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ORIGINAL PAPER

Grain yield, evapotranspiration, and water-use efficiency of maize hybrids differing in drought tolerance

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Abstract

Adoption of drought-tolerant (DT) hybrids is a viable strategy for maize production in drought-prone environments. We conducted four-year field studies (2011–2014) to investigate yield, crop evapotranspiration (ETc), and water-use efficiency (WUE) in one conventional (N58L) and one DT hybrid (N59B-DT) under three water regimes (I_{100}, I_{75}, and I_{50}, where the subscripts were the percentage of irrigation applied relative to meeting full ETc) and three plant densities. At I_{100} and I_{75}, N59B-DT did not show advantage in yield and WUE relative to N58L, however, at I_{50} it showed an advantage of 8.5% and 10.5%, respectively. At I_{100} and I_{75}, high plant density treatment had greater grain yield (9.1%) and WUE (9.4%) than low plant density. Comparing hybrids, N59B-DT had greater yield (5.9%) and WUE (7.3%) than N58L at high plant density. N59B-DT had large advantage over N58L in yield (18.0%) and WUE (26.2%) when the hybrids were grown under severe water deficit (I_{50}) and high plant density (9.9 plants m^{-2}). At I_{50}, increasing plant density reduced yield (14.1%) for N58L but did not affect yield for N59B-DT. On average, plant density had no effect on seasonal ETc but N59B-DT had more seasonal ETc than N58L at I_{100} and I_{75}. The results of this study indicate that DT hybrid was tolerant to high panting density. Planting a DT hybrid with a higher plant density may provide greater yield stability under water-limited conditions while also maintaining maximum yield potential when moisture is sufficient.

Introduction

The global population is expected to reach 9.4 billion by 2050 (USCB 2015). It is predicted that the world will need 44% more cereal production by 2050, relative to the 2005 level of production (Fischer et al. 2014). Maize (*Zea mays* L.) is currently the most important food and feed crop in total global production (Ort and Long 2014). To meet the goal of a 44% increase in cereal production, global maize production will need to increase from 736 million Mg in 2005 to 1178 million Mg (Alexandratos and Bruinsma 2012; Fischer et al. 2014). The United States is by far the world's largest producer and exporter of maize, accounting for 38% of global maize production and 52% of global maize exports over the last 10 years (NCGA 2015). Therefore, maize production in the United States is an important determinant of the world maize supply. One of the most important environmental stresses affecting maize production in the United States is drought (Campos et al. 2006; Lobell et al. 2014; Sammons et al. 2014). For example, in 2012, the severe and widespread drought in the United States led to reductions of 21% and 15% in national maize yields and maize production, respectively (Boyer et al. 2013; Edmeades 2013). New research has suggested that drought may become more severe in the US Southwest and Great Plains in the coming decades due to climate change (Cook et al. 2015).

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Maize grain yield in the United States increased by about 100 kg ha^{-1} $year^{-1}$ or 2% $year^{-1}$ from 1939 to 2004, and about 75% of the yield improvement has been attributed to genetic gain (Tollenaar and Lee 2006; Araus et al. 2008, 2012). The genetic gain was associated with better tolerance to stress such as drought and high plant density (Cassman 1999; Duvick 1999, 2005; Tollenaar et al. 2000; Tollenaar and Lee 2002, 2006; Gonzalez et al. 2018). Drought tolerance is an important component for the success of maize hybrids grown in drought-prone environments (Cooper et al. 2014a, b), and will be of even greater importance in the future as water resources for agronomic uses become even more limiting (Bruce et al. 2002). Seed companies are using diverse strategies such as conventional breeding and genetic engineering to produce new hybrids with enhanced tolerance to drought stress (Claeys and Inzé 2013; McKersie 2015). Monsanto (Monsanto Company, St. Louis, MO, USA) has released its new biotech transgenic DT DroughtGard maize hybrid (MON 87460), which was shown to enhance productivity in water-limited environments, and without yield penalty under favorable moisture conditions (Castiglioni et al. 2008; Chang et al. 2014; Nemali et al. 2014; Sammons et al. 2014). Additionally, Syngenta's Agrisure Artesian and Pioneer's Optimum AQUAmax programs have successfully released a number of non-transgenic DT maize hybrids using conventional breeding (Syngenta-US, http://www.syngenta-us.com; DuPont Pioneer, Johnston, IA, USA). Previous studies have reported that Pioneer's AQUAmax hybrids have a yield advantage under drought conditions with little or no yield penalty under favorable growing conditions as compared with non-AQUAmax hybrids (Pioneer 2013; Cooper et al. 2014a; Gaffney et al. 2015; Hao et al. 2015a). In addition, Mounce et al. (2016) in the High Plains of Texas observed that, compared with the conventional hybrid, the AQUAmax hybrid had lower water use and greater water-use efficiency. However, there have been few studies that have investigated the yield performance and water use of Syngenta's recently released DT Agrisure Artesian maize hybrids.

Tollenaar and Wu (1999) suggested that, under water-limited conditions, maize productivity under high plant density is generally associated with resistance to drought stress. Cooper et al. (2014a) found that, compared to drought-sensitive hybrids, Pioneer AQUAmax hybrids showed higher tolerance to moderate and higher plant density under water-limited conditions. Similarly, Gaffney et al. (2015) reported that AQUAmax hybrids maintained an approximate 8% yield advantage over the non-AQUAmax hybrids under higher population densities and water-limited conditions. It has also been found that the newer maize hybrids have higher optimum plant density than the older hybrids (Duvick 2005). For example, in the US Corn Belt, the yield plateau occurred at about 3 plants m^{-2} for maize hybrids released up to the 1960s and about 5–6 plants m^{-2} for hybrids released in the 2000s (Hammer et al. 2009). Recently, Hao et al. (2015a) reported that, as plant density increased from 5.9 to 8.4 plants m^{-2}, AQUAmax maize yield increased markedly under well-watered conditions but did not respond to plant density under severe water stress conditions. However, little information is known about the yield response to plant density in recently released Syngenta DT Agrisure Artesian maize hybrids, especially under water-limited environments. Hence, our objectives were (1) to investigate water use, grain yield and water-use efficiency (WUE) of an Agrisure Artesian DT hybrid under different water regimes, and (2) to evaluate the response of the DT hybrid to plant density compared to a conventional hybrid.

Materials and methods

Experimental site

The field experiments were conducted at the Texas A&M AgriLife North Plains Research Field near Etter, TX (35°60′N, 101°59′W; elevation 1114 m above mean sea level) from 2011 to 2014. The soil type in the experimental area was a Sherm silty clay loam. The chemical properties of the 0–0.3 m soil layer were as follows: pH 7.6, 60 kg KCl-extracted NO_3–N ha^{-1}, 13 mg kg^{-1} of Mehlich-3-extractable P, 404 mg kg^{-1} ammonium acetate-extractable-K and 11 g organic matter kg^{-1}. Meteorological data for the 2011, 2012, 2013, and 2014 maize growing seasons were obtained from an agricultural meteorological station located at the experimental site, which was part of the Texas High Plains Evapotranspiration (TXHPET) network (Table 1). Daily data were obtained from the TXHPET website (https://txhighplainset.tamu.edu/weather.jsp).

Experimental design and treatments

The experimental design was a split–split plot design with four replications. The whole plot factor was irrigation treatment with the combination of hybrid and plant density as sub-plot factor. There were three irrigation treatments (I_{100}, I_{75}, and I_{50}, where the subscripts were the percentage of irrigation applied relative to meeting full crop evapotranspiration, ETc) and three plant densities (9.9, 7.9, and 5.9 plants m^{-2}). The plant density in this study refers to seeding density in terms of seeds per square meter. All fields were irrigated with a center pivot irrigation system using low elevation spray application (LESA) heads. In each season (except 2014), no irrigation was applied before planting and initial irrigations were applied right after planting in all the plots at a uniform level (I_{100}) to ensure uniform emergence and stands. For the I_{100} treatment, irrigation scheduling was determined according to reference evapotranspiration

Table 1 Summary of monthly average maximum air temperature (T_{max}), minimum air temperature (T_{min}), reference evapotranspiration (ETo), and precipitation during the 2011, 2012, 2013, and 2014 growing seasons at Etter, Texas

Parameter	Year	May	June	July	Aug.	Sept.	Oct.	Mean/total
T_{max} (℃)	2011	26.6	35.3	37.1	35.8	28.2	23.2	31.0
	2012	28.4	33.9	35.3	33.2	29.2	21.9	30.3
	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
T_{min} (℃)	2011	7.8	16.3	18.9	18.6	11.6	5.6	13.1
	2012	10.9	16.5	18.5	16.1	11.3	4.2	12.9
	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
ETo (mm)	2011	234	272	237	202	152	132	1229
	2012	217	235	241	196	152	119	1160
	2013	224	250	197	180	152	126	1129
	2014	204	210	201	199	125	101	1040
Precipitation (mm)	2011	16	1	13	33	27	13	102
	2012	0	54	6	37	55	8	160
	2013	4	30	58	53	43	7	196
	2014	80	33	50	59	24	4	252

(ETo), a crop coefficient, and available soil water at the root zone on a daily basis (Marek et al. 2011). 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 using the initial soil water content and subtracting ETc. The irrigation requirement was adjusted based on 90% application efficiency for LESA system (Kapanigowda et al. 2010). Total plant available water (TAW) was estimated from the soil water at upper (− 0.033 MPa) and lower (− 1.5 MPa) limits (Marek et al. 2011), and irrigation events were initiated generally when the root zone soil PAW reached to 50% of TAW. For the I_{75} and I_{50} treatments, irrigation frequency was the same as that of the I_{100} treatment and the irrigation amount was proportional to that of the I_{100} treatment, using nozzles with a reduced rate once the crop was established (27–31 days after planting) from 2011 to 2013. However, the reduced irrigation rate started earlier in 2014. The total irrigation amounts for the I_{100}, I_{75}, and I_{50} treatments were 754, 584, and 414 mm, respectively, in 2011, 612, 473, and 334 mm, respectively, in 2012, 608, 474, and 340 mm, respectively, in 2013, and 651, 490, and 326 mm, respectively, in 2014 (Fig. 1).

The hybrids used were N58L (106-day relative maturity) and N59B-DT (107-day relative maturity) from Syngenta Seeds Company. Both hybrids had high yield potential, strong seedling vigor and stalk strength. The two hybrids had similar height but differed in their drought-tolerance characteristics with N59B-DT being designated as the DT hybrid with Agrisure Arteisan trait (Syngenta-US, http://www.syngenta-us.com). The maize was planted on May 3, 2011, May 10, 2012, May 16, 2013, and May 14, 2014, using a four-row Max-Emerge (John Deere, East Moline, IL) planter. The plots were harvested in mid-October in each season, using a Massie Ferguson 8-XP Plot Combine (Kincaid Equipment Manufacturing, Haven, Kansas, USA).

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 334–111–0–0 (N–P–K–S) kg ha^{-1} in 2011, 278–112–0–33 (N–P–K–S) kg ha^{-1} in 2012 and 290–109–0–11 (N–P–K–S) kg ha^{-1} in 2014, based on soil testing. In 2013, 100–67–0–0 (N–P–K–S) kg ha^{-1} was applied before planting, and 100 kg ha^{-1} 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 conducted for spider mite (*Tetranychus urticae*) control in 2011 and 2013.

Measurements

In the 2011, 2012, and 2013 seasons, 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 subplot after harvest. Gravimetric soil water in each depth was converted to volumetric water by multiplying by the soil bulk density, which was measured by taking soil cores. Crop seasonal ETc was

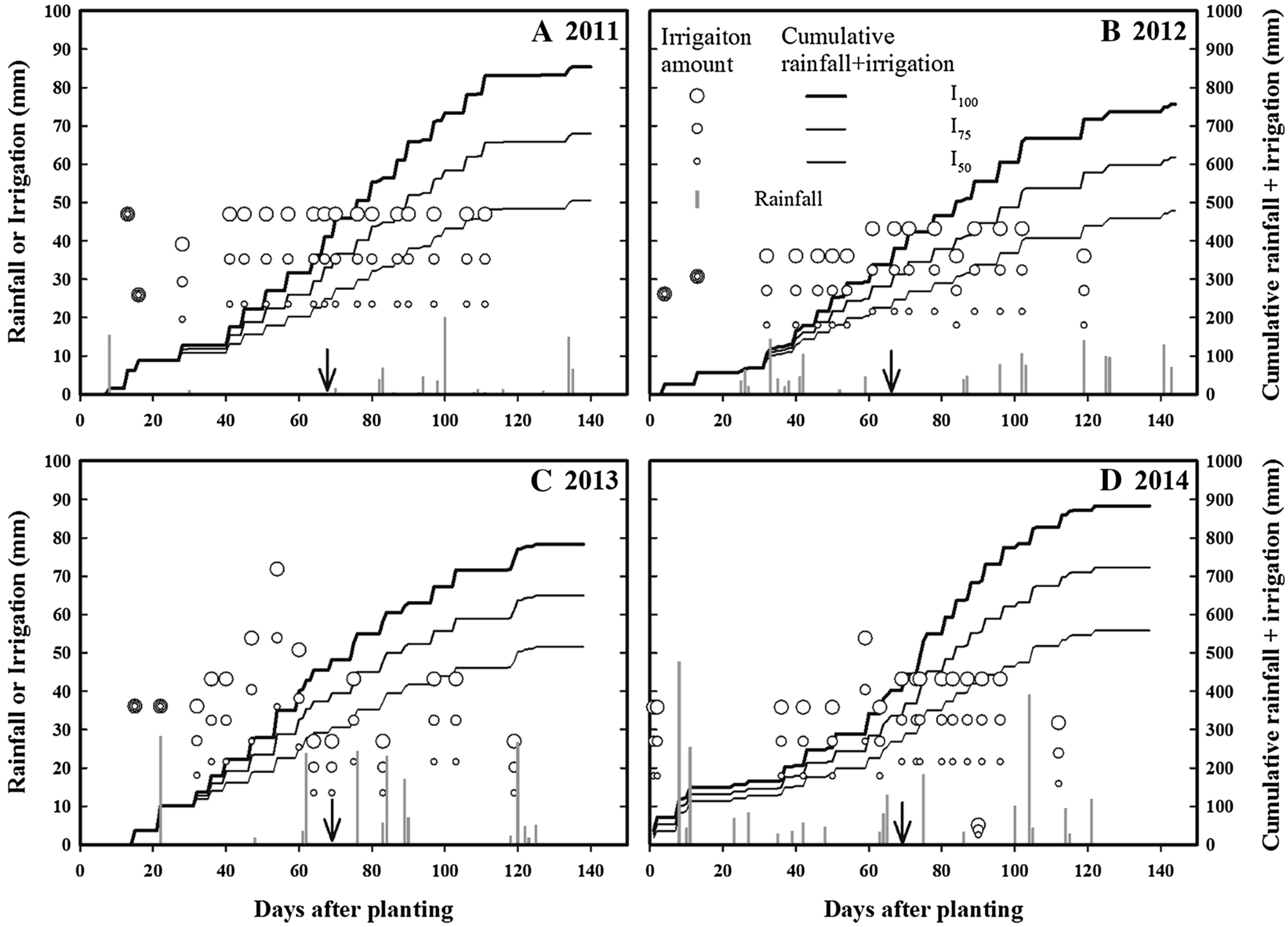

Fig. 1 Rainfall and irrigation, and cumulative rainfall and irrigation during the 2011 (**a**), 2012 (**b**), 2013 (**c**), and 2014 (**d**) maize growing seasons at Etter, Texas. Arrows indicate the silking dates

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. We assumed runoff and deep percolation were negligible. The field was furrow diked and plots were leveled, and the irrigation system speed was manually adjusted to uniformly apply water to the soil at a rate less than the soil intake rate to prevent runoff from occurring. In another maize study at the same field with the same center pivot irrigation system, we measured soil water content at 1.4 m throughout the growing season in 2012 and 2013, which indicated no movement of water into lower soil depths (Hao et al. 2015b). In 2014 season, the soil water contents were only measured in the plots with medium plant density (7.9 seeds m^{-2}). Therefore, the ETc data were not included in this season. Water-use efficiency (WUE, kg m^{-3}) was calculated as the ratio of grain yield and seasonal ETc. Yield was determined by harvesting the central two rows in each plot and grain moisture was adjusted to 15.5%.

Statistical analysis

Statistical analysis was conducted using the SAS v9.2 statistical program (SAS Institute Inc. 2009). Analysis of variance (ANOVA) was conducted by the PROC MIXED procedure to evaluate each factor and interaction. The year, water regime, hybrid, and plant density were treated as fixed effects. Replication was considered a random effect. Mean values were compared by least significant difference (LSD) at the 5% level.

Results

Weather conditions

Weather conditions in this study varied markedly among the four growing seasons (Table 1). The 2011 season was unusually dry and hot and represented the second driest season of record. The 2013 and 2014 seasons were relatively cool and wet. The average maximum air temperatures for June, July, and August in 2011 were higher than in 2012 and much higher than in 2013 and 2014. The seasonal rainfall (May–October) was lower in 2011 and 2012 than in 2013 and 2014. In the 2011 growing season, only three rainfall events of more than 10 mm occurred. In 2012, approximately 40% of seasonal rainfall occurred during the later growth period (September and October). Seasonal rainfall in 2011, 2012, 2013, and 2014 only accounted for 8%, 14%, 17%, and 24% of seasonal ETo (May–October), respectively.

Table 2 Analysis of variance ($P > F$) of maize grain yield (GY), seasonal crop evapotranspiration (ETc), and water-use efficiency (WUE) as affected by water regime (WR), hybrid (HB), and plant density (PD)

Effect	*df*	GY	*df*	ETc	WUE
Year (Y)	3	< 0.0001	2	< 0.0001	< 0.0001
Water regime (WR)	2	< 0.0001	2	< 0.0001	0.0001
Hybrid (HB)	1	0.0003	1	0.0016	0.2623
Plant density (PD)	2	< 0.0001	2	0.6973	0.0003
Y × WR	6	< 0.0001	4	< 0.0001	< 0.0001
Y × HB	3	0.2977	2	0.0849	0.1325
Y × PD	6	< 0.0001	4	0.0005	< 0.0001
WR × HB	2	0.1641	2	0.0516	0.0041
WR × PD	4	< 0.0001	4	0.9676	0.0075
HB × PD	2	0.0460	2	0.1241	0.0069
Y × WR × HB	6	0.0955	4	0.2242	0.0008
Y × WR × PD	12	0.2399	8	0.1370	0.2155
Y × HB × PD	6	0.4795	4	0.5024	0.7126
WR × HB × PD	4	0.4505	4	0.5236	0.2411
Y × WR × HB × PD	12	0.2233	8	0.1968	0.8598

Grain yield

Grain yield was affected significantly ($P < 0.05$) by all main effects and all two-way interactions except year × hybrid ($P = 0.2977$) and water regime × hybrid ($P = 0.1641$) (Table 2). The three-way year × water regime × hybrid interaction for grain yield was significant at $P < 0.10$ level (Table 2). In each season, grain yield decreased with decreasing irrigation supply (Table 3). Compared to I_{100}, grain yield at I_{75} decreased more in 2011 (12.4%) and 2012 (14.7%) than in 2013 (4.0%) and 2014 (0.7%). These differences may be caused by the adverse climatic conditions in 2011 and 2012 compared to 2013 and 2014. At I_{50}, grain yield decreased more and ranged from 29.8 to 48.7% compared to I_{100}.

The grain yield of the two hybrids showed different responses to water regime among the 4 years (Table 3). At I_{100} and I_{75}, the yield difference between the two hybrids was generally small and not significant, except at I_{75} in 2014, in which, N59B-DT had greater yield than N58L. At I_{50}, N59B-DT generally had greater grain yield than N58L. Averaged across year and plant density, grain yield of N58L was reduced by 8.2%$^{-1}$ at I_{75} and 42.9% at I_{50} as compared to I_{100} (Table 3). The corresponding values for N59B-DT were only 6.9% and 38.9% at I_{75} and I_{50}, respectively. The results indicate that N59B-DT had less yield reduction under water stress as compared to N58L.

Table 3 Grain yield (GY), seasonal crop evapotranspiration (ETc), and water-use efficiency (WUE) of the two hybrids under three water regimes during the 2011, 2012, 2013, and 2014 maize growing seasons at Etter, Texas

Year	Hybrid	GY (Mg ha^{-1})			ETc (mm)			WUE (kg m^{-3})		
		I_{100}	I_{75}	I_{50}	I_{100}	I_{75}	I_{50}	I_{100}	I_{75}	I_{50}
2011	N58L	12.18a[†]	10.53a	6.05b	749a	572a	488a	1.63a	1.84a	1.24b
	N59B-DT	12.54a	11.14a	6.63a	758a	578a	489a	1.65a	1.93a	1.36a
	Mean	12.36A[‡]	10.83B	6.34C	753A	575B	489C	1.64B	1.89A	1.30C
2012	N58L	11.93a	10.01a	6.51a	623a	562a	485a	1.91a	1.82a	1.35a
	N59B-DT	12.02a	10.42a	6.73a	629a	568a	487a	1.93a	1.86a	1.36a
	Mean	11.98A	10.21B	6.62C	626A	565B	486C	1.92A	1.84A	1.36B
2013	N58L	12.58a	12.20a	8.17b	616b	530b	482a	2.04a	2.30a	1.68b
	N59B-DT	12.32a	11.69a	9.27a	645a	560a	476a	1.92b	2.08b	1.95a
	Mean	12.45A	11.96A	8.47B	631A	545B	479C	1.98B	2.20A	1.82C
2014	N58L	14.36a	14.12b	8.47a	–[§]	–	–	–	–	–
	N59B-DT	14.80a	14.86a	8.97a	–	–	–	–	–	–
	Mean	14.58A	14.49A	8.72B	–	–	–	–	–	–

[†]Within each year in each column for each water regime, means with the same lowercase letter were not significantly different at $P = 0.05$

[‡]Within each year in each row, means with the same uppercase letter were not significantly different at $P = 0.05$

[§]Seasonal crop evapotranspiration and water-use efficiency were not measured in 2014

The effect of plant density on grain yield (across hybrids) was different under the three water regimes (Table 4). At I_{100} and I_{75}, higher plant density resulted in greater grain yield. At I_{50}, grain yield did not increase significantly when plant density increased from 5.9 to 7.9 plants m^{-2}, and decreased significantly as plant density increased to 9.9 plants m^{-2}. These results indicated that increased plant density would result in increased yield under well-watered conditions, and caused some yield reduction under water-limited conditions. Both hybrids at all three water regimes showed an increase in grain yield when plant density increased from 5.9 to 7.9 plants m^{-2}, and the average increase was a little higher for N58L than N59B-DT. However, as plant density increased from 7.9 to 9.9 plants m^{-2}, at both I_{100} and I_{75}, grain yield did not change for N58L, whereas a slight yield increase was observed for N59B-DT, and at I_{50}, grain yield did not change for N59B-DT but was reduced by 14.1% for N58L. A significant difference in grain yield between hybrids was only detected at I_{50} with high plant density, at which grain yield was 18.0% greater for N59B-DT than N58L. These results indicated that, under sufficient water supply (I_{100}) or mild water stress (I_{75}), N59B-DT always responded positively to increased plant density (5.9–7.9–9.9 plants m^{-2}), but N58L only responded positively to increased plant density of 5.9–7.9 plants m^{-2}. Under severe water stress (I_{50}), N59B-DT did not respond negatively to increased plant density, but N58L did show a negative response. Across hybrids, on average, grain yield for the high plant density was 11.8% and 6.4% greater than for the low plant density at I_{100} and I_{75}, respectively (Table 4).

Evapotranspiration

The seasonal ETc was affected significantly ($P < 0.05$) by year, water regime and hybrid, but not by plant density ($P = 0.6973$). In addition, the water regime × hybrid interaction was significant at $P < 0.10$ level (Table 2). On average, the seasonal ETc for I_{100}, I_{75}, and I_{50} water regimes was 673, 561, and 484 mm, respectively (Table 3), suggesting a 16.6% and 28.1% reduction in seasonal ETc when irrigation was reduced from I_{100} to I_{75} and I_{50}, respectively. Hybrid differences in seasonal ETc were related to water regime. At I_{50}, the two hybrids had similar seasonal ETc. However, N59B-DT had greater seasonal ETc than N58L at both I_{100} and I_{75}. Compared to the 2011 season, the 2012 and 2013 seasons had lower seasonal ETc, which was due to the hot and dry conditions in 2011 that resulted in high ETo (Table 3).

Water-use efficiency

At both I_{100} and I_{75}, N59B-DT generally had similar or lower WUE than N58L for 3 years (Table 3). At I_{50}, WUE was significantly higher for N59B-DT than that for N58L in 2011 and 2013. However, no significant differences in WUE were observed between N59B-DT and N58L in 2012. Averaged across hybrids, the I_{50} treatment consistently had the lowest WUE in all 3 years. The I_{75} treatment had greater WUE in 2011 and 2013, and slightly less WUE in 2012 as compared to I_{100} (Table 3). Compared to I_{100}, WUE increased by 7.4% at I_{75} but decreased by 22.7% at I_{50} (Table 3). At I_{100} and I_{75}, there were no significant differences in WUE (across hybrids) between the high and moderate plant density, and both had significantly higher WUE than the low

Table 4 Maize grain yield and water-use efficiency (WUE) for the two hybrids under three plant densities and three water regimes at Etter, Texas

Water regime	Hybrid	Plant density (plants m^{-2})					
		Grain yield (Mg ha^{-1})			WUE (kg m^{-3})		
		5.9	7.9	9.9	5.9	7.9	9.9
I_{100}	N58L	11.80a[†]B[‡]	13.25aA	13.24aA	1.71aB	1.93aA	1.91aA
	N59B-DT	12.18aB	13.02aA	13.57aA	1.73aB	1.82aAB	1.94aA
	Mean	11.99B	13.13A	13.40A	1.72B	1.88A	1.93A
I_{75}	N58L	11.22aB	11.95aA	11.97aA	1.92aA	2.06aA	2.04aA
	N59B-DT	11.60aB	12.20aA	12.31aA	1.85aB	1.97aAB	2.06aA
	Mean	11.41B	12.07A	12.14A	1.89B	2.02A	2.05A
I_{50}	N58L	7.35aAB	7.80aA	6.70bB	1.46aA	1.52aA	1.29bB
	N59B-DT	7.85aA	7.94aA	7.90aA	1.52aA	1.57aA	1.63aA
	Mean	7.60AB	7.87A	7.30B	1.49A	1.54A	1.46A
Mean	N58L	10.18aC	11.00aA	10.64bB	1.70aB	1.84aA	1.75bB
	N59B-DT	10.54aB	11.03aA	11.26aA	1.70aB	1.78aB	1.88aA

[†]Within each water regime in each column for each plant density, means with the same lowercase letter were not significantly different at $P = 0.05$

[‡]Within each water regime in each row, means with the same uppercase letter were not significantly different at $P = 0.05$

plant density (Table 4). On average, WUE at I_{100} and I_{75} was greater at the high plant density than at the low plant density, respectively. There were no significant differences in WUE (across water regimes) between N59B-DT and N58L at the low and moderate plant density. But WUE was significantly greater for N59B-DT than N58L at the high plant density.

Discussion

Grain yield

Providing grain yield stability under water-limited conditions is a major goal of breeding drought-tolerant hybrids in maize (Campos et al. 2004, 2006). In our results, the DT hybrid N59B-DT had greater yield than the conventional N58L in 2 of 4 years (2011, 9.6% or 0.58 Mg ha^{-1}; 2013, 13.5% or 1.10 Mg ha^{-1}) under severe water stress conditions (I_{50}). In our results, under severe water stress conditions (I_{50}), the DT hybrid N59B-DT did not show yield advantage relative to N58L under low and moderate densities, but under high density (9.9 plants m^{-2}), it had greater yield than N58L. At I_{50}, N58L produced more grain at moderate density compared to low and high densities; however, the yield of N59B-DT did not differ among three densities. Previous reports had shown that Pioneer AQUAmax hybrids also had yield benefits when compared to non-AQUAmax hybrids under water-limited conditions (Cooper et al. 2014a; Gaffney et al. 2015; Zhao et al. 2018). Recently, under water-limited conditions, Gaffney et al. (2015) reported that grain yield (across 2006 locations) was 0.37 Mg ha^{-1} (6.5%) greater in AQUAmax hybrids than in non-AQUAmax hybrids, and Hao et al. (2015a) pointed out that two AQUAmax hybrids yielded 1.19 Mg ha^{-1} (19.1%) more than the conventional hybrid. In addition, Sammons et al. (2014) reported that the Monsanto MON 87460 can provide a yield advantage relative to a control hybrid under water-limited conditions, and Nemali et al. (2014) reported that grain yields (across the years 2007–2010) were 0.7 Mg ha^{-1} (8.8%) greater in MON 87460 than in a control hybrid. However, due to the complexities of drought (e.g., drought timing, duration, intensity, and interactions with soil type), DT hybrids may not always show a yield benefit (Gaffney et al. 2015). For example, in Northwest Indiana, Roth et al. (2013) reported that no yield advantage was observed in AQUAmax hybrids when compared to non-AQUAmax hybrids.

Besides drought-tolerance, as farmers adopt drought-tolerant hybrids, they are also concerned about the yield potential of DT hybrids when water supply is sufficient (Boyer et al. 2013). Therefore, yield performance under both drought and favorable environmental conditions needs to be considered in breeding for drought tolerance in maize (Ziyomo and Bernardo 2013). In this study, N59B-DT at the I_{100} treatment yielded 12.92 Mg ha^{-1} compared to 12.76 Mg ha^{-1} for N58L, indicating there was no yield penalty for the DT hybrid under well-watered conditions. Similar results are reported by Nemali et al. (2014) and Sammons et al. (2014), using MON 87460, and Gaffney et al. (2015) and Hao et al. (2015a), using AQUAmax hybrids. However, Cooper et al. (2014a) found that, when compared with drought-sensitive hybrids under the conditions of sufficient water supply, there was a small yield penalty for the AQUAmax hybrid.

Evapotranspiration

In this study, N59B-DT showed greater seasonal ETc at both I_{100} and $I_{75,}$ and the same seasonal ETc at I_{50} as compared to N58L. These results are different from a more recent study conducted at the same location, in which Pioneer DT hybrids had the same or less seasonal ETc relative to a conventional hybrid for all irrigation regimes (I_{100}, I_{75}, and I_{50}) (Hao et al. 2015a). Contrasting results between studies could be related to different water use characteristic between Agrisure Artesian and AQUAmax hybrids. In this study, seasonal ETc at I_{100} ranged from 608 to 774 mm, which was within the range (571–984 mm) measured during 1975–1994 in the Texas High Plains (Steiner et al. 1991; Howell et al. 1995, 1998). Additionally, other studies on the Texas High Plains showed similar ETc values. For example, a synthesis of the 15-year period from 1991 to 2006 showed that crop evapotranspiration for maize was 745 mm (Kapanigowda et al. 2010). In addition, for maize under favorable moisture conditions, Colaizzi et al. (2011) reported seasonal ETc of 711–815 mm. Our results also showed that the average seasonal ETc at I_{75} and I_{50} was 561 mm and 484 mm, respectively. At the same water regime, Colaizzi et al. (2011) reported seasonal ETc of 696 mm (I_{75}) and 574 mm (I_{50}) in their 2010 field study. The different findings could be explained by the relatively low grain yield in this study (11.87 and 7.59 Mg ha^{-1} for I_{75} and I_{50}, respectively) compared to Colaizzi et al. (2011) (14.07 and 11.84 Mg ha^{-1}, respectively).

Water-use efficiency

Our results showed that higher WUE in N59B-DT (1.57 kg m^{-3}) than N58L (1.42 kg m^{-3}) at I_{50} was associated with greater grain yield (8.5%) and almost the same seasonal ETc (− 0.2%) in N59B-DT relative to N58L. Similar to these results, Hao et al. (2015a) recently reported that DT hybrids consistently had higher WUE than a check hybrid at I_{50}, resulting from greater grain yield and less or similar seasonal ETc. However, the data from the current study indicated that no differences in WUE were detected between N59B-DT and N58L at I_{75}, which was different from the results of Hao et al. (2015a).

In this study, WUE for I_{100} and I_{75} water regimes was relatively lower in 2011 (1.43–2.15 kg m^{-3}) than in 2012 and 2013 (1.70–2.33 kg m^{-3}), which was associated with higher evaporative demand and higher temperature in 2011. Based on prior studies conducted in the Texas High Plains from 1975 to 1994, the estimated WUE range for maize was 1.15–1.99 kg m^{-3}, measured under the conditions from fully irrigated to mildly water limited (Steiner et al. 1991; Howell et al. 1995, 1998). These results suggested that newer maize hybrids used in this study tend to have higher WUE than those hybrids used in the other studies due to the increased yield but similar or reduced ET in this study (Steiner et al. 1991; Howell et al. 1995, 1998). In this study, the highest WUE was obtained at I_{75}, which was 7.4% greater than that at I_{100}, and the lowest WUE was obtained at I_{50}, which was 22.7% lower than that at I_{100}. Contrary to our findings, higher WUE values at I_{50} than I_{75} and I_{100} were reported by Aydinsakir et al. (2013) and Colaizzi et al. (2011), in which, ETc and yield at I_{50} was reduced by 29.4–32.0% (28.1% in this study) and 15.6–18.6% (40.9% in this study), respectively, compared to that at I_{100}. These differences may be attributed to more favorable climatic conditions in Colaizzi et al. (2011) (milder temperatures) and Aydinsakir et al. (2013) (lower evaporative demand) compared with this study.

Plant density

Increased plant density has been a major change in maize management practice in the United States since the 1930s (Duvick 2005). Water supply needs to be taken into consideration before increasing plant density in maize production (Lyon et al. 2003). Our results showed that higher plant density resulted in greater grain yield as well as higher WUE under sufficient water supply (I_{100}) or mild water stress (I_{75}). Under severe water stress (I_{50}), grain yield and water-use efficiency did not respond to plant density as plant density increased from 5.9 to 7.9 plants m^{-2}, and grain yield showed a significant decrease as plant density increased from 7.9 to 9.9 plants m^{-2}, particularly for the conventional hybrid N58L. Hao et al. (2015a) reported similar results.

Enhanced response to high plant density as well as drought stress in modern hybrids has made a large contribution to the yield improvement of maize over the past 30 years (Cassman 1999; Duvick 1999, 2005; Tollenaar et al. 2000; Tollenaar and Lee 2002, 2006). Our results indicated that, under non- and mild water stress, the yield of DT hybrid showed increasing trend with increasing density, while the yield did not change for conventional hybrid as density increased from 7.9 to 9.9 plants m^{-2}; under severe water stress (I_{50}), N59B-DT did not respond negatively to increased plant density, but N58L did show a negative response. The responses of yield for DT hybrid to increased density in this study are similar to the results reported by Cooper et al. (2014a). However, Roth et al. (2013) and Hao et al. (2015a) found that, in both non-limiting and water-limiting environments, the yield of DT hybrids did not increase with increasing plant density as compared to conventional hybrids. Contrasting results among the studies were presumably due to differences in hybrids, plant densities, and drought conditions. In this study, grain yield at I_{100} and I_{75} was increased by 11.8% and 6.4%, respectively, as plant density increased from 5.9 to 9.9 plants m^{-2}. Correspondingly, Hao et al. (2015a) reported a yield increase of 6.3% (I_{100}) and 5.8% (I_{75}) when plant density increased from 5.9 to 8.4 plants m^{-2}.

Conclusion

In most cases, DT hybrid produced more grain as compared with conventional hybrid under sufficient water supply and mild water stress. As planting density increased from 7.9 to 9.9 plants m^{-2}, the yield of DT hybrid showed increasing trend with increasing density, while the yield did not change for conventional hybrid. In the severely water-limited environment (I_{50}), the yield advantage of DT hybrid only occurred at high plant density (9.9 plants m^{-2}), the DT hybrid N59B-DT showed yield (18.0%) and WUE (26.2%) advantages over the conventional hybrid N58L. Therefore, planting a DT hybrid with a higher plant density may provide greater yield stability under water-limited conditions while also maintaining maximum yield potential when moisture is sufficient.

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