration is impacted by many factors, including soil and crop characteristics, climate, crop phenology and physiology, soil and crop nutrients status, etc. Several researchers have reported the combined effects of nitrogen (N) and irrigation on yield (Russelle et al., 1981; Martin et al., 1982; Eck, 1984; Fernández et al., 1996; Sexten et al., 1996; Ogola et al., 2002; Al-Kaisi and Yin, 2003; Mansouri-Far et al., 2010). It has been reported that addition of N fertilization on N-deficient soils increases water use efficiency when water is available (Viets, 1962; Olson et al., 1964; Pandey et al., 2000a). However, crop N uptake is dependent on water availability, which results in CWP being influenced differently with varying rates of N and irrigation management. Pandey et al. (2000a) observed water use efficiency to be linearly related to N application amounts for all five investigated irrigation treatments; however, the grain yield response to N rate was usually quadratic and differed between irrigation treatments. They concluded that under water-limiting conditions (e.g., deficit irrigation) N must be correspondingly adjusted to optimize economic crop production. Mansouri-Far et al. (2010) evaluated the effects of water stress imposed at less-sensitive crop growth stages and level of N supply on two maize hybrids. They found that an increase in N supply improved yield and IWUE when maize plants endured one irrigation shortage during the vegetative stage, but the performance of high N was reduced or eliminated when water deficit was imposed once at the reproductive stage or twice at the vegetative and reproductive stages, respectively. Ogola et al. (2002) conducted three field experiments in Sonning, U.K., with water regimes as main plots (rainfed and irrigated) and N as subplots (0 and 100 kg N ha^{-1}) and found for all experiments that the addition of N fertilizer increased water use efficiency of biomass and grain production. Erkossa et al. (2011) simulated water productivity of maize in the Blue Nile basin under varying soil fertility scenarios (poor, near-optimal, and non-limiting) under rainfed conditions. When comparing poor fertility conditions to near-optimal and non-limiting conditions, they found that grain yield increased from 2.5 metric tons ha^{-1} to 6.4 tons

ha⁻¹ and 9.2 tons ha⁻¹, soil evaporation decreased from 446 mm to 285 mm and 204 mm, and transpiration increased from 146 mm to 268 mm and 355 mm, which resulted in an increase in CWP of 48% and 54%, respectively. However, they did not report any experimental verification of any variables simulated with the model.

Historically, irrigation and N management practices have been developed and executed independently for research settings as well as in production fields in practice. Experiments conducted on large-scale production fields (16 center-pivot irrigated maize fields of 65 ha each) for multiple years in Nebraska have found that well-managed limited irrigation approaches (i.e., 75% FIT as compared to farmer-managed fully irrigated treatment) can decrease irrigation amounts and increase IWUE and CWUE with minimal or no effect on yield (Irmak et al., 2012b). Shapiro et al. (2008) developed fertilizer N recommendations for maize based on expected yield, amount of residual soil nitrate-nitrogen (NO₃-N), soil organic matter, other N sources, timing of application, and price of fertilizer. However, it has been reported that maize grown under deficit irrigation requires less N fertilizer to achieve maximum grain yield than that required with well-watered conditions (Moser et al., 2006). Furthermore, combining deficit irrigation and optimum fertilizer application can lead to a higher grain yield increase (higher CWUE) than the sum of the separate yield increases obtained by both factors (Geerts and Raes, 2009).

With increasing concerns for water availability and the adoption of variable-rate irrigation and N application systems in irrigated and rainfed agricultural crop production, development of concurrent management strategies for irrigation and N to enhance crop productivity are needed. In many areas of the world and in the U.S., including Nebraska, the groundwater level is decreasing due to lower-than-average precipitation amounts, less-than-optimal management practices, maximization of irrigated land, and in some cases poor irrigation management strategies. Furthermore, water litigation and restrictions are being imposed in certain areas to meet interstate allocations (e.g., Kansas-Nebraska-COLORADO Republican River Compact) as well as intrastate water appropriations. In addition, restrictions on N application amounts are being implemented or considered for implementation in certain regions in Nebraska (e.g., Little Blue basin, Central Platte basin, Upper Big Blue basin, etc.) and other states to improve groundwater quality. With uncertainty about future irrigation water availability and regulations on nutrient application amounts, experimentally determined effects of “controllable” management strategies such as N, water, and their combination on CWP and ET_a, especially for local climate and soil characteristics and soil and crop management practices, are essential. Furthermore, this knowledge will aid in the development of concurrent management strategies for irrigation and N application amounts and timings. The objectives of this research were to quantify and evaluate how various N rates, under fully irrigated, limited irrigation, and rainfed conditions, affect yield and water response, CWUE, IWUE, and ETWUE of maize under linear-move sprinkler irrigation in south central Nebraska’s typical maize production systems.

MATERIALS AND METHODS

SITE DESCRIPTION AND EXPERIMENTAL DESIGN

Extensive field research was conducted at the University of Nebraska South Central Agricultural Laboratory (SCAL), located near Clay Center, Nebraska, in the 2011 and 2012 growing seasons. The research laboratory is located at latitude 40° 34′ N and longitude 98° 8′ W with an elevation of 552 m above mean sea level. The long-term average annual precipitation, maximum temperature, and minimum temperature are 680 mm, 25°C, and -5°C, respectively (Irmak and Mutiibwa, 2009a, 2009b). The dominant soil series for all experimental plots is a Hastings silt loam soil with field capacity of 0.34 m³ m⁻³, permanent wilting point of 0.14 m³ m⁻³, and slopes ranging between 0% and 1% (Irmak, 2010; Djaman and Irmak, 2012). The primary agricultural production systems in the region are continuous maize and maize-soybean rotation, primarily under center-pivot irrigation and some with surface (furrow) irrigation.

The research was conducted using a split-plot design with irrigation treatments as the primary effect and N application amounts as subplots (secondary effect). The irrigation regimes investigated were fully irrigated (FIT), which imposed no water stress on the crop; limited irrigation (i.e., receiving 75% of FIT during an irrigation event), which imposed minimal to moderate stress; and rainfed conditions. The N application amounts were 84, 140, 196, and 252 kg ha⁻¹; however, in 2012 a control (0 kg ha⁻¹) N treatment was also included in the experimental design. The research site in 2012 was shifted to a different location in the field to prevent N residual effects on experimental treatments. The subplots were eight rows wide, 45 m long, and the row spacing was 0.76 m with a north-south planting direction. All irrigation and N treatments were replicated four times with a randomized complete block design.

CROP MANAGEMENT

In 2011, maize (*Zea mays* L.) hybrid Pioneer 541 AM-RR was planted on May 4 with population densities of 74,100 and 59,300 plants ha⁻¹ for irrigated and rainfed conditions, respectively. The growing season extended 156 days until harvest on October 7, 2011. Earlier planting occurred in 2012 due to warmer temperatures and substantially below-normal early season precipitation. In 2012, maize hybrid Pioneer P1498HR was planted on April 25 with population densities of 84,000 and 56,800 plants ha⁻¹ for irrigated and rainfed conditions, respectively, and harvested on September 25. Planting depth for both growing seasons was 0.05 to 0.06 m, and pesticides, herbicides, insecticides, and fungicides were applied to all plots uniformly when required.

Irrigation amounts were applied using a GPS-guided seven-span variable-rate linear-move irrigation system (Valmont Industries, Valley, Neb.). All irrigation management decisions were based on the fully irrigated and highest N application amount treatments (FIT and 252 kg ha⁻¹). A total of four irrigation events occurred in 2011 on the following dates: July 27 and August 4, 10, and 27; FIT received 25 mm and 75% FIT received 19 mm of irrigation

water in each irrigation application. In 2012, four irrigation events occurred on the following dates: July 7 and 17 and August 1 and 12; however, FIT received 40 mm and 75% FIT received 30 mm of irrigation water in each irrigation application. Greater irrigation application amounts in 2012 were due to much drier and warmer conditions and greater atmospheric evaporative demands as compared with the 2011 season, along with irrigation system scheduling conflicts with other studies located under the same linear-move irrigation system. In addition, an irrigation system controller malfunction occurred during the first irrigation event in 2012, which resulted in a uniform application of 33 mm of water to all irrigation regimes, including rainfed treatments. Although the rainfed plots experienced an irrigation event in 2012, it is suspected that minimal, if any, short-term benefit in preventing yield reduction occurred due to the following day (July 8, R1 growth stage) receiving a 19.4 mm of precipitation event. Therefore, with or without the irrigation amount, the rainfed plots received water that in part reduced water and/or heat stress during the R1 growth stage, which is especially susceptible to water stress. However, greater rainfed grain yields occurred in 2012 due to the additional stored soil moisture. Nitrogen fertilizer in the form of urea-ammonium nitrate (UAN 32%) was side-dressed on June 6-7, 2011, and May 17, 2012, using an eight-row capstan liquid unit. Both growing seasons received 47 L ha⁻¹ of ammonium polyphosphate (10-34-0) as a starter fertilizer at the time of planting.

SOIL MOISTURE MEASUREMENT, PLANT DEVELOPMENT MONITORING, AND STATISTICAL ANALYSES

A Troxler 4302 soil depth moisture gauge (Research Triangle Park, N.C.) and Watermark granular matrix sensors (Irrometer Co., Inc., Riverside, Cal.) were used to monitor soil moisture status and consequently schedule irrigations. Weekly neutron gauge readings (Troxler) were taken with a 0.30 m interval down to 1.50 m depth in three replications of all treatments. The Watermark granular matrix sensors were installed every 0.30 m down to a depth of 1.20 m, and soil matric potential was monitored on an hourly basis throughout the season to complement the neutron probe data.

Field calibration curves were developed for both soil moisture monitoring technologies to obtain volumetric water content. The calibration method and related information for the Watermark granular matrix sensors are described in detail by Irmak et al. (2012b). The neutron gauge-measured soil water content data were used to quantify seasonal ET_a for all treatments using the universal soil water balance method:

$$ET_a = P + I + U - R \pm \Delta S - D \quad (4)$$

where ET_a is actual evapotranspiration (mm), *P* is precipitation (mm), *I* is irrigation (mm), *U* is upward water flux (mm), *R* is runoff (mm), Δ*S* is change in soil moisture storage (mm) between initial and end of the growing season, and *D* is deep percolation from the crop root zone (mm). The water table is approximately 30 m below the surface; therefore, upward water flux was assumed negligible. Run-

off was calculated using the USDA-NRCS curve number method (USDA-NRCS, 1985). No runoff was calculated for the 2011 growing season; however, 2.2, 3.8, and 5.0 mm of minimal runoff was calculated in 2012 for rainfed, 75% FIT, and FIT, respectively. Deep percolation was calculated using a daily water balance computer program (Bryant et al., 1992; Payero et al., 2009; Djaman and Irmak, 2012). A total of 29 and 36 mm of deep percolation was calculated in the 2011 and 2012 growing seasons, respectively. The deep percolation amounts for both growing seasons occurred early in the season around crop emergence when the soil was at or near field capacity due to winter and spring precipitation; therefore, no deep percolation was associated with irrigation events later in the season.

Crop phenological development was visually observed throughout both seasons. Images were captured weekly and documented to infer visual differences among irrigation and N treatments. As an example, the images captured on September 8, 2011, are presented in figure 1. In addition, growing degree days (GDD) were computed to relate accumulated exposed temperature to maize growth development for the two seasons. A base temperature of 10°C was used for computing GDD; however, a maximum threshold was not included. The upper temperature threshold was withheld due to plant growth still existing at higher temperatures than the commonly used threshold of 30°C along with the known performance of the selected maize hybrids in high temperatures in the region.

All crop water productivity indices (CWUE, IWUE, and ETWUE) were calculated using grain yield adjusted to 15.5% moisture content. Analysis of variance (ANOVA) was conducted using Proc Mixed in SAS (SAS Institute, Inc., Cary, N.C.). The developed CWP relationships were evaluated at a 95% confidence interval using Fisher's protected least significant difference test. The strength of the developed relationships was measured using the coefficient of determination (R²).

RESULTS AND DISCUSSION

WEATHER CONDITIONS

Weather data were obtained from one of the Bowen ratio energy balance systems (BREBS) located at SCAL as part of the Nebraska Water and Energy Flux Measurement, Modeling and Research Network (NEBFLUX; Irmak, 2010) for both seasons. A deluxe version of a BREBS (Radiation and Energy Balance Systems (REBS), Bellevue, Wash.) was located on an adjacent irrigated maize field that is only 50 m from the research field to monitor climatic and surface energy flux variables on an hourly basis. The fetch distances of the BREBS were 520 m in the north-south direction and 280 m in the east-west direction. The prevailing wind direction at the site is south-southwest. Measured variables included precipitation, air temperature, relative humidity, incoming shortwave and net radiation, wind speed and direction, soil temperature, latent heat flux, soil heat flux, sensible heat flux, and soil temperature. Detailed description of the BREBS instrumentation and other opera-

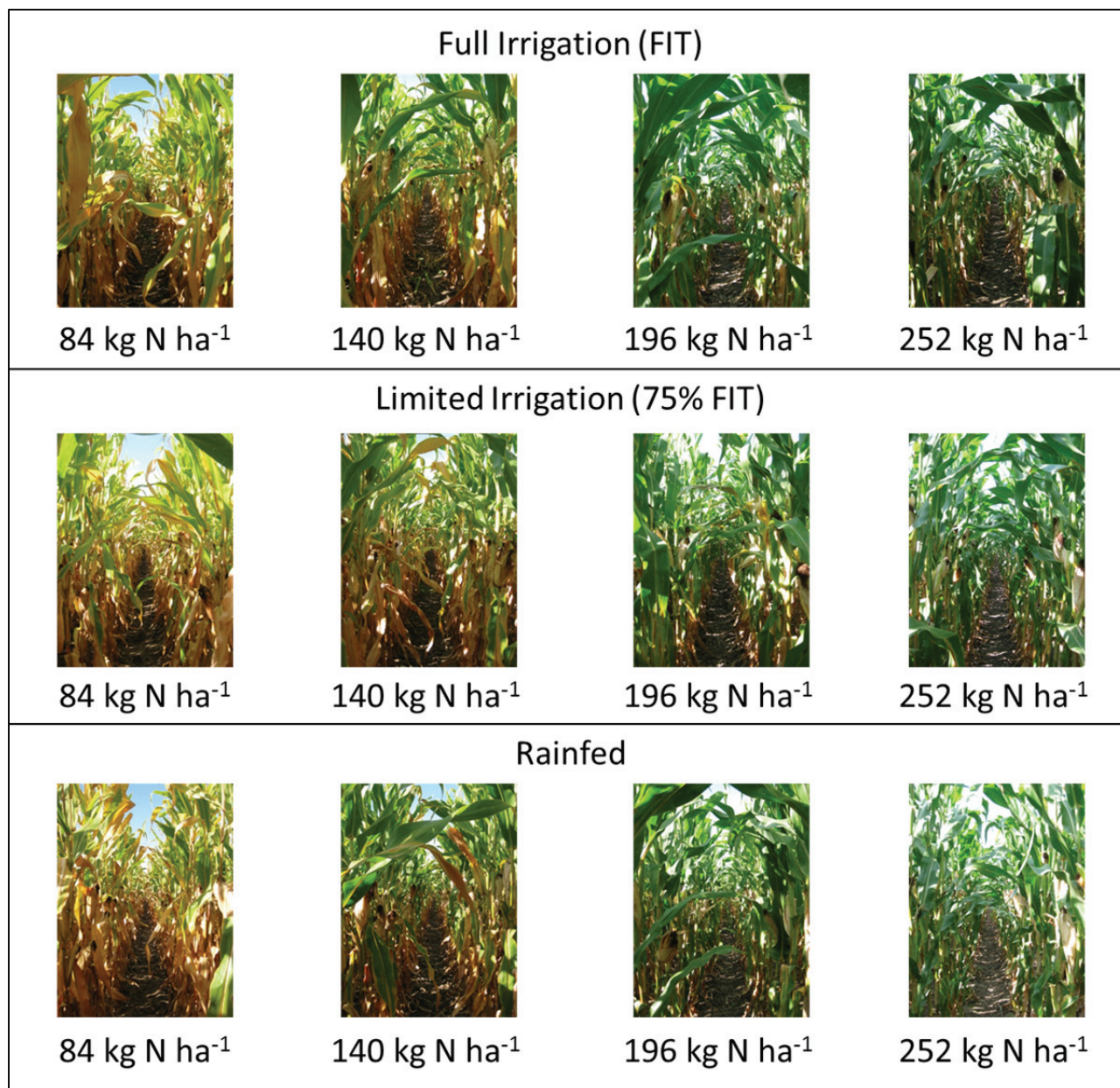


Figure 1. Visual differences among nitrogen and irrigation treatments captured on September 8, 2011.

tional characteristics are described by Irmak (2010). Greater atmospheric evaporative demands were observed in 2012 as compared with 2011. In addition, 2012 had 22 fewer precipitation events than 2011, which resulted in a difference of 75 mm in seasonal total precipitation (fig. 2). Nevertheless, both growing seasons experienced below-normal precipitation amounts during the growing season as compared with the long-term average of 469 mm (May 1 to September 30). A slightly longer growing season of 156 days existed in 2011 compared with 153 days in 2012. Due to warmer conditions and an increase in evaporative demands, crop development progressed slightly faster in 2012. However, it should be noted that the observed growth stages were subjected to the time period within the growth stage in which the plants were observed.

Plant water consumption and surface water losses are heavily influenced by several climatic variables, including

wind speed, relative humidity, solar radiation, temperature, etc. Temporal patterns of daily average wind speed, relative humidity, and incoming shortwave radiation for the 2011 and 2012 growing seasons are shown in figure 3. Modest differences in seasonal wind speed patterns existed between the two growing seasons. Greater wind speed velocities existed early in the growing season (April to June), which is common for the area. However, both years experienced below-normal wind speed velocities at 2 m height (u_2) late in the growing season (August to October). As a result of minimal precipitation amounts and events in 2012 compared with 2011, large temporal differences in relative humidity (RH) were observed between the two growing seasons; in general, RH was lower in 2012 than in 2011. For instance, the monthly average RH in August (i.e., the month with the greatest RH) was 81.9% and 68.5% for 2011 and 2012, respectively, as compared with the long-

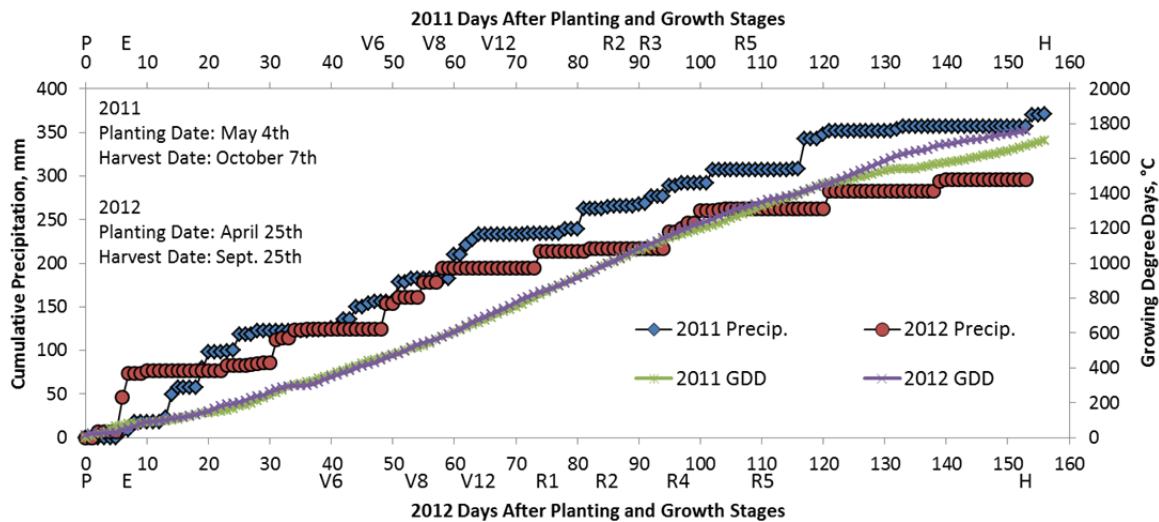


Figure 2. Cumulative precipitation (mm), growing degree days (GDD, °C) and observed crop phenological growth and development stages in the 2011 and 2012 growing seasons (P: planting; E: emergence; H: harvest; V: vegetative stage; R: reproductive stage).

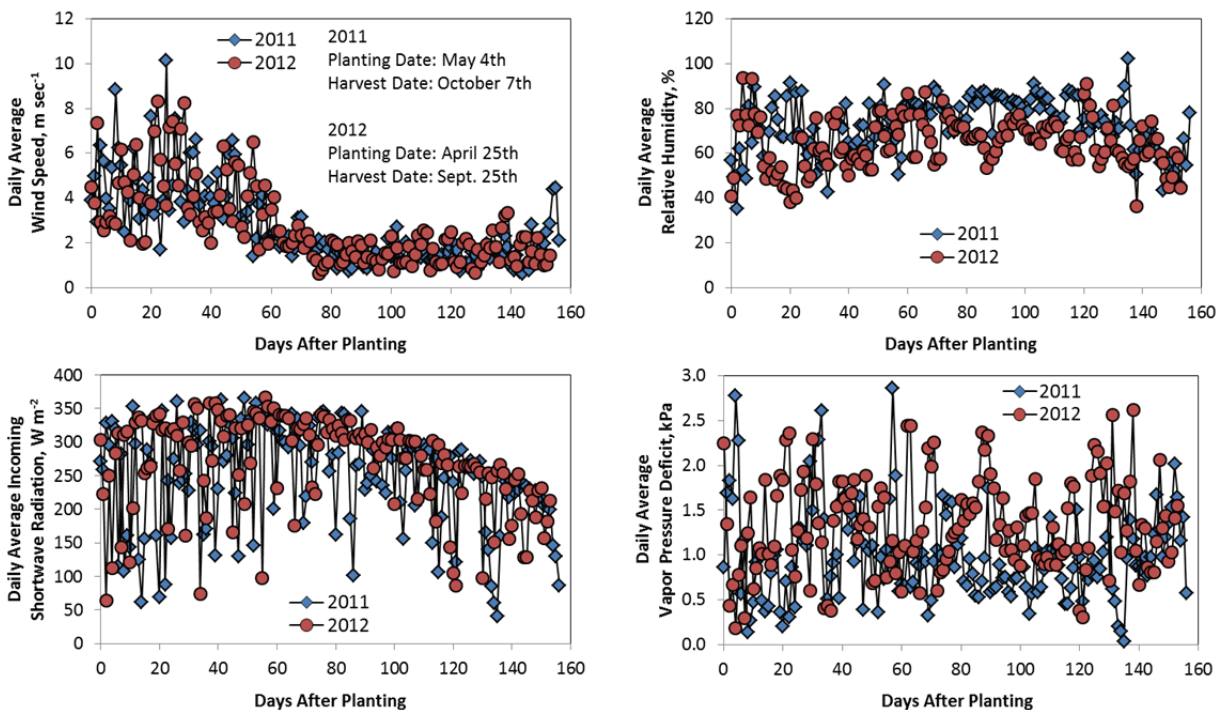


Figure 3. Daily average wind speed (u), relative humidity (RH), incoming shortwave radiation (R_s) and vapor pressure deficit (VPD) for the 2011 and 2012 growing seasons at the South Central Agricultural Laboratory (SCAL).

term average of 75.3%. Incoming shortwave radiation (R_s) was, on average, greater in 2012 than in 2011.

The gradient of vapor pressure between plant stomata and the surrounding atmosphere is one of the driving forces of plant transpiration. Typically, this gradient is defined as the difference between saturated and actual vapor pressure and is referred to as vapor pressure deficit (VPD). The temporal VPD patterns for the 2011 and 2012 growing seasons are presented in figure 3. In general, greater VPD values were observed in 2012 than in 2011 and the long-term average. The average VPD values in July, August, and September were 0.94, 0.81, and 0.89 kPa in 2011; 1.49, 1.26, and 1.40 kPa in 2012; and the long-term averages are 1.17, 1.03, and 1.00 kPa, respectively (1983 to 2009 VPD values

were calculated using the climate data from the High Plains Regional Climate Center - Automated Weather Data Network (HPRCC-AWDN), near Clay Center, Neb.).

TREATMENT EFFECTS ON GRAIN YIELD

The grain yields (metric tons ha^{-1}) that were measured for all N treatments under fully irrigated (FIT), limited irrigation (75% FIT), and rainfed conditions for the 2011 and 2012 growing seasons are presented in table 1. Greater grain yield response existed in 2012 (drier year) for irrigated conditions than in 2011. In 2012, it is likely that the supplementary irrigation water through properly scheduled irrigation events was able to prevent crop water stress and allowed near-maximum transpiration rates to occur because

Table 1. Grain yield, actual evapotranspiration (ET_a), crop water use efficiency (CWUE), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE) for 0, 84, 140, 196, and 252 kg ha⁻¹ nitrogen treatments under fully irrigated (FIT), limited irrigation (75% FIT), and rainfed settings for the 2011 and 2012 growing seasons.

Year	Irrigation Regime	Nitrogen (kg ha ⁻¹)	Irrigation (mm)	Rainfall (mm)	ET _a (mm)	^[a] Grain Yield ^[b] (tons ha ⁻¹)	CWUE (kg m ⁻³)	IWUE (kg m ⁻³)	ETWUE (kg m ⁻³)
2011	Rainfed	84	0	370.8	434	a 8.48 a	1.84	-	-
		140	0	370.8	433	a 10.02 b	2.35	-	-
		196	0	370.8	426	a 11.08 c	2.58	-	-
		252	0	370.8	486	a 11.14 c	2.25	-	-
	75% FIT	84	76.2	370.8	485	ab 8.22 a	1.68	-0.34	0.23
		140	76.2	370.8	509	a 10.48 b	2.03	0.60	0.22
		196	76.2	370.8	521	b 12.19 c	2.38	1.45	1.46
		252	76.2	370.8	494	b 12.51 c	2.53	1.80	-
	FIT	84	101.6	370.8	517	b 7.61 a	1.52	-0.85	-0.21
		140	101.6	370.8	524	a 10.42 b	2.01	0.39	0.37
		196	101.6	370.8	550	b 12.12 c	2.29	1.02	1.30
		252	101.6	370.8	530	b 12.68 c	2.37	1.51	3.74
2012	Rainfed	0	33	295.8	401	a 8.26 a	2.29	-	-
		84	33	295.8	448	ab 10.20 b	2.30	-	-
		140	33	295.8	426	a 11.31 bc	2.64	-	-
		196	33	295.8	451	a 11.40 c	2.59	-	-
		252	33	295.8	437	a 11.70 c	2.72	-	-
	75% FIT	0	123	295.8	469	a 8.21 a	1.76	-0.04	-0.07
		84	123	295.8	486	a 9.39 b	1.97	-0.66	0.83
		140	123	295.8	483	ab 12.18 c	2.52	0.71	1.84
		196	123	295.8	513	b 13.12 c	2.48	1.40	1.77
		252	123	295.8	512	b 13.21 c	2.50	1.23	1.87
	FIT	0	153	295.8	485	a 8.14 a	1.49	-0.08	-0.14
		84	153	295.8	516	b 10.54 b	2.06	0.22	0.70
		140	153	295.8	521	b 12.54 c	2.30	0.81	0.72
		196	153	295.8	512	b 13.77 d	2.71	1.55	3.65
		252	153	295.8	535	c 14.42 d	2.64	1.78	2.67

^[a] Grain yields between irrigation regimes (i.e., comparing irrigation regimes under the same N application amount) preceded by the same letters are not statistically different ($\alpha = 0.05$).

^[b] Grain yields within an irrigation regime (i.e., comparing N rates within an irrigation regime) followed by the same letters are not statistically different ($\alpha = 0.05$).

Grain yield and IWUE: four replications in 2011 and 2012. ET_a, CWUE, and ETWUE: one replication in 2011 and three replications in 2012.

high temperatures can stimulate N mineralization and consequently increase photosynthesis (Kirschbaum, 1999, 2000) and transpiration. This results in greater carbon assimilation, which most likely resulted in greater yield in 2012. Similar results were observed by Howell et al. (1995), who reported a 187 mm difference in water use for the T-100 treatment (i.e., full replenishment of soil water use in the 1.50 m soil depth) between the 1992 and 1993 growing seasons at Bushland, Texas. They reported that the gap in water use was partially explained by the higher evaporative conditions and the earlier leaf area development in response to warmer conditions in 1993, which resulted in grain yield results of 12.46 and 15.50 tons ha⁻¹ in 1992 and 1993, respectively. The maximum grain yield results obtained at SCAL were 12.68 and 14.42 tons ha⁻¹, which occurred under the FIT and 252 kg N ha⁻¹ treatment for the 2011 and 2012 growing seasons, respectively (fig. 4). The lowest grain yield was also observed under fully irrigated conditions; however, it occurred at the lowest N treatment. The minimum grain yield values were 7.61 tons ha⁻¹ (FIT and 84 kg N ha⁻¹) and 8.14 tons ha⁻¹ (FIT and 0 kg N ha⁻¹) in 2011 and 2012, respectively. This was due to population differences between rainfed and irrigated conditions as well as potential losses of N at higher irrigation levels.

A quadratic relationship was observed between grain yield and N application amounts for all irrigation regimes for both years (fig. 4). Due to greater grain yields in 2012,

the R² values between the yield and N for the pooled data (0.78, 0.82, and 0.75 for rainfed, 75% FIT, and FIT, respectively) were lower than for the individual years but still indicated a strong increase in yield with increasing N fertilizer. An interaction between irrigation and N application amounts existed for both growing seasons ($p = 0.0006$ for 2011 and $p = 0.0054$ for 2012). In 2011, there was no statistical difference between 75% FIT and FIT at a significance level of 0.05, which supports the finding that limited irrigation can be effectively used to conserve water with minimal to no effect on grain yield, as previously observed by Irmak et al. (2012b) and Djaman and Irmak (2012). However, both 75% FIT and FIT were statistically different from rainfed conditions, with mean differences of 0.67 and 0.53 tons ha⁻¹, respectively. With a strong quadratic response between yield and applied N amount, all N application treatments were significantly different, with the exception of 196 and 252 kg N ha⁻¹ ($p = 0.1155$). Unlike 2011, there was a statistical difference in grain yield between 75% FIT and FIT ($p = 0.0104$) as well as between 75% FIT and rainfed ($p = 0.0113$) and between FIT and rainfed ($p < 0.0001$). The greater atmospheric demand in 2012 resulted in larger total irrigation application amount as compared with 2011 and, as expected, resulted in a larger difference in grain yield between 75% FIT and FIT in 2012.

With fewer precipitation events and amounts, coupled with warmer growing conditions in 2012, grain yield responded more favorably to irrigation amount as compared

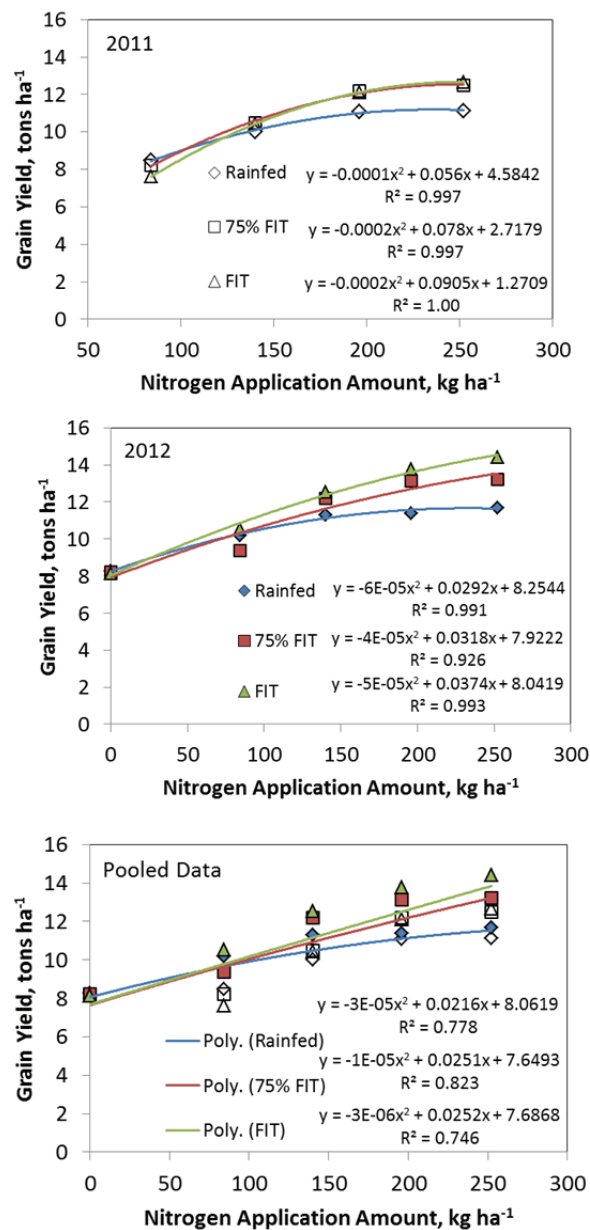


Figure 4. Grain yield response to nitrogen application amount (kg ha^{-1}) under fully irrigated (FIT), limited irrigation (75% FIT) and rainfed conditions in the 2011 and 2012 growing seasons.

with 2011 (fig. 5). In addition, higher N treatments typically experienced a greater increase in grain yield with increasing irrigation water than lower N treatments. For example, in 2012, the 0 kg N ha^{-1} treatment showed relatively no grain yield response to irrigation, whereas the 252 kg N ha^{-1} treatment had a strong positive quadratic grain yield response to irrigation. The pooled data indicated that lower N treatments were more susceptible to interannual effects on grain yield response to irrigation; however, further research is still needed to assess the interannual effects over several years and under different land and crop management practices. The pooled data R^2 values were 0.31, 0.64, 0.96, and 0.98 for the 84, 140, 196, and 252 kg N ha^{-1} treatments, respectively. As intended, the lower N treatments imposed some level of N deficiency on the crop. The greater variability in the grain yield vs. irrigation amount

relationship at lower N treatments was attributed to N deficiency, water deficiency, and their combined effect on plant response to interannual differences in climate (precipitation, relative humidity, solar radiation, temperature, etc.) as well as differences in residual nutrients (e.g., nitrogen). Whereas the higher N treatments in general did not impose N deficiency on the crop; therefore, the grain yield vs. irrigation amount relationships were stronger. These results are similar to those reported by Eck (1984), who found that at lower N rates, N deficiency limited yield to the point where water stress (e.g., irrigation) had only a small effect on grain yield, but at higher N rates, water stress was the main yield-limiting factor.

GRAIN YIELD VS. ACTUAL EVAPOTRANSPIRATION (CROP WATER PRODUCTION FUNCTIONS)

The responses of grain yield to ET_a (crop water production function) for the fully irrigated, limited irrigation, and rainfed conditions are presented in (fig. 6). Average values of grain yield and ET_a were taken for the irrigation and N treatments to reduce any potential differences in yield caused by variation in soil physical and chemical properties within the research area, following Barrett and Skogerboe (1978). A positive linear relationship was observed for all irrigation regimes; however, in both growing seasons, stronger relationships, along with steeper slopes, were observed for irrigated conditions as compared with rainfed conditions. The R^2 values were 0.10, 0.37, and 0.62 in 2011; 0.55, 0.71, and 0.69 in 2012; and 0.17, 0.49, and 0.38 for the pooled data for rainfed, 75% FIT, and FIT, respectively. Observing the linear relationships of the pooled data, an increase in grain yield of 0.63, 1.97, and $2.01 \text{ tons ha}^{-1}$ occurred for every 25.4 mm of ET_a above the basal ET_a to produce grain (i.e., x-intercept) for rainfed, 75% FIT, and FIT, respectively. For the same location, Djaman et al. (2013) reported an increase of 1.2 and 1.7 tons ha^{-1} per 25.4 mm of ET_a in 2009 and 2010, respectively, beyond 280 mm (in 2009) and 403 mm (in 2010) of ET_a that was used by maize to start producing grain yield. Values of $0.76 \text{ tons ha}^{-1}$ (Schneekloth et al., 1991), $0.76 \text{ tons ha}^{-1}$ (Klocke et al., 2004), and $0.71 \text{ tons ha}^{-1}$ (Payero et al., 2006) were found per 25.4 mm of ET_a in west central Nebraska. Payero et al. (2006) collected and reported nine different maize grain yields vs. ET_a functions found in the literature along with their own obtained function. They concluded that maize response to ET_a can change with environment and time as new crop hybrids are developed and management practices improve. In addition, the large variability in reported slopes of the linear function can be due to differences in seasonal precipitation amount and distribution, soil and crop characteristics, and other climatic and management conditions (Djaman et al., 2013).

The overall pooled response (i.e., 2011 and 2012) of grain yield to ET_a for all irrigation regimes had a slope of $0.021 \text{ tons ha}^{-1} \text{ mm}^{-1}$ with a positive intercept of $0.961 \text{ tons ha}^{-1}$ (fig. 6, pooled data). Assuming yield is linearly correlated with ET_a (Robins and Domingo, 1953; Hanks, 1974; Barrett and Skogerboe, 1978; Stegman, 1982; Schneekloth et al., 1991; Klocke et al., 2004; Payero et al., 2006; Djaman and Irmak, 2012), a positive intercept should not

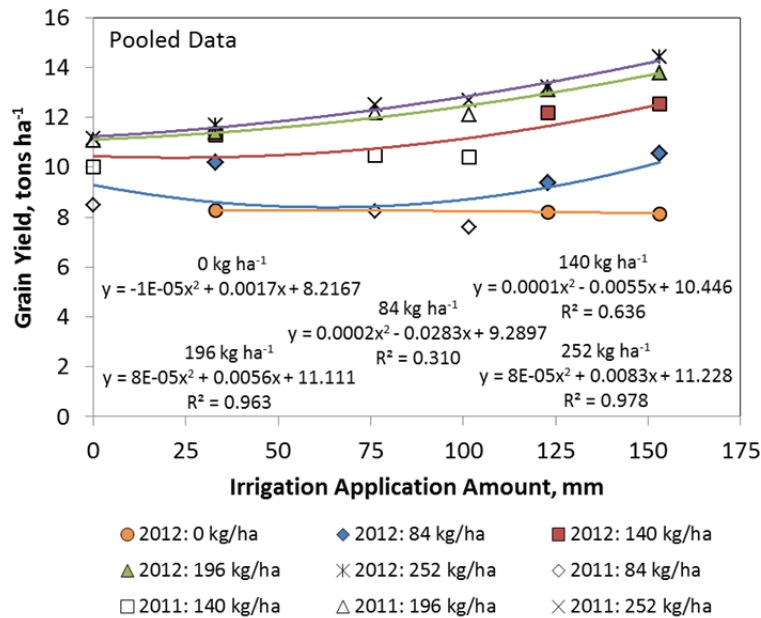


Figure 5. Grain yield response to irrigation application amount (mm) for 0, 84, 140, 196, and 252 kg ha⁻¹ nitrogen treatments for the 2011 and 2012 growing seasons' individual and pooled data.

exist due to the basal ET_a associated with plant growth and not grain development. The obtained response in this research was attributed to the greater observed grain yield results under the rainfed treatment than those in the irrigated conditions at lower N application amounts. The dynamic relationship between N and water availability, coupled with precipitation, irrigation, and N distribution/redistribution can affect both grain yield and ET_a , resulting in greater variability in the grain yield and ET_a relationship.

TREATMENT EFFECTS ON CWUE

The CWUE ranged from 1.52 kg m⁻³ (FIT and 84 kg N ha⁻¹) to 2.58 kg m⁻³ (rainfed and 196 kg N ha⁻¹) with an average of 2.15 kg m⁻³ in 2011, and from 1.49 kg m⁻³ (FIT and 0 kg N ha⁻¹) to 2.72 kg m⁻³ (rainfed and 252 kg N ha⁻¹) with an average of 2.33 kg m⁻³ in 2012 (table 1). As expected, these results were typically greater than the CWUE range of 0.80 to 1.60 kg m⁻³ reported in FAO 33 (Doorenbos and Kassam, 1979). A positive quadratic relationship was observed between CWUE and N application amount in 2011 and 2012 (fig. 7). In 2011, R² values were greater than 0.98 for all irrigation regimes. With the exception of the rainfed and 252 kg N ha⁻¹ treatment, both the presence and the amount of irrigation decreased CWUE at a given N application amount. A lower observed CWUE value for the rainfed and 252 kg N ha⁻¹ treatment as compared with irrigated conditions was due to a substantially larger magnitude of change in ET_a between the 196 and 252 kg N ha⁻¹ treatments under rainfed conditions. In 2012, lower, but still very high, R² values of 0.81, 0.87, and 0.97 were observed for rainfed, 75% FIT, and FIT, respectively. The weaker regression responses were due to the inclusion of control (0 kg N ha⁻¹) treatments. In general, the 84 kg N ha⁻¹ treatment CWUE values were below the quadratic response lines. Unlike 2011, at higher N application amounts (e.g., 196 and 252 kg N ha⁻¹), FIT had greater CWUE val-

ues than the 75% FIT treatments. Nevertheless, similar responses existed between years, with 2012 having slightly greater CWUE values at almost all observed N and irrigation treatments. The higher CWUE values in 2012 were the result of differences in climatic conditions between the two growing seasons along with greater population densities (stand count) occurring in 2012 (data not shown) as well as a greater response of crop yield to water. As a result of the higher CWUE values in 2012, smaller R² values were obtained when pooling the 2011 and 2012 data. The CWUE values were in close agreement with those reported in the literature. Halvorson et al. (2006) compiled five years of data and found a curvilinear increase in CWUE with increasing N availability under both conventional and no-till practices. Similar results were found by Carlson et al. (1959), Viets (1962), Olson et al. (1964), and Al-Kaisi and Yin (2003). Carlson et al. (1959) found that N fertilizer did not greatly influence CWUE under non-irrigated conditions but had a positive response under irrigated conditions in central North Dakota. Di Paolo and Rinaldi (2008) reported that adequate soil water availability led to both a better uptake and use of the N in the cell metabolic processes, increasing crop biomass and yield, and for that reason CWUE and IWUE were positively affected by the amount of N fertilizer. Howell et al. (1995) reported that maize CWUE values in Bushland, Texas, varied from 0.89 to 1.55 kg m⁻³ using a low-energy precision application (LEPA) system in 1992 and 1993. The fully irrigated treatment received a recommended N fertilizer amount based on soil sampling and yield goals, whereas the limited irrigation treatments received proportionally less N fertilizer. Howell et al. (1995) reported that it was unlikely crop yields were affected to any significant extent by the different N application amounts due to all treatments being managed to avoid any crop nutrient deficiency. However, given previous literature information on the response between N and irriga-

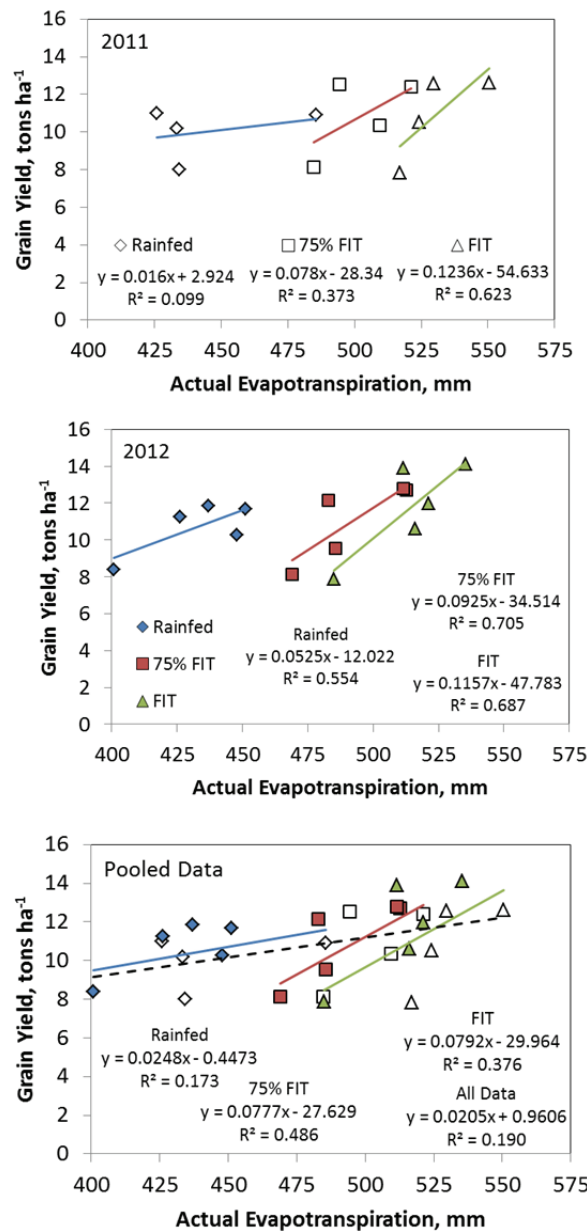


Figure 6. Grain yield response to actual evapotranspiration (ET_a) amount (crop water production functions) under fully irrigated (FIT), limited irrigation (75% FIT), and rainfed conditions in the 2011 and 2012 growing seasons.

tion on CWUE, it is possible that their observed differences in CWUE were related not only to differences in irrigation amount but also to differences in N fertilizer amounts.

We suggest that there are various response relationships between CWUE and N application amount in terms of both the range of N application amount and between irrigation regimes. The dynamic interrelation between N and water availability can affect both grain yield and ET_a , which consequently affects CWUE. Therefore, it is possible that the response surface of CWUE to N application amount can change depending on the availability of N and water. In other words, when water availability is limited (e.g., rainfed or limited irrigation) and N application amounts are low, plant N uptake can be considerably hindered; however, as N amount increases, it can reach a level at which it is ade-

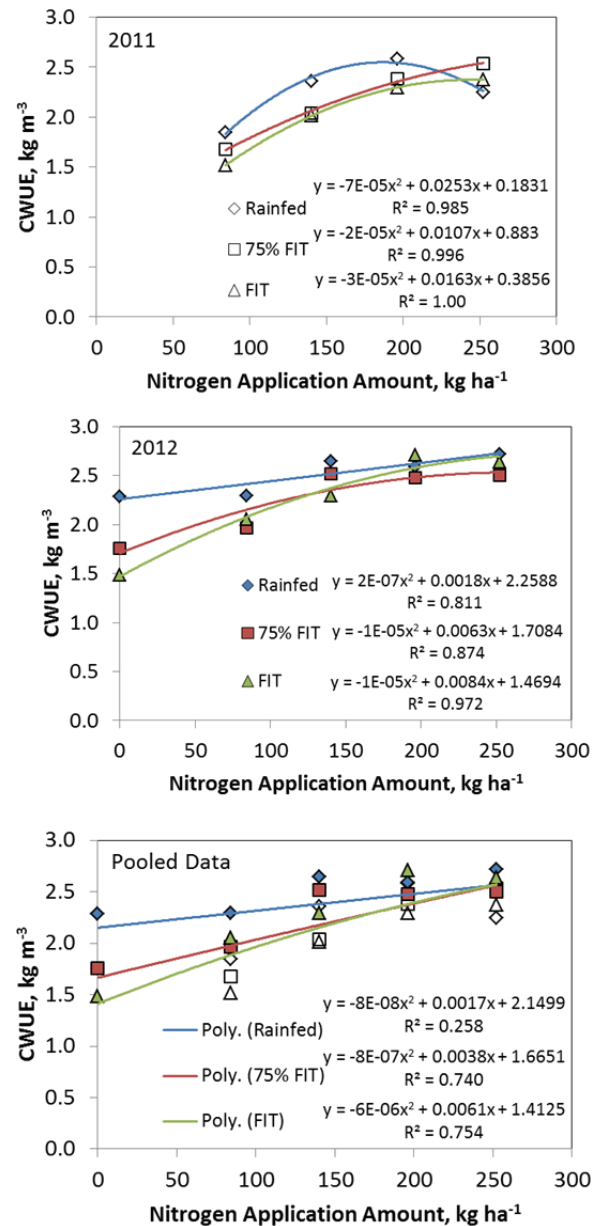


Figure 7. Crop water use efficiency (CWUE) response to nitrogen application amount (kg ha⁻¹) under fully irrigated (FIT), limited irrigation (75% FIT), and rainfed conditions in the 2011 and 2012 growing seasons.

quate to be taken up more effectively by the crop under limited water conditions. For example, the 75% FIT in 2012 appeared to have two separate response relationships between CWUE and N application amount (fig. 7, 2012 data). At low N application amounts (0 to 84 kg N ha⁻¹), CWUE increased only modestly, whereas CWUE had a strong quadratic response from 84 to 252 kg N ha⁻¹. Furthermore, the R^2 values of the regression lines increased with both the presence and amount of irrigation in both 2011 and 2012. Additionally, a single response curve appeared to be suitable for FIT, which is most likely due to the ability of water to transport N to the plants even when N levels were low. This suggests that the curvilinear response between CWUE and N application amount may not hold at low N application levels when water availability is

limited, but may be appropriate when water availability is adequate. Additional research to observe the effects of smaller N application increments on CWUE would help determine if the initial CWUE vs. N application amount relationship, under different irrigation regimes, is linear or quadratic and at what N level does the response change.

The CWUE values over the range of observed grain yields was greatest under rainfed and decreased with both the presence and amount of irrigation applied. However, greater focus should be on the difference between limited and fully irrigated conditions due to rainfed crops frequently using water more effectively (e.g., higher CWUE) but at lower production levels (Viets, 1962; Howell and Hiler, 1975). The results for limited vs. fully irrigated conditions support the notion that limited (deficit) irrigation can increase CWUE at a given grain yield. Deficit irrigation consists of withholding water at growth development stages that are less sensitive to water stress than other growth stages, which may result in a small yield reduction that is less than the concomitant reduction in transpiration (Kijne et al., 2002). Several studies have reported that deficit and limited irrigation management strategies can increase CWUE (Geerts and Raes, 2009; Ko and Piccinni, 2009; Irmak et al., 2012b). However, Payero et al. (2006) reported deficit irrigation had no beneficial increase on CWUE in the semi-arid environment of west central Nebraska. Stockle and James (1989) concluded that large soil water holding capacity, high soil water contents at planting, and deep root exploration were important for successful implementation of deficit irrigation. Therefore, it is possible for limited (deficit) irrigation to have a positive response on CWUE at SCAL and not in west central Nebraska due to greater water holding capacity of the Hastings silt loam soil as compared with the Cozad silt loam, coupled with greater early season precipitation and snowmelt recharge at SCAL as compared with west central Nebraska and in other studies mentioned earlier that were conducted in drier regions.

Similar to the results reported by Howell (2000), CWUE was greater at higher observed grain yield in both 2011 and 2012. In 2012, FIT had greater CWUE and grain yield results than limited irrigation. These results support the findings of Payero et al. (2006) that no beneficial increase in CWUE occurred under deficit irrigation. In addition, it appears that these results contradict previous findings reported in this article. However, both results have merits. If no restrictions are imposed on water and nutrient application amounts, then the greatest CWUE and grain yield results occurred under FIT. Conversely, if maximum grain yield is prevented due to restrictions in N, then limited irrigation provided higher CWUE values than FIT. Without adequate nitrogen, FIT cannot reach maximum grain yield (Pandey et al., 2000a, 2000b; Di Paolo and Rinaldi, 2008). With plant N uptake being heavily influenced by water availability, each deficit irrigation management strategy has a different optimal N level (Tavakkoli and Oweis, 2004; Cabello et al., 2009). Therefore, additional management factors should be considered in parallel to maximize the effectiveness of limited or deficit irrigation. In 2011, CWUE was greater under limited irrigation than FIT, regardless whether or not N was restricted, due to effective deficit manage-

ment strategies, coupled with less severe atmospheric evaporative demands and frequent precipitation events. The positive response of CWUE within an irrigation regime was attributed to N application amount. However, as irrigation water was applied to lower N application treatments, CWUE decreased due to ET_d increasing without comparable increases in yield. This implies that at lower N application amounts under irrigated conditions, a greater amount of non-beneficial use of water (evaporation) existed.

TREATMENT EFFECTS ON IWUE

Minimal studies have investigated the effects of N application amount on irrigation water use efficiency (IWUE). Typically, IWUE is evaluated for crops under various irrigation management strategies while holding other management practices (e.g., nutrient, land, and crop) constant. As stated previously, IWUE was calculated as the difference between irrigated and rainfed grain yield over the seasonal irrigation application amount (Bos, 1980, 1985). In 2011, IWUE ranged from -0.34 kg m^{-3} (84 kg N ha^{-1}) to 1.80 kg m^{-3} (252 kg N ha^{-1}) and from -0.85 kg m^{-3} (84 kg N ha^{-1}) to 1.51 kg m^{-3} (252 kg N ha^{-1}) for 75% FIT and FIT, respectively. In 2012, IWUE ranged from -0.66 kg m^{-3} (84 kg N ha^{-1}) to 1.40 kg m^{-3} (196 kg N ha^{-1}) and from -0.08 kg m^{-3} (0 kg N ha^{-1}) to 1.78 kg m^{-3} (252 kg N ha^{-1}) for 75% FIT and FIT, respectively (table 1). The negative values in both 2011 and 2012 are due to greater observed grain yield results under the rainfed treatment than in irrigated conditions at lower N application amounts. The greater yield at lower N application amounts for rainfed conditions was primarily attributed to planting population differences, along with potential N losses under irrigated conditions. As N application amount increased, irrigation water was more effective at increasing the grain yield above rainfed (fig. 8). However, IWUE response to N application amount was not linear, but rather quadratic, which implied that there is an optimal N application amount to maximize the effectiveness of irrigation water on increasing grain yield above rainfed yields. As mentioned previously, the crop appeared to respond differently at a lower range of N application amount (0 to 84 kg N ha^{-1}); therefore, regression analysis was conducted without including the 0 kg N ha^{-1} treatments in 2012.

Greater IWUE values were observed for 75% FIT than for FIT in 2011, whereas the opposite trend was observed in 2012. The limited irrigation management strategy in 2011 allowed for modest differences between 75% FIT and FIT grain yields at all N application levels, resulting in the two regression lines (i.e., IWUE vs. N application amount) being nearly parallel. Due to more severe climatic conditions in 2012, the crop responded more favorably to irrigation water at both low and high N application amounts, resulting in higher IWUE values for FIT than for 75% FIT. Furthermore, on average, the fully irrigated treatments experienced greater water extraction amounts in the deeper soil profile as compared with the limited irrigation treatments, which implies that FIT was able to make better use of soil water storage under drier conditions (data not shown). Similar quadratic relationships were observed between IWUE and N application amount in 2011 and 2012,

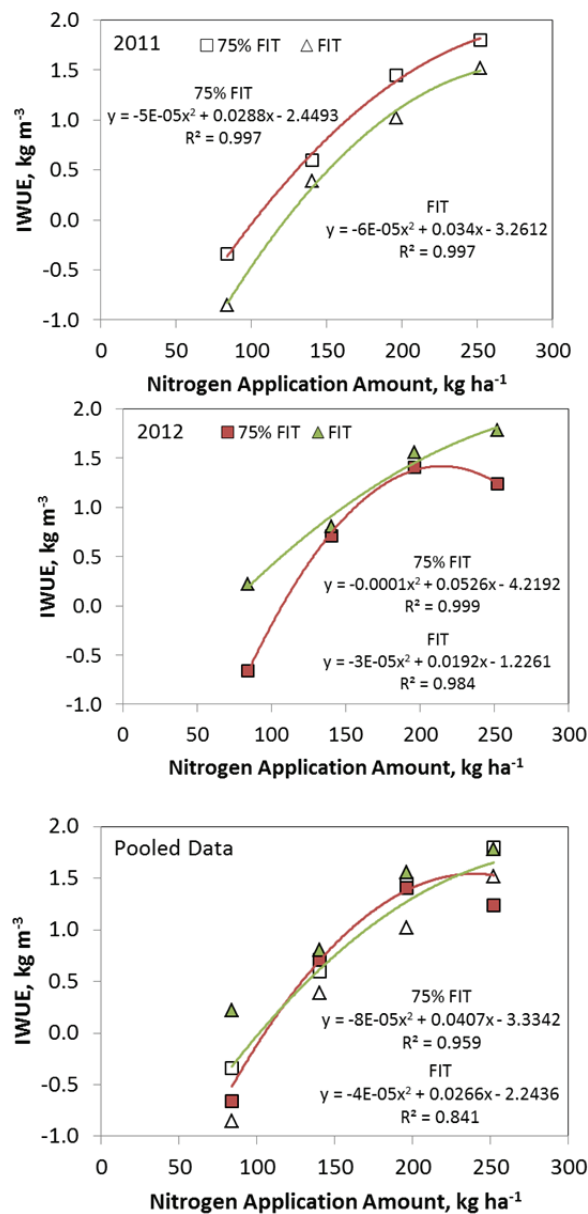


Figure 8. Irrigation water use efficiency (IWUE) response to nitrogen application amount (kg ha^{-1}) under fully irrigated (FIT), limited irrigation (75% FIT) and rainfed conditions for the 2011 and 2012 growing seasons.

which resulted in R^2 values of 0.96 and 0.84 for the pooled 75% FIT and FIT data, respectively. In 2011, neither of the regression lines indicated an optimal N application amount to maximize the effectiveness of irrigation water on increasing grain yield above rainfed yields (i.e., regression lines did not plateau). Similar to 2011, FIT did not provide an optimal N application amount; however, an optimal N application amount of 196 kg ha^{-1} was identified for 75% FIT in 2012 and the overall pooled data. These results support previous findings that greater N availability is required with increasing irrigation application amount. Further increasing the N application amount range investigated in this research will strengthen the results reported here and provide much needed information on the IWUE vs. N application amount relationship for the fully irrigated treatments.

Similar IWUE values and trends have been reported in the literature. Di Paolo and Rinaldi (2008) found that N fertilizer positively affected IWUE; however, most studies evaluated IWUE and ETWUE using a non-yield-limiting N application amount for all investigated treatments. Thus, this research is unique in a sense that various N levels were studied in each irrigation level in two significantly contrasting years in terms of climatic conditions. Evett et al. (2001) compared manual vs. automatic drip irrigation scheduling without varying N application amount and found that IWUE ranged from 0.23 to 1.96 kg m^{-3} (manual) and from 1.77 to 2.23 kg m^{-3} (automatic) in 1997. For the same location as our research (SCAL), Djaman and Irmak (2012) reported IWUE ranging from 3.63 to 5.9 kg m^{-3} with an average of 4.87 kg m^{-3} in 2009 and from 2.52 to 3.24 kg m^{-3} with an average of 2.97 kg m^{-3} in 2010 under a center-pivot irrigation system with all treatments receiving equal N fertilizer amount. Their results were in all cases greater than the values obtain in this research. Howell et al. (1995) found that IWUE ranged from 1.95 to 2.48 kg m^{-3} in 1992 and from 1.51 to 1.71 kg m^{-3} in 1993 under a low-energy precision applicator (LEPA). Their study involved varying rates of N fertilizer; however, all treatments received adequate fertilizer amounts to prevent any crop nutrient deficiency. Howell (2000) compared several reported CWUE and IWUE values of maize and determined that both efficiencies did not differ greatly among irrigation methods when operated to avoid or minimize application losses. However, caution is advised when comparing IWUE from different studies due to some studies (Stegman, 1982; Payero et al., 2009; Mansouri-Far et al., 2010; Irmak et al., 2012b) not including rainfed grain yield in the IWUE equation. Similar to our 2011 findings, other studies have reported a decrease in IWUE with increasing irrigation application amounts (Howell, 2000; Di Paolo and Rinaldi, 2008; Djaman and Irmak, 2012). Other studies have indicated that IWUE is greater than CWUE (Howell, 2000); however, this was not evident in our research, possibly due to differences between the rainfed and irrigated planting populations. In addition, unlike in other aforementioned studies that were primarily conducted in arid or semi-arid regions, soil water storage played a critical role in rainfed grain yield production in our research.

TREATMENT EFFECTS ON ETWUE

Irrigation water use efficiency (IWUE) provides vital information on the effects of irrigation on increasing grain yield above rainfed yields; however, IWUE can be susceptible to misleading results due to potential non-beneficial uses of irrigation water (e.g., deep percolation, runoff, and water left in the soil profile). Another expression proposed by Bos (1980, 1985) has been recognized to better account for the influences of irrigation water on increasing grain yield above rainfed settings. The proposed expression is the difference in grain yield divided by the difference in ET_a between irrigated and rainfed settings and is referred to as evapotranspiration water use efficiency (ETWUE) in this article. In 2011, maize ETWUE values ranged from 0.22 kg m^{-3} (140 kg N ha^{-1}) to 1.46 kg m^{-3} (196 kg N ha^{-1}) and from -0.21 kg m^{-3} (84 kg N ha^{-1}) to 3.74 kg m^{-3} (252 kg N ha^{-1}) for 75% FIT and FIT,

respectively. In 2012, ETWUE ranged from -0.07 kg m^{-3} (0 kg N ha^{-1}) to 1.87 kg m^{-3} (252 kg N ha^{-1}) and from -0.14 kg m^{-3} (0 kg N ha^{-1}) to 3.65 kg m^{-3} (196 kg N ha^{-1}) for 75% FIT and FIT, respectively (table 1). The higher N application ETWUE values are similar to those reported in the literature. Zhang et al. (2004) reported maize ETWUE of 2.53 kg m^{-3} in 2011. Howell (2000, 2001) reported maize ETWUE values ranging from 1.95 to 3.85 kg m^{-3} for different irrigation fractions using four different irrigation methods: surface, LEPA, subsurface drip, and surface drip. Unlike the results reported by Howell (2001), greater ETWUE values were found under fully irrigated treatments as compared with limited irrigation. To our knowledge, Djaman and Irmak (2012) were the first to report maize ETWUE relationships with respect to ET_a , irrigation, and grain yield under full and limited irrigation and rainfed settings, and the current research is the first to report ETWUE values for full and limited irrigation and rainfed settings under various N application amounts. Their results indicated that ETWUE decreased with ET_a , irrigation amount and grain yield in 2009, and the opposite relationship existed in 2010.

Greater differences in ETWUE were observed between 75% FIT and FIT in 2012 compared to 2011. For instance, 75% FIT showed modest differences between N application amounts of 140 to 252 kg ha^{-1} , with ETWUE values ranging between 1.77 and 1.87 kg m^{-3} , which implies that the crop responded proportionally to irrigation in terms of grain yield and ET_a . Unlike 75% FIT, ETWUE increased over a larger N application amount range under the fully irrigated treatment. The wetter conditions in 2011 could have potentially allowed the irrigated treatments at higher N application amounts to make better use of N availability during the reproductive stages, which allowed for a greater increase in grain yield as compared with ET_a between the irrigated and rainfed crops. The greater atmospheric demand in 2012 resulted in grain yield being more closely correlated with transpiration losses. This was also supported by the stronger linear relationship observed between grain yield and ET_a in 2012 than in 2011 (fig. 6). Nitrogen application amount positively affected grain yield more so than ET_a , as shown in the CWUE vs. N application amount relationships (fig. 7), and greater increases in grain yield with increasing N application amount occurred under irrigated conditions than in rainfed settings; therefore, it is not surprising that greater ETWUE values occurred at higher observed grain yields. With N fertilizer affecting ET_a more modestly as compared with grain yield, it was difficult to infer any relationship between ETWUE and ET_a , N, and/or yield. We suggest that this relationship would prove to be more beneficial when applied to research with several limited irrigation treatments, such as the research conducted by Djaman and Irmak (2012), due to irrigation affecting ET_a more so than N fertilizer.

SUMMARY AND CONCLUSIONS

Crop water productivity, measured as crop water use efficiency (CWUE), irrigation water use efficiency (IWUE), and evapotranspiration water use efficiency (ETWUE), was

quantified and evaluated for five nitrogen (N) application rates for maize produced under fully irrigated (FIT), limited irrigation (75% FIT), and rainfed conditions through extensive field tests conducted at the University of Nebraska-Lincoln South Central Agricultural Laboratory (SCAL), located near Clay Center, Nebraska, in 2011 and 2012. Earlier crop growth and development existed in 2012 as compared with 2011 due to greater solar radiation, air temperature, and greater atmospheric demands. Greater grain yield values were observed in 2012 (drought conditions) than in 2011 (near-average year), with maximum grain yield results of 12.68 and $14.42 \text{ metric tons ha}^{-1}$ under the fully irrigated and 252 kg N ha^{-1} treatment for the 2011 and 2012 growing seasons, respectively. An interaction between irrigation and N application amounts on grain yield existed for both growing seasons. Grain yield was linearly related to actual evapotranspiration (ET_a) and curvilinearly related to N and irrigation application amounts. The results indicated that lower N treatments were more susceptible to interannual effects on the grain yield response to irrigation water amount; however, further research is needed to confirm this response under different land and crop management conditions. In addition, differences in treatment grain yields between 2011 and 2012 support the importance of assessing irrigation management decisions in regards to current climate conditions.

Crop water use efficiency had a positive quadratic relationship with N application amount and decreased with both the presence and amount of irrigation at a given N application amount. The dynamic interrelation between N and water availability affected both grain yield and ET_a . Therefore, the response of CWUE to N application amount can change depending on the availability of N and water. We suggest that there can be several response relationships between CWUE and N application amount in terms of both the range of N application amount and between irrigation regimes. Further investigation of the CWUE vs. N application amount relationship in various climatic, soil, and crop management conditions with smaller N application amount increments under various irrigation levels than those investigated in this research is necessary. Under yield-limiting conditions, CWUE was greater under limited irrigation as compared with FIT; however, if no restrictions were imposed on water and N application amounts (e.g., FIT and 252 kg N ha^{-1} treatment), then CWUE and grain yield was greatest for the fully irrigated treatment in 2012. As irrigation water was applied to lower N application treatments, CWUE decreased due to ET_a increasing without comparable increases in yield. This implied that at lower N application amounts under irrigated conditions, a greater amount of non-beneficial use or losses of water existed.

Irrigation water was more effective at increasing grain yield above rainfed settings (i.e., greater IWUE) when N application amount increased. An optimal N application amount of 196 kg ha^{-1} was identified to maximize IWUE for the 75% FIT in 2012 and pooled data. The FIT treatment experienced maximum IWUE values under the 252 kg N ha^{-1} treatments. Temporal influences including weather conditions, management practices, and other external factors primarily affected IWUE due to their effects on

the rainfed grain yield. Nitrogen fertilizer affected grain yield more so than ET_a, as observed in the CWUE relationships, along with greater increases in grain yield with increasing N application amount under irrigated conditions, resulted in greater ETWUE values at higher observed grain yields.

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