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ABSTRACT
Hybrid adoption, irrigation, and planting density are important factors for maize (*Zea mays* L.) production in semiarid regions. For this study, a 2-yr field experiment was conducted in the Texas High Plains to investigate maize yield determination, seasonal evapotranspiration (ETc), and water-use efficiency (WUE) under limited irrigation. Two hybrids (N74R, a conventional hybrid, and N75H, a drought-tolerant (DT) hybrid) were planted at three water regimes (I_{100}, I_{75}, and I_{50}, referring to 100%, 75%, and 50% of the evapotranspiration requirement) and three planting densities (PD 6, PD 8, and PD 10, referring to 6, 8, and 10 seeds m^{-2}). At I_{50}, drought stress reduced grain yield by 4.78 t/ha for the conventional hybrid but only 4.22 t/ha for the DT hybrid, when compared to I_{100}. Although ETc decreased at I_{75} and I_{50}, the highest WUE was found at I_{75}. The DT hybrid did not yield more than the conventional hybrid but had greater yield stability at lower water regimes and extracted less soil water. Drought decreased biomass, harvest index, and kernel weight but did not affect kernel number. Higher planting densities increased biomass and kernel number but decreased kernel weight. Kernel number and kernel weight of the conventional hybrid were more sensitive to planting density than the DT hybrid. These data demonstrated that limited irrigation at I_{75} is an effective way to save water and maintain the maize yield in semiarid areas, and that DT hybrid shows a greater yield stability to plant density under water stress.

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Introduction

Maize (*Zea mays* L.) plays an important role in global food security. However, with climate change, severe and frequent droughts will greatly reduce soil water available for plant uptake (Rurinda et al. 2015). In such conditions, the increasing shortage of freshwater will be the most limiting factor to maize productivity, particularly under arid or semi-arid climatic conditions (Wang et al. 2017). Limited irrigation, with an amount less than the crop water requirement, has been recognized as a viable water-saving technique in preparation for future

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water-shortage scenarios. The mild stress developed by limited irrigation has minimal effects on the yield, but increases water-use efficiency (WUE), resulting in significant water savings (Gheysari et al. 2017; Wang et al. 2017).

Adoption of new hybrids possessing drought-tolerant traits has been recognized to be an important intervention for water limited conditions (Tollenaar and Lee 2002; Campos et al. 2006). Under water limited conditions, these drought-tolerant (DT) hybrids had yield advantages over conventional or drought-sensitive hybrids in several studies (Boomsma and Vyn 2008; Cooper et al. 2014; Sammons et al. 2014; Hao et al. 2015a, 2015b). Therefore, greater yield stability through improved drought tolerance is a common objective in breeding programs in the US corn-belt (Cooper et al. 2014). Moreover, identification and understanding of traits associated with improved crop drought tolerance have been the focus for hybrid maize development (Zhan, Schneider, and Lynch 2015).

Finally, apart from limited irrigation and drought-tolerant hybrids, adjusting planting density is another important practice to increase the maize yield per unit of scarce water (Passioura 2006), since the optimum density is related to soil water availability (Ren, Sun, and Wang 2016). During the past 30 years, due to genetic improvements, increased planting density contributed to greater maize yield worldwide (Duvick 2005; Testa, Reyneri, and Blandino 2016; Jia et al. 2018). Compared with older hybrids, new hybrids yielded more at higher densities (Echarte et al. 2000; Tokatlidis et al. 2004; Duvick 2005; Qian et al. 2016). As a result, the average maize planting density has increased from 3 plants/m^2 in the 1930s to 8 plants/m^2 currently in the US Corn Belt (Duvick 2005; Li et al. 2015). However, crop growth showed a quadratic response to planting density (Tollenaar and Wu 1999; Echarte et al. 2000), and the density that is greater than optimum may cause accelerated leaf senescence rate, thin stems, decreased biomass, more water requirement, and lower yield (Nyakudya and Stroosnijder 2014). In previous studies, optimal densities for maize were reported between 8 to 11 plants/m^2 (Li et al. 2015; Ren, Sun, and Wang 2016; Testa, Reyneri, and Blandino 2016). Maize yield response to planting density is inconsistent across environments (Milander et al. 2016), and generally, the optimal planting density is higher under full irrigation than limited irrigation or dryland in the same place (Ren, Sun, and Wang 2016).

The Texas High Plains (THP) is a highly productive maize area under irrigation (Howell 2001; Farfan et al. 2013; Xue et al. 2017). However, the irrigation source, Ogallala Aquifer, continues to decline and threatens the sustainable maize production in the area (Scanlon et al. 2010; Ziolkowska 2015). Several recent studies have shown a yield benefit in DT hybrids under limited irrigation. The DT hybrids had greater biomass, harvest index (HI), and higher resource use efficiency (e.g., water and radiation) (Hao et al. 2015a, 2015b, 2016; Mounce et al. 2016). However, yield determination of hybrids under different planting densities was not addressed. The objective of this study was to investigate the maize yield determination at planting densities under limited irrigation.

Materials and methods

Experimental site

Field experiments were conducted at the Texas A&M AgriLife North Plains Research Field, near Etter, Texas (35°60′N, 101°59′W; elevation 1114 m above mean sea level), during the 2013 and 2014 growing seasons. The soil type in the experimental area was a Sherm silty clay loam. Meteorological data for the two growing seasons was obtained from an agricultural meteorological station located at the experimental site, which was part of the Texas High Plains Evapotranspiration (TXHPET) network (Marek et al. 2011).

Experimental design and treatments

The experimental design was a split plot design with four replications. Irrigation treatment was the main plot with planting density as sub-plot factor and hybrid as sub-sub-plot factor. There were three irrigation treatments: I_{100}, I_{75}, and I_{50}, corresponding to 100%, 75%, and 50% of the crop evapotranspiration requirement, respectively. And there were three planting densities: PD 10, PD 8, and PD 6, corresponding to 10, 8, and 6 seeds/m^2. All plots were irrigated with a center pivot irrigation system using low elevation spray application heads. In each season, no irrigation was applied before planting. After planting, initial irrigation with a uniform rate for all treatments was applied to ensure uniform emergence and stands for all plots. For the I_{100} treatment, irrigation scheduling was determined according to maize crop evapotranspiration (ET_c) calculated using a multiple stage crop coefficient method with the TXHPET website. Maize crop coefficients were previously determined using the large lysimeters at the USDA-ARS facility at Bushland, Texas. Plant available soil water (PAW) was estimated as the difference between current root zone soil water and that at the lower limit (−1.5 MPa) (Marek et al. 2011). The initial soil water content in the root zone was measured by the gravimetric method using soil cores. Then, the daily soil water balance was calculated by using the soil water of the first day and subtracting ET_c, while adding effective precipitation and irrigation values using a 90% application efficiency value. Irrigation events were initiated generally when the root zone soil PAW reached 50%. After crop establishment, for the I_{75} and I_{50} treatments, irrigation continued at the same frequency as that of the I_{100} treatment, but the irrigation amount was reduced proportionally to that of the I_{100} treatment, by using nozzles with a reduced rate. The total irrigation amounts for the I_{100}, I_{75}, and I_{50} treatments were respectively 608, 474, and 340 mm in 2013, and 651, 490, and 326 mm in 2014 (Figure 1).

Two Syngenta hybrids were selected, a conventional hybrid, N74R, with 113-day relative maturity, and a DT hybrid (i.e., having the Agrisure Artesian drought tolerant trait), N75H, with 114-day relative maturity. Syngenta rated drought tolerance using a drought score ranging from 1 to 9 (where

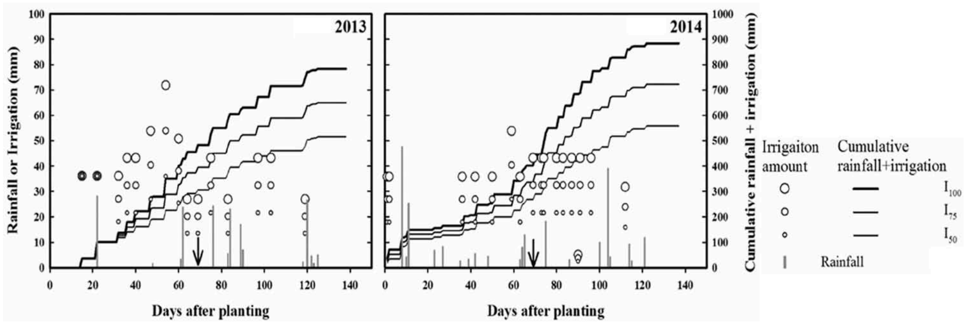

Figure 1. Rainfall and irrigation, and cumulative rainfall and irrigation during the 2013 and 2014 maize growing seasons at Etter, Texas.

1 = Excellent, 9 = Poor). The drought score was 1 for N75 (Agrisure Artesian hybrid) and 2 for N74R (conventional hybrid). The maize was planted on 16 May 2013, and 14 May 2014, using a four-row Max-Emerge (John Deere, East Moline, IL) planter. The plots were harvested in the middle of October in each season, using a Kincaid 8-XP Plot Combine (Kincaid Equipment Manufacturing, Haven, KS).

Each plot was 3.0 m wide and 9.1 m long and consisted of four rows spaced at 0.76 m. The cropping system was a corn-wheat rotation with strip tillage. The field was fertilized before planting at 290-109-0-11 (N-P-K-S) kg/ha in 2014, based on soil testing. In 2013, 100-67-0-0 (N-P-K-S) kg/ha was applied before planting, and 100 kg/ha N was applied by fertigation during the growing season. Weed control involved herbicide applications at pre-plant and post-emergence. One aerial application of Oberon (spiromesifen) was made for spider mite (*Tetranychus urticae*) control in 2013.

Measurements

In 2013, gravimetric soil water contents were determined by taking soil cores at 0–0.15, 0.15–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.2 m depth at planting and after harvest. Six soil cores were collected in the field of each irrigation level at planting, and one soil core was taken in each plot after harvest. Gravimetric soil water in each depth was converted to volumetric water by multiplying by the soil bulk density, which was also measured by soil cores. Crop seasonal ET was determined by summing the precipitation, applied irrigation water, and the difference of soil water in the 0–1.2 m profile between planting and post-harvest. Surface runoff was negligible when calculating ET due to leveled plots. Water-use efficiency (kg/m^3) was calculated as the ratio of grain yield and seasonal ET. The water stress index (WSI) was calculated as (1-ET/ET$_0$) for all the plots. In 2014, the soil water content at planting and harvest were only measured in the plots with one planting density (8 seeds/m^2). As such, ET data were not reported because our focus was on planting density effect. In addition, the effect of irrigation on ET for these hybrids was reported from another study (Zhao et al. 2018).

To better understand the soil water extraction over the growing season, the volumetric soil water content (SWC, cm^3/cm^3) in PD 8 was measured from V8 stage to maturity by neutron moisture meter [Model 503 DR 1.5, Instrotek (Campbell Pacific Nuclear), Concord, Calif.] for the two hybrids in 2013. Soil water (mm) for each depth was calculated from the volumetric soil water content multiplied by the corresponding depth increment. The total profile soil (0–2.0 m) water was the sum of the soil water from 0 to 2.0 m deep. Net soil water extraction (SWE, mm) in the 0–2.0 m profile was calculated as the difference in soil water between the two dates.

In both seasons, biomass, grain yield, kernel number, and kernel weight were measured at physiological maturity. Six plants were hand harvested from the outer two rows in each plot. These six plants were separated into stover, cobs, and grain, which were oven-dried at 70°C until constant weight. HI was calculated as the ratio of the grain weight (0% moisture) to the total aboveground plant biomass. Kernel weight (0% moisture) was measured by weighing 250 randomly selected seeds, and the values were adjusted to a water content of 155 g/kg (wet basis) for statistical analysis. Kernel number per square meter was calculated based on single kernel weight and the total kernel weight per square meter. Grain yield was determined by harvesting the two center rows with a plot combine, and adjusting the water content to 155 g/kg (wet basis) for statistical analysis.

Statistical analysis

Statistical analysis was conducted using the SAS v9.4 statistical program (SAS Institute Inc 2014). Analysis of variance (ANOVA) was conducted by the PROC MIXED using split-split-plot design. Year was treated as main plot, water regime as sub-plot, and the combination of hybrid and planting density as sub-sub-plot, and appropriate error terms were used for different effects. Replication was considered a random effect. Mean values were compared by least significant difference (LSD) at the 5% level. The regression analysis was conducted by PROC REG procedure.

Results

Weather conditions

The monthly mean maximum and minimum temperatures during the growing season (May to October) were 29.7°C and 13.0°C in 2013, and 28.9°C and 13.1°C in 2014, which were close to the 17-yr (1995–2011) average values (29.2°C and 12.9°C) (Table 1). The total precipitation during the growing season was 196 mm in 2013 and 252 mm in 2014, which was less than the 17-yr average of 291 mm at the experimental site. In 2013, only 4 mm precipitation was

Table 1. Summary of monthly mean maximum temperature (T_{max}), minimum temperature (T_{min}), reference evapotranspiration (ET_0) and total rainfall during the growing seasons of 2013 and 2014, and the 17-year (1995–2011) average at Etter, Texas.

Parameter	Year	May	June	July	August	September	October	Mean/Total
T_{max} (°C)	2013	27.5	33.6	31.9	32.6	30.0	22.6	29.7
	2014	27.0	30.9	31.8	33.8	26.7	22.9	28.9
	17-yr. avg.	26.7	31.6	33.6	32.5	28.6	22.3	29.2
T_{min} (°C)	2013	8.8	16.6	17.4	17.3	14.2	3.8	13.0
	2014	8.8	15.8	17.3	16.6	13.4	6.9	13.1
	17-yr. avg.	9.9	15.2	17.4	16.9	12.4	5.4	12.9
ET_0 (mm)	2013	224	250	197	180	152	126	1129
	2014	204	210	201	199	125	102	1040
	17-yr. avg.	194	214	210	181	143	108	1050
Precipitation (mm)	2013	4	30	58	53	43	7	196
	2014	80	33	50	59	24	4	252
	17-yr. avg.	37	56	57	58	36	47	291

observed in May, while the 17-yr average was 37 mm. Much less precipitation was observed in June (30 mm and 33 mm) and October (7 mm and 4 mm) than the long term averages (56 mm and 47 mm) during both 2013 and 2014 seasons. Total seasonal reference ET (ET_0) was 1129 mm in 2013 and 1040 mm in 2014, which means seasonal rainfall only accounted for 17% and 24% of seasonal ET_0, respectively.

Grain yield, seasonal ET, and WUE

Grain yield was affected by water regime, plant density, and hybrid, but no interactions (Table 2). For both seasons, no differences in grain yield were found between I_{100} and I_{75} for both hybrids. In the I_{50} treatment, compared to the

Table 2. Analysis of variance (P > F) of maize biomass (BM) at maturity, harvest index (HI), kernel weight (KW), kernel number (KN), grain yield (GY), seasonal crop evapotranspiration (ET_c), and water use efficiency (WUE) as affected by year (Y), water regime (WR), hybrid (HB), and plant density (PD).

Effect	d.f.	BM	HI	KW	KN	GY	ET_c†	WUE†
Year (Y)	1	0.1295	0.1309	0.7341	0.4506	0.0114		
Water regime (WR)	2	**<0.0001**	**0.0005**	**<.0001**	**0.0265**	**<.0001**	**0.0001**	0.1604
Hybrid (HB)	1	0.6099	**0.0137**	0.0753	**0.0387**	**0.0001**	0.8142	0.0705
Plant density (PD)	2	**0.0218**	0.6317	0.0001	0.0009	0.0266	0.2893	0.4631
Y × WR	2	0.1060	0.1748	0.1028	0.6206	0.0784		
Y × HB	1	0.9571	0.3693	0.7916	0.6776	0.3205		
Y × PD	2	**0.0370**	0.5343	0.2013	0.0325	0.4122		
WR × HB	2	0.4980	0.2496	0.9816	0.8094	0.4130	**0.0207**	0.8496
WR × PD	4	0.7364	0.1571	0.4482	0.8086	0.2849	0.0714	0.4574
HB × PD	2	0.2701	0.0014	0.2207	0.3216	0.1305	0.0868	**0.0359**
Y × WR × HB	2	0.1780	0.1403	0.0998	0.1235	0.5034		
Y × WR × PD	4	0.8416	0.1704	0.5662	0.9680	0.2193		
Y × HB × PD	2	0.8298	0.2619	0.0650	0.7416	0.0623		
WR × HB × PD	4	0.9055	0.1152	0.6530	0.8462	0.7567	0.0701	**0.0413**
Y × WR × HB × PD	4	0.1312	0.8852	0.1702	0.6705	**0.0506**		

†ETc and WUE data were only for 2013. Therefore, there was no year effect.

I_{100} and I_{75} treatments, grain yield was reduced by 4.78 t/ha and 4.53 t/ha for N74R, and 4.22 t/ha and 3.75 t/ha for N75H, respectively ($P < 0.05$, Figure 2). However, the grain yield of the two hybrids showed different responses to planting density in both years (Figure 2). There were no yield differences among the three planting densities for N74R, while grain yield for N75H increased as planting density increased. Compared to PD 6, N75H in PD 10 had 1.48 t/ha and 1.46 t/ha greater ($P < 0.05$) grain yield in 2013 and 2014.

In 2013, the effects of water regime on the seasonal ET and WUE were significant for both hybrids, and seasonal ET decreased with decreasing water supply (Table 3). Compared to I_{100}, the seasonal ET in I_{75} and I_{50} was reduced by 88 mm and 175 mm for N74R, and 104 mm and 206 mm for N75H (Table 3). The highest WUE was found at I_{75} for both hybrids (2.39 kg/m^3 and 2.26 kg/m^3), and no differences were found between I_{100} and I_{50}. The effects of planting density on ETc and WUE were different between the two hybrids. For N74R, plants at low density had lower ETc but planting density did not affect ETc for N75H. For both hybrids at I_{100}, WUE increased as PD increased. At lower water regimes I75 and I50), there were no differences in WUE among planting densities for N74R. For N75H, WUE increased as the density increased to 10 plants/m^2 (Table 3).

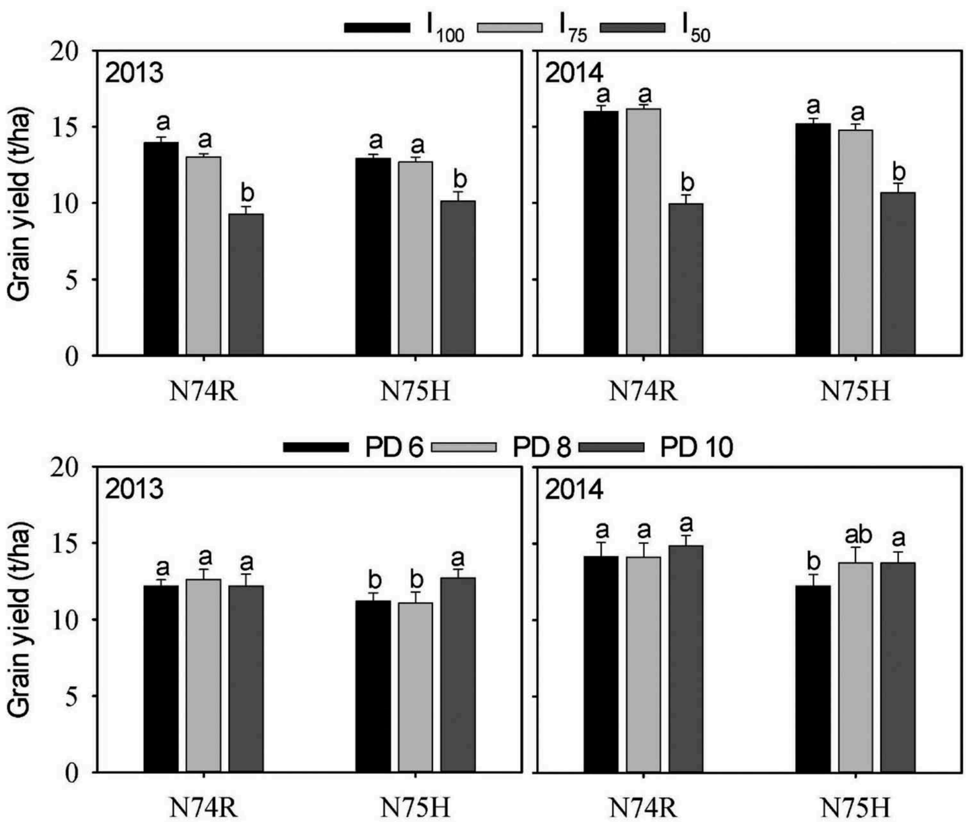

Figure 2. Grain yield of the two maize hybrids under three water regimes (I_{100}, I_{75} and I_{50}) and three plant densities (PD 6, PD 8 and PD 10) in 2013 and 2014.

Table 3. Maize seasonal evapotranspiration (ETc) and water use efficiency (WUE) for the two hybrids at three plant densities and three water regimes at Etter, Texas in 2013.

Water regime	Plant density (PD)	N74R		N75H	
		ETc mm	WUE kg/m^3	ETc mm	WUE kg/m^3
I_{100}	6	637b†	1.99b	662a	1.85b
	8	667a	2.18ab	659a	2.01ab
	10	632b	2.36a	663a	2.03a
	Mean	**646A†**	**2.18AB**	**662A**	**1.96B**
I_{75}	6	546b	2.46a	558a	2.26ab
	8	568a	2.32a	571a	2.04b
	10	559ab	2.39a	544a	2.48a
	Mean	**558B**	**2.39A**	**558B**	**2.26A**
I_{50}	6	462b	2.24a	467a	1.81a
	8	461b	2.26a	450a	1.76a
	10	486a	1.65a	450a	2.35a
	Mean	**471C**	**2.02B**	**456C**	**1.98AB**

†Means followed by different uppercase letters are significantly different among water regimes at the 0.05 probability level; means followed by different lowercase letters are significantly different among planting densities at the 0.05 probability level.

For both hybrids, grain yield decreased linearly as WSI increased (Figure 3). The slope of yield response increased with increasing planting density for N74R. However, the slope of yield response decreased as PD increased for N75H. For N74R, increasing WSI by 0.1 may reduce yield by 1.1, 2.1, and 3.8 t/ha under PD 6, PD 8 and PD 10, respectively. For N75H, increasing WSI by 0.1 may reduce yield by 1.6, 1.4, and 1.1 t/ha under PD 6, PD 8, and PD 10.

Biomass, harvest index, kernel number, and kernel weight

Biomass at maturity was affected by main effects of water regime ($P < 0.01$) and planting density ($P = 0.03$) (Table 2). On average, no difference in biomass was found between I_{100} and I_{75}, but biomass at I_{50} was less than that at the two other water regimes (Table 4). Moreover, biomass under PD 6 was less than the two other planting densities, while no difference was found between PD 8 and PD 10.

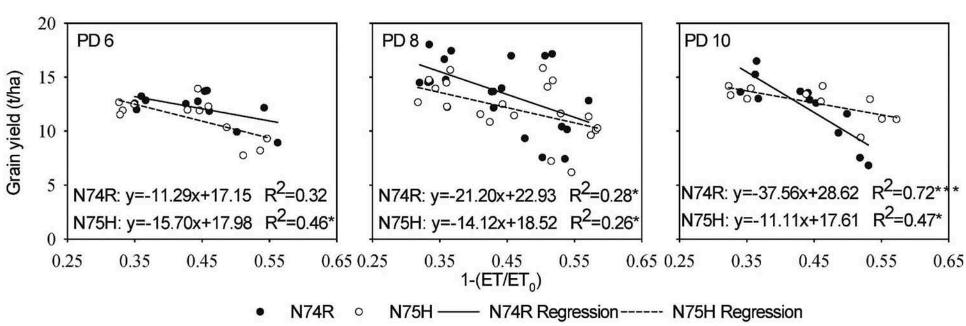

Figure 3. Linear regressions of grain yield versus the stress index based on the ratio of evapotranspiration (ET) and reference evapotranspiration (ET_o) for the two hybrids in the two seasons.

Table 4. Biomass (BM), harvest index (HI), kernel weight (KW) and kernel number (KN) as affected by the main effects of year, water regime, hybrid and planting density in 2013 and 2014.

		BM t/ha	HI	KW mg/kernel	KN kernels/m^2
Year	2013	23.02a†	0.57b	345.4a	4507a
	2014	21.93a	0.58a	342.7a	4459a
Water regime	I_{100}	24.42a	0.60a	382.8a	4540a
	I_{75}	24.87a	0.57b	366.7b	4608a
	I_{50}	18.14b	0.55c	282.6c	4301a
Hybrid	N74R	22.66a	0.58a	338.3a	4669a
	N75H	22.30a	0.57b	349.8a	4297b
Planting density	6	21.08b	0.58a	364.1a	3990b
	8	23.21a	0.57a	336.8b	4704a
	10	23.15a	0.57a	331.2b	4755a

†Means in each column for each main effect followed by different letters are significantly different at the 0.05 probability level.

In 2013, average biomass across water regimes and hybrids under PD 6 was less ($P < 0.05$) than the two other planting densities, while there were no differences among the three planting densities in 2014 (Figure 4).

Harvest index was affected by water regime and hybrid (Table 2). Higher ($P < 0.05$) HI was found in 2014 than 2013, and N74R had a slightly higher HI than N75H (Table 4). Compared with HI at I_{100}, water stress at I_{75} and I_{50} reduced HI by 0.01 and 0.02 in 2013. However, in 2014, HI dropped more at I_{75} and I_{50} (0.03 and 0.03), which resulted in a year × water regime interaction (Figure 5).

Kernel weight was strongly ($P \leq 0.01$) affected by water regime and planting density (Table 2). Water stress at I_{75} and I_{50} reduced the kernel weight by 16.1 mg/kernel and 100.2 mg/kernel compared to I_{100} (Table 4), and the same trend was found in both hybrids in both years (Table 5).

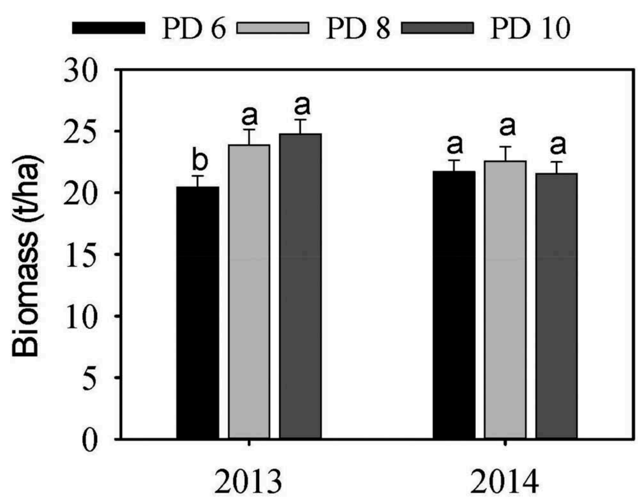

Figure 4. Biomass of the two maize hybrids under three plant densities (PD 6, PD 8 and PD 10) in 2013 and 2014.

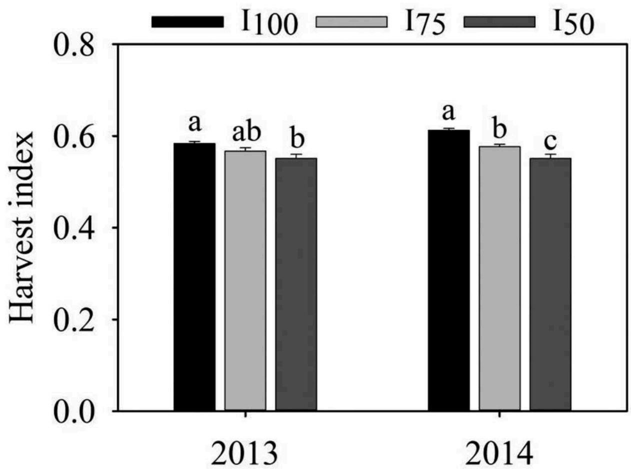

Figure 5. Harvest index (HI) of the two maize hybrids under three water regimes (I_{100}, I_{75} and I_{50}) in 2013 and 2014.

Table 5. Kernel weight (KW) and kernel number (KN) as affected by year, water regime, and hybrid in 2013 and 2014.

		Kernel weight mg/kernel			Kernel number kernels/m^2		
Year	Hybrid	I_{100}	I_{75}	I_{50}	I_{100}	I_{75}	I_{50}
2013	N74R	381.7aA†	356.3aA	278.4aB	4800aA	4998aA	4170aB
	N75H	398.2aA	383.1aA	274.5aB	4418aA	4273aA	4382aA
	Mean	**390.0A**	**369.7A**	**276.4B**	**4609A**	**4635A**	**4276A**
2014	N74R	371.9aA	367.3aA	274.1aB	4812aA	4626aA	4699aA
	N75H	379.4aA	360.0aA	303.3aB	4130bA	4534aA	3953aA
	Mean	**375.6A**	**363.7A**	**288.7B**	**4471A**	**4580A**	**4326A**

†Means followed by different uppercase letters are significantly different among water regimes at the 0.05 probability level; means followed by different lowercase letters are significantly different between hybrids at the 0.05 probability level.

Averaged across hybrids, years, and water regimes, higher planting densities under PD 8 and PD 10 decreased the kernel weight by 27.3 mg/kernel and 32.9 mg/kernel ($P < 0.05$) compared to PD 6 (Table 4). Both hybrids had lower kernel weights at I_{50} than at I_{100} or I_{75}. However, higher planting densities only reduced ($P < 0.05$) the kernel weight for N74R in 2013, and no differences in kernel weight were found among the three planting densities for N75H (Table 6).

Kernel number/m^2 was only affected by planting density (Table 2). Averaged across years, water regimes, and planting densities, N74R had 372 more kernels m^{-2} ($P < 0.05$) than N75H (Table 4) due to more ($P < 0.05$) kernels for N74R at I_{100} in 2014 (Table 5). There were no differences in kernel numbers among the three water regimes, except that water stress at I_{50} reduced kernel numbers ($P < 0.05$) of N74R in 2013. More ($P < 0.05$) kernel numbers were found under PD 8 and PD 10 than under PD 6 in 2013.

Table 6. Kernel weight (KW) and kernel number (KN) as affected by year, hybrid and planting density in 2013 and 2014.

		Kernel weight mg/kernel			Kernel number kernels/m^2		
Year	Hybrid	PD 6	PD 8	PD 10	PD 6	PD 8	PD 10
2013	N74R	378.6aA†	329.0aAB	308.8aB	3652aC	4841aB	5475aA
	N75H	363.6aA	351.6aA	340.5aA	3797aB	4609aA	4667bA
	Mean	**371.1A**	**340.3AB**	**324.6B**	**3725B**	**4725A**	**5071A**
2014	N74R	350.8aA	318.5aA	344.1aA	4441aA	4828aA	4776aA
	N75H	363.5aA	347.8aA	331.4aA	4069aA	4537aA	4103aA
	Mean	**357.1A**	**333.2A**	**337.7A**	**4255A**	**4682A**	**4440A**

†Means followed by different uppercase letters are significantly different among planting densities at the 0.05 probability level; means followed by different lowercase letters are significantly different between hybrids at the 0.05 probability level.

Correlations and regressions

For both N74R and N75H, yield increased linearly as biomass, HI, and kernel weight increased ($P < 0.0001$) (Figure 6). However, the linear relationship between kernels per square meter and grain yield was not significant for both hybrids. That indicated that maize grain yield was largely determined by biomass, HI, and kernel weight.

Soil water extraction

SWE in the 0–2.0 m profile from V8 stage to maturity under PD 8 at the three water regimes are shown in Figure 7. At I_{100}, the total net SWE (0–2.0 m) for both hybrids was negative (−20 mm for N74R and −39 mm for N75H). However, N74R extracted a net of 11 mm from the 0.2–1.0 m depth and N75H extracted a net of 6 mm from the 0.2–0.8 m depth. At I_{75}, N74R extracted water from the 0–1.0 m soil depth while N75H extracted from the 0.2–0.8 m depth. And N75H extracted less soil water than N74R in all the layers. However, the total net SWE for N74R was 30 mm, while that for N75H was −17 mm at I_{75}. The maximum depth of soil water extraction was 1.2 m for both hybrids at I_{50}, and the total net SWE was 84 mm for N74R and 69 mm for N75H.

Discussion

Grain yield, seasonal ET, and WUE

Using deficit irrigation together with drought-adapted genotypes is considered a good practice to save water and optimize crop yield in drought regions (Gheysari et al. 2015). In our study, the average grain yields ranged from 10.01 t/ha to 14.91 t/ha among the three water regimes, which were within the range (6.4–14.8 t/ha) of previous studies in the THP (Howell et al. 1995; Colaizzi, Evett, and Howell 2011). Irrigation at I_{75} did not reduce the grain yield for either hybrid in either season (Figure 2). On the other hand, the seasonal ETc reduced

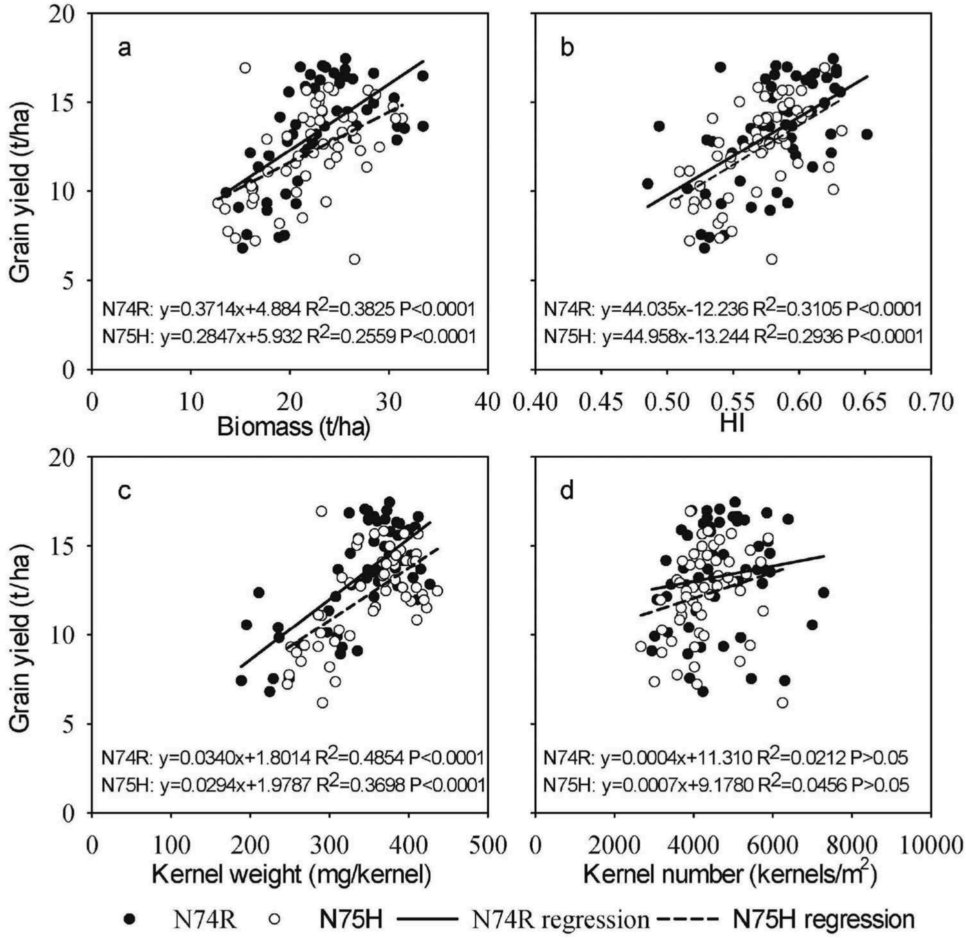

Figure 6. Linear regressions between grain yield (t/ha) and biomass (t/ha), harvest index, kernel weight (mg/kernel) and kernel number (kernels/m^2) for the two hybrids.

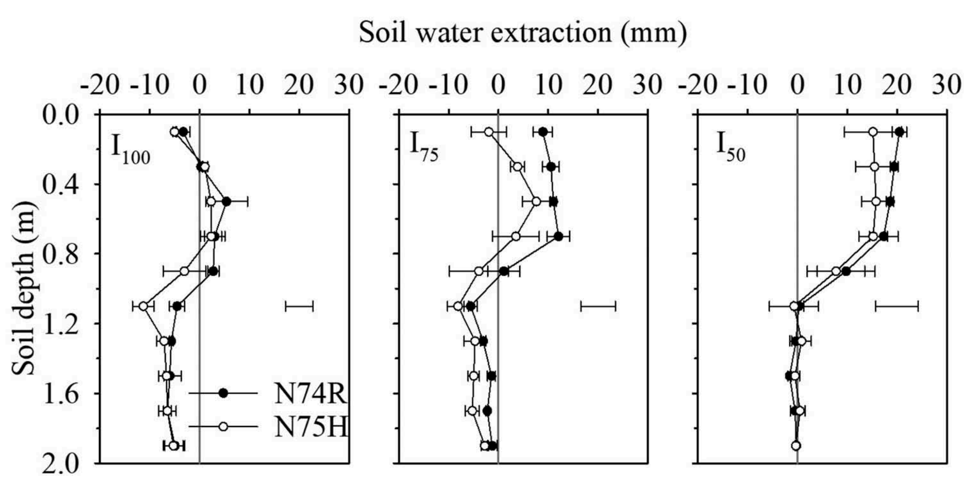

Figure 7. Soil water extraction along the 0–2.0 m profile from V8 stage to maturity in two hybrids at PD 8 in the 2013 seasons in three water regimes (I_{100}, I_{75} and I_{50}).

significantly ($P < 0.05$) as the irrigated inputs decreased for both hybrids, and the highest WUE was found at I_{75}. Higher WUE at I_{75} indicated a full use of irrigation, stored soil water, and rainfall (Howell 2001; Hao et al. 2015b), which is a target of crop improvement under water-limited conditions (Blum 2009). In our previous studies, significant differences in grain yield were found between I_{100} and I_{75} among Pioneer hybrids during 2011–2013 (Hao et al. 2015a, 2015b), while WUE at I_{75} was lower than I_{100} in 2012. The different findings may be due to the much less precipitation during the maize growing seasons of 2011 and 2012 compared to 2013 and 2014.

In this study, yield in the hybrid with Agrisure Artesian DT trait (N75H) did not differ with the conventional hybrid (N74R), due to the similar drought score in the two hybrids. However, we did find that the yield reduction by water stress at I_{50} for N75H (4.22 t/ha) was less than N74R (4.78 t/ha), demonstrating more yield stability for the DT hybrid. Moreover, N75H extracted less soil water than N74R at all the three water regimes, a characteristic found in our other studies with DT hybrids from Pioneer (Hao et al. 2015b).

In general, maize yield responses to increased planting density were reported to follow quadratic (Milander et al. 2016) or quadratic-plateau models (Hammer et al. 2009) in the high-rainfall and irrigated environments. The availability of resources per plant and yield will decrease or keep constant when the density is higher than optimum planting density (Sarlanguel et al. 2007). And the optimum planting density is based on detailed exploring genotype and environment (Assefa et al. 2016). A synthesis-analysis pointed out that a higher planting density is needed to achieve the maximum yield in the high-yield zones (Assefa et al. 2016). In a model study, the optimum planting density was affected by available soil water at planting (Lyon et al. 2003). However, tolerance to planting density in modern maize hybrids has been improved over the decades (Tollenaar and Wu 1999; Tollenaar and Lee 2002) such that the optimum planting density in the U.S. maize belt has increased by 0.1 plants/m^2/year over the past 25 years (Fischer and Edmeades 2010). As planting density has increased, DT hybrids showed greater tolerance to water stress under moderate and high densities than the conventional hybrids (Cooper et al. 2014). In this study, planting density did not affect grain yield, ETc, or WUE for the conventional hybrid (N74R). However, yield and WUE significantly increased as the density increased for the DT hybrid (N75H).

Biomass, HI, kernel weight, kernel number, and yield determination

For both maize hybrids, grain yield was strongly ($P < 0.0001$) determined by biomass at maturity, HI, and kernel weight. Similar results were also found in another two-year study with Pioneer hybrids (Hao et al. 2015b). Although a linear relationship between grain yield and kernel number was found in four hybrids in our previous study (Zhao et al. 2018), in this study grain yield was more related to kernel weight than kernel number. Consistent with previous studies (Colaizzi, Evett, and Howell 2011; Hao et al. 2015b; Magaia et al. 2017), water deficits decreased biomass at maturity, HI, and kernel weight. Instead of HI, an increase in biomass at maturity is the key driver for increased maize yield in the new hybrids (Zhao et al. 2015). In this study, reduced biomass was only found at I_{50} as compared to I_{100}. It is significant that irrigation at the I_{75} level resulted in water savings as compared to I_{100} in this semiarid region. Averaged across years, planting densities, and hybrids, the kernel weights were 382.8, 366.7, and 282.6 mg kernel^{-1} at I_{100}, I_{75}, and I_{50}, respectively, which were greater than the values reported in the previous studies on Pioneer hybrids (less than 300 mg/kernel) (Hao et al. 2015b; Mounce et al. 2016; Tolk et al. 2016). Our previous study showed that Syngenta hybrids had greater kernel weight than Pioneer hybrids (Zhao et al. 2018). In this study, water stress at I_{75} and I_{50} reduced the kernel weight by 16.1 mg/kernel and 100.2 mg/kernel compared to I_{100}, while there were no significant difference in kernel number among the three water regimes. Hao et al. (2015b) and Zhao et al. (2018) also reported that kernel weight was more sensitive to water stress than kernel number.

In this study, higher planting densities increased total aboveground biomass per square meter but decreased biomass per plant. Kernel number per m^2 also increased under higher density, which may be caused by the increased number of ears per m^2 instead of number of kernels per ear (Kruger et al. 2018). Kernel weight showed a decreasing trend under the higher density, especially in 2013, which may be influenced by the stressful environment during grain filling (Abendroth et al. 2011). Similar trends in kernel number and kernel weight were also reported in previous dryland and partially irrigated sites (Norwood 2001; Pavlista et al. 2010). For example, Echarte et al. (2000) found an increase in planting density from 5.0 to 14.5 plants/m^2 increased kernel number from 38% to 56% and decreased kernel weight by 6% to 17%. In addition, there were no differences in biomass, HI, kernel weight, and kernel number between PD 8 and PD 10. This indicated that the optimal planting density should be in the range of 8–10 plants/m^2 in the research area, consistent with Marek et al. (2016). Although N74R had more kernels per square meter than N75H when averaged across years, water regimes, and planting densities, kernel number and kernel weight of N74R were more sensitive to planting density than N75H. That may be attributed to recent breeding efforts that have also produced hybrids that better tolerate the stresses created by increased plant density (Gaffney et al. 2015). Kernel weight of N74R decreased significantly following the increased densities while no differences were found in that of N75H in 2013. Meanwhile, kernel number of N74R increased by 49.9% from PD 6 to PD 10, while that of N75H increased by 22.9% in 2013.

Conclusion

Regardless of year, hybrid, or planting density, no significant differences in grain yield were found between I_{100} and I_{75}. However, I_{50} significantly reduced the grain yield by 4.78 t/ha for N74R and 4.22 t/ha for N75H compared to I_{100}. Seasonal ETc decreased in water-limited conditions (I_{75} and I_{50}), and the highest WUE was found at I_{75} for both hybrids (2.36 kg/m^3 and 2.23 kg/m^3). For both hybrids, water deficits decreased biomass, HI, and kernel weight. However, differences in kernel number were not significant among three water regimes. Higher planting densities, on the other hand, increased biomass and kernel number per unit area, but decreased kernel weight, especially in 2013. Although N75H, with the Agrisure Artesian DT trait, did not have a yield benefit over the conventional hybrid N74R, N75H provided greater yield stability under high plant densities when water stress increased. Planting a DT hybrid with a greater plant density may provide greater yield stability under water-limited conditions while also maintaining yield potential when moisture is sufficient. Overall, limited irrigation at I_{75} is an effective way to save water and maintain maize yield level in semiarid areas. In addition, DT hybrids showed a greater yield stability to plant density under water stress.

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No potential conflict of interest was reported by the authors.

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