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Grain yield, crop and basal evapotranspiration, production functions and water productivity response of drought-tolerant and non-drought-tolerant maize hybrids under different irrigation levels, and population densities: Part I. In western Nebraska's semi-arid environments

Ali T. Mohammed

Suat Irmak

William Kranz

Simon van Donk

C. Dean Yonts

Grain Yield, Crop and Basal Evapotranspiration, Production Functions and Water Productivity Response of Drought-tolerant and Non-drought-tolerant Maize Hybrids under Different Irrigation Levels and Population Densities: Part I. In Western Nebraska's Semi-arid Environments

A. T. Mohammed, S. Irmak, W. L. Kranz, S. van Donk, C. D. Yonts

Abstract. *Grain yield, crop evapotranspiration (ET_c), basal evapotranspiration (ET_b), ET_c-yield production functions (ETYPF), and crop water use efficiency (CWUE) response of three drought-tolerant (DT) and one non-drought-tolerant (NDT) maize (*Zea mays* L.) hybrids to two plant population densities (PPDs) [84,000 plants ha^{-1} (high PPD) and 59,300 plants ha^{-1} (low PPD)] and three irrigation levels were researched at two semi-arid locations: North Platte (WCREC) and Scottsbluff (MAL), Nebraska, in 2010, 2011, and 2012. The irrigation levels were fully irrigated (FIT), early cutoff (ECOT), and rainfed (RFT). Precipitation in 2010 was above average, 2011 was a normal year, and 2012 was one of the driest and hottest years in Nebraska's recorded history. Generally, DT hybrids performed better than the NDT hybrid. The performances of the DT hybrids were stronger in the driest year and driest location (MAL), especially with low PPD. ET_c exhibited inter-annual variation for the same hybrid in the same location and between the two locations and also with the PPD and irrigation treatments. There were significant differences ($P<0.05$) between the ET_c values for the same hybrids across three irrigation treatments. The grain yield response to hybrids and treatments also exhibited substantial variation for the same hybrid between the PPDs and had inter-annual variation between the years and locations. The greatest grain yields of 14.6 and 18.0 Mg ha^{-1} were observed with 548 and 837 mm of ET_c, which were recorded for the DT hybrid H3 (high PPD) at WCREC and MAL, respectively. There were significant differences ($P<0.05$) in performance among the DT hybrids in performance variables (ET_c, ET_b, ETYPF, CWUE). In most cases, the DT hybrids produced greater grain yield than the NDT hybrid with lower ET_c. In terms of ETYPF response for individual hybrids, the slope of the production functions exhibited an inter-annual variation between the hybrids and for the same hybrids between the years and location for both high and low PPDs. All hybrids exhibited a linear yield response to increasing ET_c in all years at both locations with positive slopes in all cases with DT hybrids having the greatest slopes. The ET_b values also exhibited a substantial variation between the hybrids, years, locations, and PPDs. Generally, DT hybrids had sizably lower ET_b values than the NDT hybrid in both PPD levels. It was concluded that DT hybrids increase the grain yield production per unit of ET_c in semi-arid regions not only during very dry and hot year, but also during the growing season with favorable rainfall and climate conditions.*

Keywords. *Basal evapotranspiration, Drought-tolerance, Maize, Yield production functions.*

Producing sufficient amounts of food, fiber, and biofuel, especially under water-limiting conditions, has been a longstanding challenge. With the projected substantial increase in the world's population to over 9 billion by 2050 and related increase in demand for commodity products, this challenge has more importance today. Water, in many cases, is the primary crop production and yield-limiting factor in rainfed or dryland and irrigated agricultural production settings in many parts of the world, including the Great Plains of the United States. In addition to frequent drought and heat stress, the region has sporadic rainfall patterns (Stone et al.,

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The authors are **Ali T. Mohammed,** Graduate Research Assistant, **Suat Irmak,** Distinguished Professor, **William L. Kranz,** Professor, University of Nebraska, Lincoln, Nebraska; **Simon van Donk,** Iteris, Inc. North Platte, Nebraska; and **C. Dean Yonts** (deceased), formerly Associate Professor, University of Nebraska, Lincoln, Nebraska. **Corresponding author:** Suat Irmak, University of Nebraska-Lincoln, 239 L.W. Chase Hall, Lincoln, NE 68583-0726, phone: (402) 472-4865; e-mail: sirmak2@unl.edu.

2006). Therefore, irrigation is one of the most critical factors for mitigating these adverse conditions to optimize crop growth and yield. Irrigation in this region depends primarily on groundwater, which is the Ogallala formation of the High Plains Aquifer (McGuire, 2009), as well as surface water resources. Extensive irrigation water withdrawal from this aquifer that underlies eight states has impacted most irrigated regions of Nebraska, Kansas, Oklahoma, and Texas (Gutentag et al., 1984). The availability of groundwater and surface water as well as yield potential, particularly in the 3.6 million ha of cropland currently under irrigation in Nebraska is also impacted by extensive water withdrawals (Irmak and Mutiibwa, 2010; Irmak et al., 2013).

Groundwater levels have declined over 15 m in some areas of southwestern Nebraska, eastern Colorado, and in large areas of Kansas between 1950 and 2003 (McGuire, 2004). Moreover, the groundwater and surface water resources are impacted by the change in climate variables, which has affected the seasonal spatial and temporal distribution and the magnitude of the rainfall. For example, the 2012 drought affected 80% of U.S. agriculture (Long et al., 2013; Mallya et al., 2013; AghaKouchak et al., 2014; Wolf et al., 2016). These changes affect agricultural productivity with regards to availability of water for irrigation during the growing season for a variety of grain crops, including maize. Maize (*Zea mays* L.) is one of the world's and Great Plains' most essential grain crops and is a major source for food, feed, fiber, and fuel, and is considered a relatively high water-demand row crop. Water requirement of fully-irrigated maize varies substantially based on the maturity class, climate, soil, crop management conditions, year, irrigation management and method, and other factors. Maize yield is sensitive to water stress particularly if exposed to water stress during critical growth stages. Obtaining adequate and profitable yields in water limiting and dry regions has been a significant concern for growers, seed companies and other institutions in many areas in the world as well as the Midwestern states in the United States, including Nebraska. In response to these challenges, the major seed companies have begun developing new genetic-based strategies to improve drought-tolerant hybrids to maximize yield production per unit of water applied and/or used by the plants to enhance the viability of growing maize in areas prone to drought stress by changing some of the physiological and/or biophysical properties and functions of the plants. These efforts usually revolve around increasing transpiration efficiency, without reducing photosynthesis, under high evaporative demand conditions. As quoted directly from Bunce (2010), "the CO_2-concentrating system in C_4 plants, such as maize, has the ability to achieve CO_2-saturated photosynthesis at substomatal CO_2 concentrations in the range of 75 to 100 μmol mol^{-1} (Polley et al., 1992). Thus, C_4 plants can maintain greater CO_2 assimilation rate at much lower stomatal conductances than C_3 plants and generally have higher values of leaf transpiration efficiency (LTE) (Tanner and Sinclair, 1983). In C_3 plants, the utility of selecting for high water use efficiency (WUE) to improve crop performance under dry conditions varies due, in part, to the relationships between WUE and photosynthetic CO_2 assimilation (Condon et al., 2004; Blum, 2009). In C_4 species, plant functioning with stomatal conductance higher than required to saturate photosynthetic CO_2 assimilation, there might not be such a trade-off, and selecting for higher LTE could improve the WUE without reducing photosynthetic CO_2 assimilation," which is directly linked to grain yield. However, "field measurements of leaf gas exchange in maize often indicate substomatal CO_2 concentrations much higher than those required to saturate photosynthetic CO_2 assimilation. Therefore, maize leaves often operate at lower LTE than potentially achievable for species with C_4 metabolism" Bunce (2010). Field measured data; however, in C_4 plants (e.g., maize) that have these critical characteristics of a drought-tolerance feature can provide useful information on the crop yield and WUE response to water, which have not been sufficiently studied. Among the few studies, Bunce (2010) researched whether several maize lines described as drought-tolerant (DT) operate with higher LTE than less drought-adapted lines. He conducted multiple years of field measurements of LTE for five DT maize lines and three conventional hybrids under non-water limiting conditions in Maryland. He observed consistent and significant differences among the lines for stomatal conductance, substomatal CO_2 concentration, and leaf LTE, but did not observe any significant differences among the lines in photosynthesis. One DT line had higher LTE than all others evaluated, and one of the conventional lines had the lowest LTE, but the DT lines as a group did not have significantly higher LTE. He concluded that significant genotypic variation in leaf LTE exists in maize and that LTE could be improved without reducing photosynthesis, which may, in part, explain equal or more grain productivity with less water use by DT maize hybrids.

While DT maize hybrids may increase WUE, the potential benefit of DT maize hybrids in terms of increasing WUE depends on numerous factors, including drought intensity and duration, crop growth stage (timing) during drought, management practices, and the array of genetically-driven drought tolerance mechanisms present in selected hybrids (Adee et al., 2016). Thus, the yield productivity of DT maize may or may not be substantial or considerable or even economically viable as compared with conventional non-DT hybrids, depending on numerous factors. For example, Adee et al. (2016) studied drought tolerance to define types of production environments where similar maturity group DT hybrids may have yield advantage as compared with non-DT hybrids via six site-years experiments conducted in different soil types, seasonal evapotranspiration (ET), and vapor pressure deficit (VPD) conditions. They used different irrigation regimes and seeding rates to create several micro-environments within each location. They characterized the hybrid response to the range of macro and micro-environmental stresses in terms of WUE, grain yield, and environmental index. Yield advantage of DT hybrids was positively correlated to ET and VPD. DT hybrids yielded 5 to 7% more than non-DT hybrids in high and moderate ET environments, corresponding to seasonal VPD greater than 1.2 kPa. Environmental index analysis confirmed that DT hybrids were superior in drought and water-stressed environments. Yield advantage for DT hybrids was more pronounced when yield dropped below 10.8 Mg ha^{-1} and averaged as much as 0.6-1.0 Mg ha^{-1} at the low yield range. In the range of micro-environments sampled, if the yield of the non-DT hybrid was equal to or greater than about 10.8 Mg ha^{-1}, the DT hybrids had only a 0.057 Mg ha^{-1} (57 kg/ha) yield advantage, essentially equal on average. However, if the yield of the non-DT hybrid was less than 10.8 Mg ha^{-1}, the yield advantage of the DT hybrids increased by an average of 0.41 kg ha^{-1} for every kg ha^{-1} decrease in yield of the non-DT hybrid. Thus, a larger yield gap, quantified as the yield difference between DT and non-DT hybrids, resulted in poor (water-limited) environments. They also observed that there was minimal yield penalty for the DT hybrids in favorable environments, confirming that the DT hybrids did not sacrifice yield in a low stress/high yielding environments. While a considerable degree of scatter/variability observed in their rather large datasets, they concluded that DT hybrids could offer a degree of buffering against drought stress by minimizing yield reduction, but also maintaining a comparable yield potential in high yielding environments. Gaffney et al. (2015) reported a 4.9% increase in yield for DT hybrids as compared with conventional non-DT hybrids in 53 water-limited environments and a 2.5% yield increase in 502 non-water-limiting environments. They also reported a 6.5% yield advantage with DT hybrids evaluated in over 2000 water-limiting environments and a 1.9% yield advantage in 8725 non-water-limiting environments. In a semi-arid climate in Bushland, Texas, Zhao et al. (2018) found that the Pioneer AQUAmax® hybrid P1151AM had about 30% greater grain yield and WUE than the conventional hybrid 33D53AM in comparison to two conventional (33D53AM and N74R) and two DT maize hybrids (P1151AM and N75H) under two water treatments of well-watered plants at 100% ET requirement and water-stressed plants at 50% ET requirement. Mounce et al. (2016) indicated that the DT AQUAmax® P0876HR maize hybrid required less water to maximize grain yield as compared with the conventional 33Y75 maize hybrid. In a first-year evaluation study of three AQUAmax® hybrids of P1151HR, P1324HR, and P1498HR in comparison to a non-AQUAmax® commercial check (P33D49) conducted by Becker et al. (2012) in TX, under four irrigation regimes (100%, 75%, 50%, and 40% of the ET requirement), the AQUAmax® P1151 had the highest grain yield at 40% and 50% ET irrigation levels than other hybrids while the non-AQUAmax® commercial check (P33D49) had highest grain yield at 75% and 100% ET irrigation levels. Lindsey at al. (2016) reported that a drought-tolerant hybrid (P1352) produced 2.5% greater grain yield than the conventional hybrid (P1184) at three Ohio locations under two plant populations of 59,000 and 104,000 plants ha^{-1}. Similarly, several researchers found higher grain production with DT maize hybrids as compared with conventional hybrids (Tollefson, 2011; Sammons et al., 2014; Cooper et al., 2014; Hao et al., 2015).

In addition to yield, another important trait such as basal ET (ET_b), which is defined as the ET required for the first increment of grain yield establishment was investigated by a very limited number of researchers for conventional hybrids. ET_b is a very important variable, especially with respect to water availability, which can provide invaluable information as to whether the evaporative losses differ among different hybrid lines. To the best of our knowledge, the ET_b values of DT maize hybrids in comparison to non-DT hybrids have not been reported. Among limited information and data reported in the literature on this topic, through six years of field research, Irmak (2015a) measured substantial inter-annual variation in non-DT maize ET_b. While the six-year average pooled data of ETYPF from 2005 to 2010 had 279 mm of ET_b, the ET_b values of individual years had a substantial inter-annual variation and ranged from 209 to 418 mm. Robins and Domingo (1953), Hillel and Guron (1973), Stewart et al. (1975), Musick and Dusek (1980) and Howell et al. (1995) reported the ET_b for non-DT required ranging from 147 to 300 mm.

While DT maize hybrids are continuously introduced in the Midwestern regions of the United States, where the majority of nation’s maize is produced, there is a significant lack of information and data regarding the crop water use, yield, and WUE response of these new DT maize hybrids under different plant population densities (PPDs) and irrigation management strategies in this region. Determining these variables locally can aid farmers, their advisors, water management agency personnel, and policy- and decision-makers to understand the crop yield productivity response to water under various climatic gradients. This information would also enable the farming community in western Nebraska or regions that have similar environmental conditions and management practices to make more effective planning and within-season irrigation management decisions for conventional and DT hybrids. Field research data could aid in making decisions on where to grow new DT maize hybrids, and what PPDs should be used, and how they perform under various water availability settings. The objectives of this research were to quantify and evaluate crop evapotranspiration (ET_c), develop crop production functions, measure ET_b, grain yield, and CWUE response of DT maize hybrids in comparison to conventional (non-drought-tolerant, NDT) hybrid under different irrigation levels, rainfed conditions and PPDs in Nebraska’s semi-arid environments.

Materials and Methods

Site Description

Field experiments were conducted in 2010, 2011, and 2012 growing seasons at the University of Nebraska-Lincoln West Central Research and Extension Center (WCREC) near North Platte, Nebraska; and Mitchell Agricultural Laboratory (MAL) 8 km east of Scottsbluff, Nebraska. The research sites had different soil properties and climate conditions (table 1). North Platte is classified as having a semi-arid climate with a long-term average annual rainfall of 510 mm yr^{-1} and frost-free dates from 30 April through 5 October (NOAA Satellite and Information Service, 2017). At the WCREC, the experiments were conducted on a Cozad silt loam (fine-silty, mixed, mesic Fluventic Haplustoll) with a 0 to 1% slope. Scottsbluff has a semi-arid climate with a long-term average annual rainfall of

Table 1. Research site description, including coordinates, elevation, soil type, field capacity, permanent wilting point, irrigation method and climate.

Research Site	Coordinates (°)	Elev. (m)	Soil Type	Field Capacity (m^3 m^{-3})	Wilting Point (m^3 m^{-3})	Irrigation Method	Climate
WCREC, North Platte, Nebr.	41.1° N 100.8° W	861	Cozad silt loam	0.29	0.11	SDI[a]	Semi-arid
MAL, Scottsbluff, Nebr.	41.9° N 103.7° W	1098	Fine Sandy Loam	0.21	0.10	SDI	Semi-arid

[a] SDI: subsurface drip irrigation.

340 mm yr^{-1} with a frost-free period of 8 May through 7 October (NOAA Satellite and Information Service, 2017). The soil at the MAL site is a Tripp fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls) and well-drained with 0 to 1% slope.

General Crop and Field Management Practices

General field and crop management practices, including fertilizer application date, amounts, and methods; planting, emergence, and harvest dates; herbicide applications, etc. are provided in table 2. Four Pioneer maize hybrids (table 3) were planted at both sites in 2010, 2011, and 2012 growing seasons. One hybrid (H1) was a conventional NDT hybrid and the other three hybrids (H2, H3, and H4) were DT hybrids. All hybrids were planted at the PPDs of 59,300 plants ha^{-1} (low PPD) and 84,000 ha^{-1} (high PPD) under each irrigation treatment at each site and year. These PPDs are commonly used for rainfed and irrigated maize production, respectively, in Midwest United States. The planting, emergence, and harvest dates differed among the sites based on each site's growing season length (table 2). Depending on the year, two or three irrigation management treatments were imposed in each year: (i) fully-irrigated treatment (FIT) that received irrigation without exposing the crop to any water stress, (ii) early cut-off treatment (ECOT) that received no irrigation application at and after blister kernel stage, and (iii) rainfed treatment (RFT) which received no irrigation. The experimental design at the WCREC site was a split-plot with four replications for each treatment. Each main plot was divided into four subplots

Table 2. General field management practices, including planting and emergence date, fertilizer and herbicide application amount and method, harvest, etc. at the West Central Research and Extension Center (WCREC) in North Platte, Nebr., and Mitchell Agricultural Laboratory (MAL) in Scottsbluff, Nebr., in 2010, 2011, and 2012 growing seasons.

Site	Year	Description	Date	Type	Amount per Hectare	Method
WCREC	2010	Planting	05 May	-	-	Planter
		Emergence	20 May	-	-	-
		Harvest	04 Nov	-	-	Combine
		Fertilizer	14 April	32-0-0	224 Kg	Pre-plant
		Herbicide	17 April	Roundup	1.6 L	Sprayer
		Herbicide	17 April	Atrazine	1.1 L	Sprayer
		Herbicide	17 April	Lumax	5.7 L	Sprayer
WCREC	2011	Planting	05 May	-	-	Planter
		Emergence	29 May	-	-	-
		Harvest	11 Nov	-	-	Combine
		Fertilizer	25 April	UAN	224.1 kg	Pre-plant Sprayer
		Herbicide	26 April	Atrazine	2.3 L	
		Herbicide	26 April	Lumax	4.6 L	Sprayer
		Herbicide	26 April	Glystar	2.3 L	Sprayer
		Herbicide	26 April	AMS	375 L	Sprayer
		Herbicide	26 April	Crop Oil	0.94 L	Sprayer
WCREC	2012	Planting	08 May	-	-	Planter
		Emergence	18 May	-	-	-
		Harvest	02 Nov	-	-	Combine
		Fertilizer	03 May	UAN	224.1 Kg	Pre-plant
MAL	2010	Planting	06 May	-	-	Planter
		Emergence	14 May	-	-	-
		Harvest	08 Nov	-	-	Combine
		Fertilizer	09 July	46-0-0	78.4 Kg	Side dress
		Fertilizer	27 July	46-0-0	78.4 Kg	Side dress
		Herbicide	31 July	Glyphosate	3.0 L	Sprayer
MAL	2011	Planting	06 May	-	-	Planter
		Emergence	21 May	-	-	-
		Harvest	31 Oct	-	-	Combine
		Fertilizer	06 July	46-0-0	78.4 Kg	Side dress
		Fertilizer	15 July	46-0-0	78.4 Kg	Side dress
		Herbicide	20 July	Glyphosate	3.0 L	Sprayer
MAL	2012	Planting	07 May	-	-	Planter
		Emergence	14 May	-	-	-
		Harvest	05 Nov	-	-	Combine
		Fertilizer	12 June	46-0-0	78.4 Kg	Side dress
		Fertilizer	18 June	46-0-0	78.4 Kg	Side dress
		Herbicide	25 June	Glyphosate	3.0 L	Sprayer

Table 3. Characteristic and ratings of drought-tolerant (DT) and conventional (non-drought-tolerant, NDT) maize hybrids used in this research (Source: DuPont Pioneer®). Ratings: 9 = Outstanding; 1 = Poor; Blank = Insufficient Data.[a]

Platform	Hybrid	Pre-commercial (experimental) name	Technology Segment	CRM	Silk CRM	Physiological CRM	GDU's to Silk	GDU's to Physiological Maturity	Grain Drydown	Stalk Strength	Root Strength	Stress Emergence	Staygreen	Drought Tolerance	High Residue Suitability	Ear Flex	Test Weight	Plant Height	Ear Height	Mid-Season Brittle Stalk	Husk Cover	Gray Leaf Spot	Northern Leaf Blight	Southern Leaf Blight	Goss's Wilt	Stewart's Wilt	Anthracnose Stalk Rot	Head Smut	Fusarium Ear Rot	Gibberella Ear Rot	Diplodia Ear Rot	Common Rust
33P83	33P84 (H1)	-	HX1,LL,RR2	111	115	106	1430	2550	8	6	5	7	4	6	S	6	7	8	6	5	4	4	4	6	6	-	3	4	4	5	5	7
P1151	P1151HR (H2)	X08A236HR	HX1,LL,RR2	111	106	107	1320	2580	6	5	7	5	6	9	S	6	5	5	4	7	6	4	5	-	6	-	3	2	4	3	4	-
P1324	P1324HR (H3)	-	HX1,LL,RR2	113	106	114	1320	2760	6	5	6	5	5	9	S	7	5	3	4	7	8	5	5	-	6	-	4	2	7	4	6	-
P0791	P0791HR (H4)	X7M326TR	HX1,LL,RR2	107	103	104	1280	2500	5	6	3	5	7	9	S	6	4	5	4	6	6	5	5	-	7	6	4	7	5	4	5	-

Product performance in water-limited environments is variable and depends on many factors such as the severity and timing of moisture deficiency, heat stress, soil type, management practices and environmental stress and disease and pest pressures. All products may exhibit reduced yield under water and heat stress. Individual results may vary.

HYBRID FAMILY: Hybrid family identifies products that have the same base genetics.

TECHNOLOGY SEGMENT: HX1 - Contains the Herculex® I Insect Protection gene which provides protection against European corn borer, southwestern corn borer, black cutworm, fall armyworm, western bean cutworm, lesser corn stalk borer, southern corn stalk borer, and sugarcane borer; and suppresses corn earworm. **LL** - Contains the LibertyLink® gene for resistance to Liberty® herbicide. **RR2** - Contains the Roundup Ready® Corn 2 trait that provides crop safety for over-the-top applications of labeled glyphosate herbicides when applied according to label directions.

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CRM (Comparative Relative Maturity): CRM ratings, and harvest moistures, for products within a family may vary slightly, depending upon the level of insect (ECB and CRW) infestation. Conventional and straight products with the RR2 gene within a family will usually be 1-2 CRMs earlier than indicated, when insect infestations are moderate to heavy. One CRM difference is about ½ point of moisture difference at harvest.

PHYSIOLOGICAL CRM: Measures differences in maturity to zero milkline stage.

GDUs TO PHYSIOLOGICAL MATURITY: Measures differences in growing degree units (GDUs) (or growing degree days, GDD) required to zero milkline stage.

MID-SEASON BRITTLE STALK: Ratings determined by frequency and severity of stalk snappage at lower to middle stalk internodes from conditions usually favored by rapid or optimum growth. Relative response of products can be affected by planting date, stage of growth, rate of growth, wind severity and other variables. Scores derived from both natural observations and artificial evaluation immediately prior to tasseling. NOTE: Scores do not reflect snappage enhanced by or due to herbicide interaction.

STRESS EMERGENCE: Stress emergence is a measure of the genetic ability or potential to emerge in the stressful environmental conditions of cold, wet soils or short periods of severe low temperatures, relative to other Pioneer brand products. Ratings of 7-9 indicate very good potential to establish normal stands under such conditions; a rating of 5-6 indicates average potential to establish normal stands under moderate stress conditions; and ratings of 1-4 indicate the product has below average potential to establish normal stands under stress and should not be used if severe cold conditions are expected immediately after planting. Stress emergence is not a rating for seedling disease susceptibility, early growth or speed of emergence.

DROUGHT TOLERANCE: Drought tolerance is a complex trait, determined by a platform's ability to maintain yield in limited-moisture environments. A higher score indicates the potential for higher yields vs. other platforms of similar maturity in limited-moisture environments.

HIGH RESIDUE SUITABILITY: HS - Highly Suitable; **S** – Suitable; **MA** – Manage Appropriately; **X** - Poorly Suited; **NS** – Not Scored. Suitability rating based on field observations and a weighted calculation of gray leaf spot, stress emergence, anthracnose stalk rot, northern corn leaf blight, and Diplodia ear rot scores. High Residue Suitability ratings may vary by environment and geography.

GRAIN DRYDOWN: Compares products of similar maturity for rate of moisture loss during grain drydown. A higher score indicates faster drydown. A lower score indicates slower drydown, or a wider opportunity for silage and high-moisture corn harvest.

EAR FLEX: Score reflects the ability of a product to flex ear size as plant density is reduced, or as growing conditions improve.

TEST WEIGHT: Higher score indicates heavier test weight.

PLANT HEIGHT: 9 = Very Tall; **1** = Short.

EAR HEIGHT: 9 = High; **1** = Low.

GRAY LEAF SPOT PRECAUTION: Disease susceptibility rating. It is suggested to avoid planting products with a lower gray leaf spot (GLS) rating in continuous corn fields that have a history of GLS infection, unless tillage operations that bury significant amounts of corn residue and inoculum are practiced.

FOLIAR FUNGICIDE RESPONSE – GLS: Probability of positive yield response to foliar fungicide applications when significant levels of Gray Leaf Spot (GLS) leaf disease is present.**HP** - High Probability; **MP** – Moderate Probability; **LP** – Low Probability. Probabilities based upon product disease scores.

NORTHERN LEAF BLIGHT CAUTION (NLB): In conditions where northern leaf blight (NLB) risk is high, it is suggested that growers should consider planting only products with at least moderate NLB resistance ratings of 4 or higher.

FOLIAR FUNGICIDE RESPONSE – NLB: Probability of positive yield response to foliar fungicide applications when significant levels of Northern Leaf Blight (NLB) leaf disease is present. **HP** - High Probability; **MP** – Moderate Probability; **LP** – Low Probability. Probabilities based upon product disease scores. Because of the unlimited number of growing environments, cropping practices, and foliar fungicide active ingredients combinations possible, DuPont Pioneer makes no warranty regarding this foliar fungicide crop response information.

FUSARIUM EAR ROT CAUTION: Ratings based upon visual symptoms at harvest. If Fusarium ear rot has caused significant damage in the past, it is suggested that growers should consider planting only products with at least moderate Fusarium ear rot ratings of 5 or higher.

GIBBERELLA EAR ROT CAUTION: Ratings based upon visual symptoms at harvest. If Gibberella ear rot has caused significant damage in the past, it is suggested that growers should consider planting only products with at least moderate Gibberella ear rot ratings of 5 or higher.

DIPLODIA EAR ROT CAUTION: Ratings based upon visual symptoms at harvest. If Diplodia ear rot has caused significant damage in the past, it is suggested that growers should consider planting only products with a Diplodia ear rot rating of 4 or higher.

(hybrids), and each water treatment in each replication was randomly assigned to one of eight subplots. Each subplot was six rows wide and 18 m long with a 0.76 m row spacing and 0.05 m planting depth. The field was irrigated using a subsurface drip irrigation (SDI) system. The experimental design at the MAL site was a split-plot. The field was irrigated using an SDI system, which allowed for independent irrigation of 122 m long strips that were twelve 0.5 m row wide with a 0.76 m row spacing and 0.05

m planting depth. Water treatments were randomized in blocks and replicated four times. Within each water treatment or strip, a combination of four hybrids and two PPDs were randomized. Irrigation amounts and number of irrigation applications per growing season varied with year, treatment, and research location as a function of climatic conditions, crop water use, and treatment. The greatest amount of cumulative applied irrigation occurred in the 2012 growing season, which was one of the driest and warmest years in recorded history in Nebraska, at both locations and was significantly greater at the MAL research site than at the WCREC site. Total irrigation amounts applied to each treatment at each year and location are presented in the Results and Discussion section.

SOIL-WATER MEASUREMENTS, QUANTIFICATION OF ET_C, ET_b, AND CWUE, AND STATISTICAL ANALYSES

The soil-water status was measured using a neutron attenuation probe at both WCREC and MAL for all three growing seasons in all treatments. The neutron probe measurements were taken every 0.30 m soil layer down to 1.20 m on a weekly or every other week basis. The neutron probe access tubes were installed on the plant row between two healthy maize plants of each treatment after maize emergence. In addition to neutron probe measurements, soil matric potential was measured using Watermark Granular Matrix sensors (Irrometer Co., Inc., Riverside, Calif.) to compliment neutron probe-measured volumetric soil-water content. Watermark sensors were installed with 0.30 m increments down to 1.20 m soil profile between the two plants in each treatment. The sensors were connected to a Watermark Monitor datalogger (Irrometer Co., Inc., Riverside, Calif.). The timing of irrigations was based on the soil matric potential readings such that irrigations were triggered when the average of the top two sensors (0.30 and 0.60 m) readings reached approximately 100-110 kPa matric potential before the tassel stage, and the average of the top three sensors (0.30, 0.60, and 0.90 m) readings was used after the tasselling stage following the irrigation management strategy described by (Irmak et al., 2010). Thus, irrigations were triggered when the soil-water was depleted by approximately 35%-40% of the water holding capacity. A soil-water balance approach was used to estimate ET_c at each site following the procedures outlined in Irmak (2015a, b) using the neutron probe-measured soil-water content precipitation, and irrigation data as inputs. In addition to ET_c, basal ET (ET_b) was quantified, which is the x-axis intercept of the ETYPF when grain yield is zero (Irmak, 2015a). This can be very important in water-limiting areas for planning and within-season water management. The CWUE was quantified for each treatment as the ratio of grain yield (Y) to the corresponding ET_c values:

$$CWUE = Y / ET_C \quad (1)$$

where CWUE, Y, and ET_c are expressed in kg m^{-3}, g m^{-2} and mm, respectively.

The statistical analyses were carried out using the GLIMMIX procedure in SAS (SAS Institute, Inc., Cary, N.C., 2003) on grain yield, crop production functions, ET_c, and other variables. To identify any potential significant differences among maize grain yields, under different PPDs and across different irrigation strategies for a given year, a Fisher's protected least significant differences (LSD) test was conducted at the 5% significance level. The statistical analyses were performed for the ET_c to identify any potential differences in ET_c between the hybrids across three irrigation treatments and two PPDs for the given year. Also, a linear regression analysis was fitted to describe the relationship between grain yield and ET_c and the slopes were tested whether they were significantly different from the unity (0) at the 95% confidence intervals. The analysis was conducted by using PROC REG procedure in SAS (SAS Institute, Inc., 2003) for each maize hybrid across the irrigation treatments at each PPD, year, and site.

RESULTS AND DISCUSSION

WEATHER CONDITIONS DURING THE 2010, 2011, AND 2012 GROWING SEASONS AT WCREC AND MAL

Weather variables at each site were measured by the High Plains Regional Climate Center (HPRCC, http://www.hprcc.unl.edu/) automatic weather station network. On average, WCREC site (table 4) had similar relative humidity (RH) in 2010 and 2011 and was 17% lower than the long-term average in 2012. Wind speed at 2 m height (U_2) was similar in all three years and was 10%, 13%, and 10% less than the long-term average in 2010, 2011 and 2012, respectively. Incoming shortwave radiation (R_s) was similar in three growing seasons and was similar to the long-term average. The total seasonal rainfall was highest in 2011 (527 mm) and was 70% and 6% higher than the total seasonal rainfall in 2012 and 2010, respectively, and 73% higher than the long-term average (304 mm). The MAL site (table 5) had different RH for each growing season with the highest recorded value (57.8%) in 2010 and lowest (48.4%) in 2012. RH was 1.5% higher, 10% lower and 15% lower than the long-term average values in 2010, 2011 and 2012, respectively. U_2 was similar among all three years and was similar to the long-term average value. The highest R_s value (19.7 MJ m^{-2} d^{-1}) was recorded in the 2012, and it was 9.4% higher than the long-term average. The 2010 and 2011 growing seasons had similar R_s, which was similar to the long-term average. The seasonal total rainfall was highest in 2011, and it was similar to the long-term average in 2010, 21% higher in 2011 and 61% lower than the long-term average in 2012.

GRAIN YIELD AND YIELD RESPONSE TO EVAPOTRANSPIRATION [ET-YIELD PRODUCTION FUNCTIONS (ETYPF)] FOR INDIVIDUAL HYBRIDS

The ET_c exhibited inter-annual variation for the same hybrid within the same location, PPD and irrigation treatments. There were significant differences ($P<0.05$) between the ET_c values for some hybrids across irrigation treatments (tables 6 and 7; each grain yield value in table 6 and 7 is an average of four replications, and each ET_c value is an average of two replications). The grain yield response to treatments also exhibited substantial variation for the same hybrid between the PPDs and had inter-annual

Table 4. Weather conditions during 2010, 2011 and 2012 growing seasons and long-term average values at the West Central Research and Extension Center (WCREC), North Platte, Nebr.

Year	Month	T_{max}[a] (°C)	T_{min} (°C)	T_{avg} (°C)	U_2[b] ($m\ s^{-1}$)	R_s[c] ($MJ\ m^{-2}\ d^{-1}$)	RH[d] (%)	Total Rainfall (mm)
2010	April	17.6	3.0	10.3	3.3	18.1	62.3	90.6
	May	20.5	6.3	13.4	3.5	20.4	66.0	60.7
	June	28.2	14.3	21.2	2.8	22.7	69.5	162.3
	July	30.4	17.4	23.9	2.8	23.8	71.3	68.2
	August	31.6	15.9	23.8	2.7	21.3	62.9	53.9
	September	26.8	7.9	17.3	2.5	17.6	64.3	29.0
	October	20.7	2.4	11.5	2.1	13.5	61.2	16.5
	November	10.1	-5.9	2.1	2.2	8.8	68.1	16.0
	Average	**23.2**	**7.7**	**15.4**	**2.7**	**18.3**	**65.7**	**497[e]**
2011	April	16.0	1.3	8.7	3.0	18.2	63.8	54.9
	May	20.4	5.5	13.0	3.0	20.4	65.3	144.8
	June	27.4	12.6	20.0	2.9	23.7	66.6	84.8
	July	32.0	18.3	25.2	2.6	24.3	71.9	98.6
	August	30.5	16.0	23.2	2.4	19.8	72.4	50.9
	September	24.7	5.4	15.0	2.1	16.1	61.4	23.6
	October	20.1	2.3	11.2	2.4	12.2	57.9	66.6
	November	12.6	-5.7	3.4	2.5	9.3	52.4	3.6
	Average	**23.0**	**7.0**	**15.0**	**2.6**	**18.0**	**64.0**	**527[e]**
2012	April	18.8	3.9	11.4	3.0	16.1	61.7	67.7
	May	25.1	8.3	16.7	2.9	21.6	53.8	16.8
	June	32.8	15.1	23.9	3.5	24.5	48.0	21.1
	July	35.2	17.7	26.5	2.8	23.5	48.0	33.8
	August	32.0	13.7	22.9	2.8	20.5	50.2	10.4
	September	28.4	6.8	17.6	2.3	17.9	46.2	2.3
	October	17.7	-0.4	8.7	2.4	12.1	58.0	6.1
	November	14.3	-5.5	4.4	2.0	8.8	61.6	0.0
	Average	**25.5**	**7.5**	**16.5**	**2.7**	**18.1**	**53.4**	**158[e]**
1983-2009 average	April	16.6	1.0	8.8	3.6	18.1	58.9	36.3
	May	22.3	7.3	14.8	3.4	20.8	63.7	56.9
	June	28.0	12.7	20.3	3.1	23.7	64.8	60.4
	July	31.1	15.6	23.4	2.9	23.6	65.3	42.1
	August	30.0	14.5	22.3	2.7	20.5	67.3	44.3
	September	25.2	8.5	16.9	2.9	16.4	63.0	27.5
	October	18.1	1.4	9.7	2.6	11.6	63.7	28.3
	November	10.4	-5.0	2.7	2.5	8.0	65.7	9.1
	Average	**22.7**	**7.0**	**14.9**	**3.0**	**17.8**	**64.1**	**304[e]**

[a] T_{max}, T_{min}, and T_{avg} = maximum, minimum and average air temperature, respectively.
[b] U_2 = wind speed at 2 m height.
[c] R_s = incoming shortwave radiation.
[d] RH = relative humidity.
[e] Seasonal total.

variation between the years and locations. Generally, the DT hybrids had lower ET_c in different irrigation levels and PPDs than the NDT hybrid in both locations. In most cases, DT H3 resulted in greater grain yield than the NDT H1 and other DT hybrids. DT hybrids, in general, not only performed well in dry years, but they also performed well in terms of grain yield and water productivity and production functions (higher slopes) in average and wet years.

The ETYPFs are presented in figures 1a-1f for WCREC for high and low PPDs for three growing seasons and the same datasets were presented in figures 2a-2f for MAL. Due to some experimental challenges in some years, the following replication data points were not included in the regression analyses at WCREC: 2010-DT H2 (low PPD) at ECOT and RFT; 2010-DT H4 (low PPD) at FIT; 2010-DT H2 (high PPD) at ECOT and RFT; 2010-DT H3 (high PPD) at ECOT and RFT; 2011-DT H1 (low PPD) at ECOT; 2011-DT H4 (low PPD) at RFT; 2011-DT H2 (high PPD) at FIT and ECOT; 2012-DT H2 (low PPD). At WCREC in 2010, the ET_c ranged between 433 and 574 mm; between 429 and 603 mm in 2011; and between 261 and 693 mm in 2012, including the RFT, ECOT, and FIT under low and high PPDs. In the 2010, and 2011 growing seasons, there were significant differences (P<0.05) among the ET_c values for the NDT and DT hybrids between the FIT and RFT (table 6). In the 2012 growing season, there was not significant differences (P>0.05) among the ET_c values for all hybrids across the three irrigation treatments, except for NDT H1 (low PPD), DT H3 (low PPD), and DT H4 (PPD) under RFT, which were significantly different (P<0.05) from the other hybrids under FIT (table 6). The ET_c for RFT in 2012 was lower than the RFT in 2010 and 2011 growing seasons, as a result of significantly lower precipitation. In FIT, there was significant grain yield decline as compared with the previous grain yield productions for the same treatment. This may be attributed to the combination of weather variables that led to uneven emergence, which negatively affected corn yield potential. The extreme dryness that occurred in early season coupled with above average maximum and minimum air temperature might have caused variations in soil moisture within the field. Therefore, the soil dryness

Table 5. Weather conditions during 2010, 2011, and 2012 growing seasons and long-term average values at the Mitchell Agricultural Laboratory (MAL), Scottsbluff, Neb.

Year	Month	T_{max}[a] (°C)	T_{min} (°C)	T_{avg} (°C)	U_2[b] (m s^{-1})	R_s[c] (MJ m^{-2} d^{-1})	RH[d] (%)	Total Rainfall (mm)
2010	April	15.5	1.1	8.3	5.0	18.1	59.4	52.7
	May	19.0	4.1	11.5	5.1	21.5	61.4	74.2
	June	27.3	11.7	19.5	4.0	23.8	59.4	92.2
	July	30.8	14.5	22.6	3.1	22.8	59.0	33.3
	August	30.9	14.0	22.4	2.4	19.0	53.9	6.1
	September	26.9	7.6	17.2	3.4	19.0	46.6	0.3
	October	19.6	3.2	11.4	3.4	12.1	56.2	15.7
	November	6.9	-5.7	0.6	4.1	7.7	66.5	5.9
	Average	**22.1**	**6.3**	**14.2**	**3.8**	**18.0**	**57.8**	**280**[e]
2011	April	14.1	0.2	7.1	5.1	16.4	63.5	59.7
	May	17.1	4.4	10.7	4.7	17.8	66.0	129.5
	June	27.3	10.9	19.1	4.2	23.9	55.6	95.8
	July	32.1	16.3	24.2	2.9	23.6	62.6	20.1
	August	31.3	14.8	23.1	2.7	22.8	31.3	1.8
	September	25.9	7.4	16.7	3.0	17.8	25.9	5.3
	October	18.5	2.0	10.3	3.2	11.9	51.3	31.0
	November	10.4	-5.0	2.7	3.8	8.5	52.6	2.5
	Average	**22.1**	**6.4**	**14.2**	**3.7**	**17.8**	**51.1**	**345**[e]
2012	April	19.8	3.0	11.4	4.8	19.4	44.9	20.3
	May	23.8	7.0	15.4	4.4	22.6	43.3	7.1
	June	32.0	14.3	23.2	4.2	26.5	38.9	28.2
	July	33.7	16.5	25.1	2.7	25.4	49.6	20.8
	August	31.5	13.5	22.5	2.7	23.6	45.6	0.0
	September	26.9	8.7	17.8	2.6	18.8	48.3	18.5
	October	16.5	0.8	8.6	3.2	11.5	59.4	9.7
	November	13.6	-3.0	5.3	3.2	9.4	57.2	6.5
	Average	**24.7**	**7.6**	**16.2**	**3.5**	**19.7**	**48.4**	**111**[e]
1997-2009 average	April	15.6	0.1	7.9	4.5	18.3	55.7	38.6
	May	21.9	6.0	14.0	4.3	21.6	54.9	43.3
	June	27.5	11.2	19.3	3.8	23.5	53.3	53.2
	July	32.0	15.2	23.6	2.9	24.0	55.0	44.7
	August	29.7	13.5	21.6	2.8	20.8	60.3	36.5
	September	24.8	7.9	16.3	2.8	16.6	58.6	35.5
	October	16.9	0.8	8.9	3.2	11.3	59.3	25.1
	November	10.7	-4.9	2.9	3.3	7.8	58.5	6.6
	Average	**22.4**	**6.2**	**14.3**	**3.5**	**18.0**	**57.0**	**283**[e]

[a] T_{max}, T_{min}, and T_{avg} = maximum, minimum and average air temperature, respectively.
[b] U_2 = wind speed at 2 m height.
[c] R_s = incoming shortwave radiation.
[d] RH = relative humidity.
[e] Seasonal total.

after planting most likely caused differences/non-uniformity in emergence and plant growth (visual observation), which potentially led to a competition between larger/or early emerged maize with smaller/or late emerged maize that resulted in grain yield reduction.

In terms of ETYPF response for individual hybrids, the slope of the production functions exhibited inter-annual variation between the hybrids and for the same hybrids between the years and locations for both PPDs. All hybrids exhibited a linear yield response to increasing ET_c in all years at both locations with positive slopes in all cases (figs. 1a-f and 2a-f). At both locations, there were significant (P<0.05) differences in ETYPS slopes for a given hybrid across the three irrigation treatments at the given PPD (table 8). Most significant slopes were observed in 2011 and 2012 at WCREC, indicating that the grain yield response was influenced significantly per unit of ET_c in the drier and hotter environment. However, at MAL all ETYPF slopes were significant (P<0.05), except for NDT H1 in 2010 under high PPD. At WCREC, the slopes of the ETYPFs ranged from 0.010 Mg ha^{-1} mm^{-1} for DT H4 under high PPD in 2010 to 0.084 Mg ha^{-1} mm^{-1} for the DT H2 under high PPD in 2010. In the high PPD category, on an all three-year average basis, the DT H2 had the greatest ETYPF slope (0.044 Mg ha^{-1} mm^{-1}), and the slope of the DT H3 was similar with 0.041 Mg ha^{-1} mm^{-1}. Among the DT hybrids, H4 had similar slopes in both low and high PPD levels (0.028 Mg ha^{-1} mm^{-1} for low PPD and 0.021 Mg ha^{-1} mm^{-1} for high PPD). Also, in the low PPD category, the three-year average slopes were 0.03, 0.016, 0.025, and 0.028 Mg ha^{-1} mm^{-1} for NDT H1, DT H2, DT H3, and DT H4 hybrids, respectively.

At MAL, the yield response to per unit of ET_c also exhibited a variation between the hybrids and years as well as between the PPDs for the same hybrids. Generally, DT hybrids produced more grain yield per unit of ET_c in drier conditions as compared to WCREC. The slopes of the ETYPFs ranged from 0.010 Mg ha^{-1} mm^{-1} for NDT H1 and DT H4 hybrids under high PPD in the 2010 to 0.035 Mg ha^{-1} mm^{-1} for the DT H2 under high PPD in 2012. The three-year average slopes were greatest for NDT H1 (0.022 Mg ha^{-1} mm^{-1}) and DT H3 (0.024 Mg ha^{-1} mm^{-1}) in the low and high PPD categories, respectively. It is important to note that in the driest year in 2012, all DT

Table 6. Rainfall, irrigation, grain yield, crop evapotranspiration (ET_c), and crop water use efficiency (CWUE) under different irrigation treatments and plant population density (PPD) at the WCREC in North Platte, Neb., during 2010, 2011, and 2012 growing seasons.[a]

Year	Treatment	H[b]	PPD	Rainfall (mm)	Irrigation (mm)	Grain Yield[c] (Mg ha^{-1})	ET_c[c] (mm)	CWUE (kg m^{-3})
2010	RFT[d]	1	High	409	0	8.7 l	474 efgh	1.83
			Low	409	0	9.9 k	487 defg	2.02
		2	High	409	0	10.7 jk	472 gh	2.26
			low	409	0	10.9 jk	491 cdefg	2.22
		3	High	409	0	10.8 jk	490 cdefg	2.19
			low	409	0	11.2 ji	460 gh	2.44
		4	High	409	0	10.8 jk	486 defg	2.22
			low	409	0	10.9 jk	433 h	2.49
2010	ECOT[e]	1	High	409	50	11.9 ghij	511 bcdefg	2.33
			Low	409	50	12.4 egh	526 abcde	2.34
		2	High	409	50	12.4 ghi	486 defg	2.56
			Low	409	50	12.6 cdegh	491 cdefg	2.57
		3	High	409	50	12.7 cdegh	475 efgh	2.66
			Low	409	50	13.6 abcde	501 bcdefg	2.71
		4	High	409	50	11.6 hij	460 gh	2.52
			Low	409	50	12.5 degh	472 gh	2.64
2010	FIT[f]	1	High	409	211	13.9 abc	556 ab	2.50
			Low	409	211	13.4 abcde	549 ab	2.44
		2	High	409	211	13.7 abcd	527 abcde	2.60
			Low	409	211	13.9 abcd	574 a	2.42
		3	High	409	211	14.6 a	548 ab	2.66
			Low	409	211	14.1 ab	523 abcdef	2.69
		4	High	409	211	12.9 bcde	534 abcd	2.41
			Low	409	211	12.9 cdeg	546 abc	2.37
2011	RFT	1	High	318	4	6.2 g	429 h	1.43
			Low	318	4	7.7 f	460 efgh	1.67
		2	High	318	4	8.5 def	509 defg	1.67
			Low	318	4	8.2 ef	448 gh	1.84
		3	High	318	4	7.7 f	447 gh	1.72
			Low	318	4	8.6 def	460 efgh	1.87
		4	High	318	4	7.7 f	454 ghf	1.69
			Low	318	4	8.1 f	459 ghf	1.77
2011	ECOT	1	High	318	79	9.2 def	524 bcdefg	1.76
			Low	318	79	10 bcde	577 abcd	1.72
		2	High	318	79	10.9 abc	524 cdefg	2.07
			Low	318	79	11.7 ab	515 defg	2.27
		3	High	318	79	9.5 cdef	492 defg	1.93
			Low	318	79	10.8 abc	519 cdefg	2.08
		4	High	318	79	11.0 ab	519 cdefg	2.12
			Low	318	79	10.3 bcd	526 bcdefg	1.96
2011	FIT	1	High	318	223	10.8 abc	596 ab	1.81
			Low	318	223	10.8 abc	593 ab	1.82
		2	High	318	223	11.1 ab	603 a	1.84
			Low	318	223	12.0 a	575 abcde	2.09
		3	High	318	223	12.1 a	582 ab	2.08
			Low	318	223	10.7 abc	575 abcde	1.86
		4	High	318	223	11.0 abc	536 abcdef	2.05
			Low	318	223	12.4 a	580 abc	2.14

[a] High PPD (84,000 plants ha^{-1}); Low PPD (59,300 plants ha^{-1}). Each grain yield is an average of four replications and each ET_c value is an average of two replications.
[b] Hybrid type.
[c] Values within a column followed by the same letter are not statistically different for the given year.
[d] Rainfed treatment.
[e] Early cutoff treatment.
[f] Fully irrigation treatment.

hybrids performed better (greater ETYPF slopes) than the NDT hybrid, especially at MAL. For example, in 2012 at MAL, DT H2 had the greatest slope at both high and low PPDs (0.035 Mg ha^{-1} mm^{-1} for high PPD and 0.024 Mg ha^{-1} mm^{-1} for low PPD). When all slopes were averaged for all years, PPDs and both locations, DT H3 had the greatest slope of 0.027 Mg ha^{-1} mm^{-1}, while for the driest year in the 2012 the DT H2 and H3 had the greatest slope value of 0.030 Mg ha^{-1} mm^{-1} at MAL among all hybrids. Generally, the ETYPF slopes were greater for all hybrids (except for DT H4) at MAL than at WCREC. The DT H4 had 24% greater slope at high PPD in 2012 (drier conditions) at WCREC than at MAL.

Table 6 (continued). Rainfall, irrigation, yield, crop evapotranspiration (ET_c), and crop water use efficiency (CWUE) under different irrigation treatments and plant population density (PPD) at the WCREC in North Platte, Neb., during 2010, 2011 and 2012 growing seasons.[a]

Year	Treatment	H[b]	PPD	Rainfall (mm)	Irrigation (mm)	Grain Yield[c] (Mg ha^{-1})	ET_c[c] (mm)	CWUE (kg m^{-3})
2012	RFT[d]	1	High	84	11	0.2 b	300 abc	0.08
			Low	84	11	0.0 bcd	267 bc	0.00
		2	High	84	11	0.1 bc	318 abc	0.04
			Low	84	11	0.0 cd	278 abc	0.00
		3	High	84	11	0.2 bc	279 abc	0.07
			Low	84	11	0.0 cd	261 c	0.00
		4	High	84	11	0.1 bcd	281 abc	0.03
			Low	84	11	0.0 d	264 bc	0.00
2012	ECOT[e]	1	High	84	279	6.3 a	513 abc	1.23
			Low	84	279	5.5 a	548 ab	1.01
		2	High	84	279	5.8 a	486 abc	1.20
			Low	84	279	5.2 a	465 abc	1.12
		3	High	84	279	5.4 a	509 abc	1.06
			Low	84	279	5.0 a	501 abc	1.00
		4	High	84	279	6.6 a	520 ab	1.26
			Low	84	279	5.4 a	497 abc	1.09
2012	FIT[f]	1	High	84	555	6.6 a	683 a	0.97
			Low	84	555	6.4 a	693 a	0.92
		2	High	84	555	7.3 a	686 a	1.06
			Low	84	555	5.8 a	679 a	0.85
		3	High	84	555	6.9 a	676 a	1.02
			Low	84	555	7.1 a	670 a	1.06
		4	High	84	555	6.7 a	681 a	0.99
			Low	84	555	7.5 a	678 a	1.10

[a] High PPD (84,000 plants ha^{-1}); Low PPD (59,300 plants ha^{-1}). Each grain yield is an average of four replications and each ET_c value is an average of two replications.
[b] Hybrid type.
[c] Values within a column followed by the same letter are not statistically different for the given year.
[d] Rainfed treatment.
[e] Early cutoff treatment.
[f] Fully irrigation treatment.

Table 7. Rainfall, irrigation, yield, crop evapotranspiration (ET_c), and crop water use efficiency (CWUE) under different irrigation treatments and plant population density (PPD) at the MAL site in Scottsbluff, Neb., during 2010, 2011 and 2012 growing seasons.[a]

Year	Treatment	H[b]	PPD	Rainfall (mm)	Irrigation (mm)	Grain Yield[c] (Mg ha^{-1})	ET_c[c] (mm)	CWUE (kg m^{-3})
2010	RFT[d]	1	High	187	0	7.4 jki	362 ed	2.05
			Low	187	0	8.5 fghi	360 ed	2.35
		2	High	187	0	4.7 l	365 ed	1.30
			Low	187	0	7.8 ghij	372 ed	2.10
		3	High	187	0	7.6 hji	354 e	2.14
			Low	187	0	5.6 kl	376 d	1.48
		4	High	187	0	7 jkl	360 ed	1.93
			Low	187	0	7.6 hjik	357 e	2.12
2010	ECOT[e]	1	High	187	140	9.9 defghi	477 bc	2.06
			Low	187	140	9.4 efghi	476 bc	1.96
		2	High	187	140	10.9 bcdefg	481 bc	2.27
			Low	187	140	9.4 efghi	487 bc	1.92
		3	High	187	140	11.8 abcdef	480 bc	2.46
			Low	187	140	10.8 bcdefg	490 b	2.21
		4	High	187	140	11.4 bcdef	478 bc	2.38
			Low	187	140	10.6 cdefgh	467 c	2.26
2010	FIT[f]	1	High	187	513	15.1 ab	748 a	2.01
			Low	187	513	13.9 abc	739 a	1.88
		2	High	187	513	13.9 abcd	752 a	1.84
			Low	187	513	12.4 abcde	747 a	1.65
		3	High	187	513	15.9 a	755 a	2.10
			Low	187	513	12 abcde	748 a	1.60
		4	High	187	513	13.2 abcd	749 a	1.77
			Low	187	513	13.2 abcd	743 a	1.77

[a] High PPD (84,000 plants ha^{-1}); Low PPD (59,300 plants ha^{-1}). Each grain yield is an average of four replications and each ET_c value is an average of two replications.
[b] Hybrid type.
[c] Values within a column followed by the same letter are not statistically different for the given year.
[d] Rainfed treatment.
[e] Early cutoff treatment.
[f] Fully irrigation treatment.

Table 7 (continued). Rainfall, irrigation, yield, crop evapotranspiration (ET_c), and crop water use efficiency (CWUE) under different irrigation treatments and plant population density (PPD) at the MAL site in Scottsbluff, Neb., during 2010, 2011, and 2012 growing seasons.[a]

Year	Treatment	H[b]	PPD	Rainfall (mm)	Irrigation (mm)	Grain Yield[c] (Mg ha^{-1})	ET_c[c] (mm)	CWUE (kg m^{-3})
2011	RFT	1	High	155	25	3.7 e	334 cd	1.11
			Low	155	25	5.7 d	321 cd	1.79
		2	High	155	25	7.2 dc	301 d	2.40
			Low	155	25	5.9 d	348 c	1.70
		3	High	155	25	6.0 d	327 cd	1.82
			Low	155	25	6.2 d	325 cd	1.90
		4	High	155	25	7.3 bdc	340 c	2.14
			Low	155	25	5.3 d	323 cd	1.63
2011	ECOT	1	High	155	325	11.4 abc	531 b	2.14
			Low	155	325	10.8 abc	567 b	1.90
		2	High	155	325	13.4 a	525 b	2.54
			Low	155	325	12.3 ab	512 b	2.40
		3	High	155	325	13.3 a	540 b	2.47
			Low	155	325	13 a	571 b	2.27
		4	High	155	325	10.5 abc	520 b	2.02
			Low	155	325	10.2 abc	520 b	1.97
2011	FIT	1	High	155	595	14.6 a	696 a	2.10
			Low	155	595	13 a	754 a	1.73
		2	High	155	595	14.8 a	723 a	2.05
			Low	155	595	12.3 ab	702 a	1.75
		3	High	155	595	14.3 a	717 a	1.99
			Low	155	595	13.1 a	737 a	1.78
		4	High	155	595	13.7 a	737 a	1.86
			Low	155	595	12.8 a	703 a	1.81
2012	RFT[d]	1	High	55	183	5.9 i	375 d	1.56
			Low	55	183	5.1 i	385 cd	1.33
		2	High	55	183	1.3 l	390 c	0.33
			Low	55	183	3.3 k	384 cd	0.87
		3	High	55	183	1.2 l	386 cd	0.32
			Low	55	183	4 j	381 cd	1.06
		4	High	55	183	3.2 k	385 cd	0.84
			Low	55	183	7.1 h	378 cd	1.87
2012	ECOT[e]	1	High	55	680	11.6 ef	761 b	1.52
			Low	55	680	12.6 de	770 b	1.64
		2	High	55	680	14.5 bcd	769 b	1.89
			Low	55	680	9.5 g	762 b	1.25
		3	High	55	680	9.1 g	748 b	1.21
			Low	55	680	10.1 fg	759 b	1.33
		4	High	55	680	15.9 abc	770 b	2.06
			Low	55	680	12.6 de	761 b	1.66
2012	FIT[f]	1	High	55	830	17.3 a	834 a	2.08
			Low	55	830	16.7 ab	831 a	2.01
		2	High	55	830	16.3 abc	852 a	1.92
			Low	55	830	15.8 abc	836 a	1.89
		3	High	55	830	18.0 a	837 a	2.15
			Low	55	830	14 dc	836 a	1.67
		4	High	55	830	15.5 abc	829 a	1.87
			Low	55	830	14 dc	849 a	1.65

[a] High PPD (84,000 plants ha^{-1}); Low PPD (59,300 plants ha^{-1}). Each grain yield is an average of four replications and each ET_c value is an average of two replications.
[b] Hybrid type.
[c] Values within a column followed by the same letter are not statistically different for the given year.
[d] Rainfed treatment.
[e] Early cutoff treatment.
[f] Fully irrigation treatment.

Comparison of Grain Yield Response to Evapotranspiration [ET_C-Yield Production Functions (ETYPF)] for Pooled Data

The ETYPFs for a given hybrid for all years, both locations, and all treatments (irrigation and PPDs) are combined to develop pooled ETYPFs for overall assessments of differences in hybrid performance (figs. 3a-e). All slopes were significantly different (P<0.05) than the unity (table 9). The pooled ETYPFs differed from those that were developed for individual hybrids and treatments by year. All pooled ETYPFs had linear and strong yield response to ET_c with positive slopes in all cases. The pooled ETYPFs had the slopes of 0.022, 0.020, 0.021, 0.019, and 0.020 Mg ha^{-1} mm^{-1} for the NDT H1, DT H2,

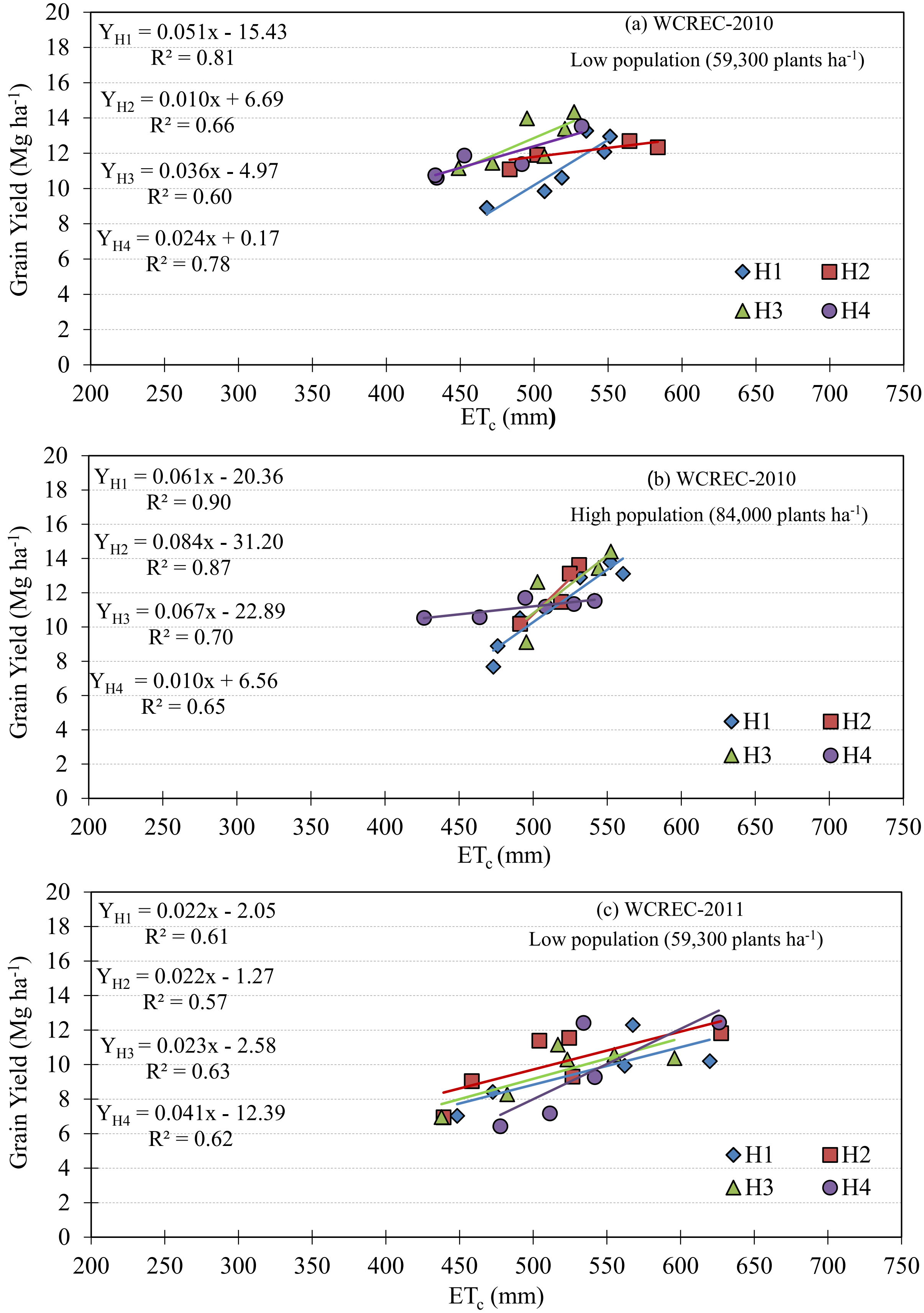


Figure 1. Relationships between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: low population-2010 (a), high population-2010 (b), low population-2011 (c), high population-2011 (d), low population-2012 (e), and high population-2012 (f) at the West Central Research and Extension Center (WCREC) site at North Platte, Neb. H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) hybrids. The ET_c values were from two replications of each treatment, which were correlated to the grain yield values from the same replications from which the ET_c values were used.

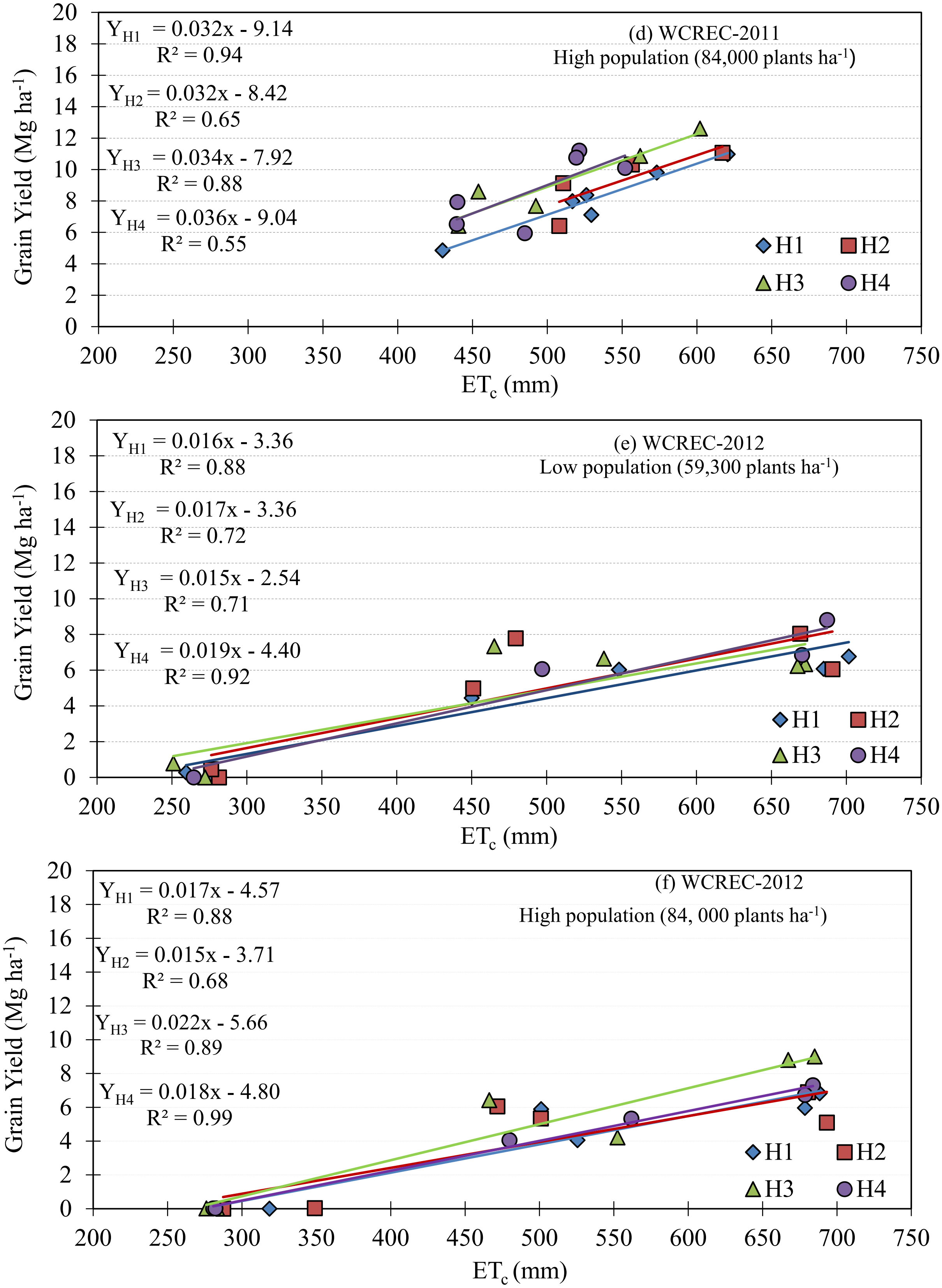


Figure 1 (continued). Relationships between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: low population-2010 (a), high population-2010 (b), low population-2011 (c), high population-2011 (d), low population-2012 (e), and high population-2012 (f) at the West Central Research and Extension Center (WCREC) site at North Platte, Neb. H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) hybrids. The ET_c values were from two replications of each treatment, which were correlated to the grain yield values from the same replications from which the ET_c values were used.

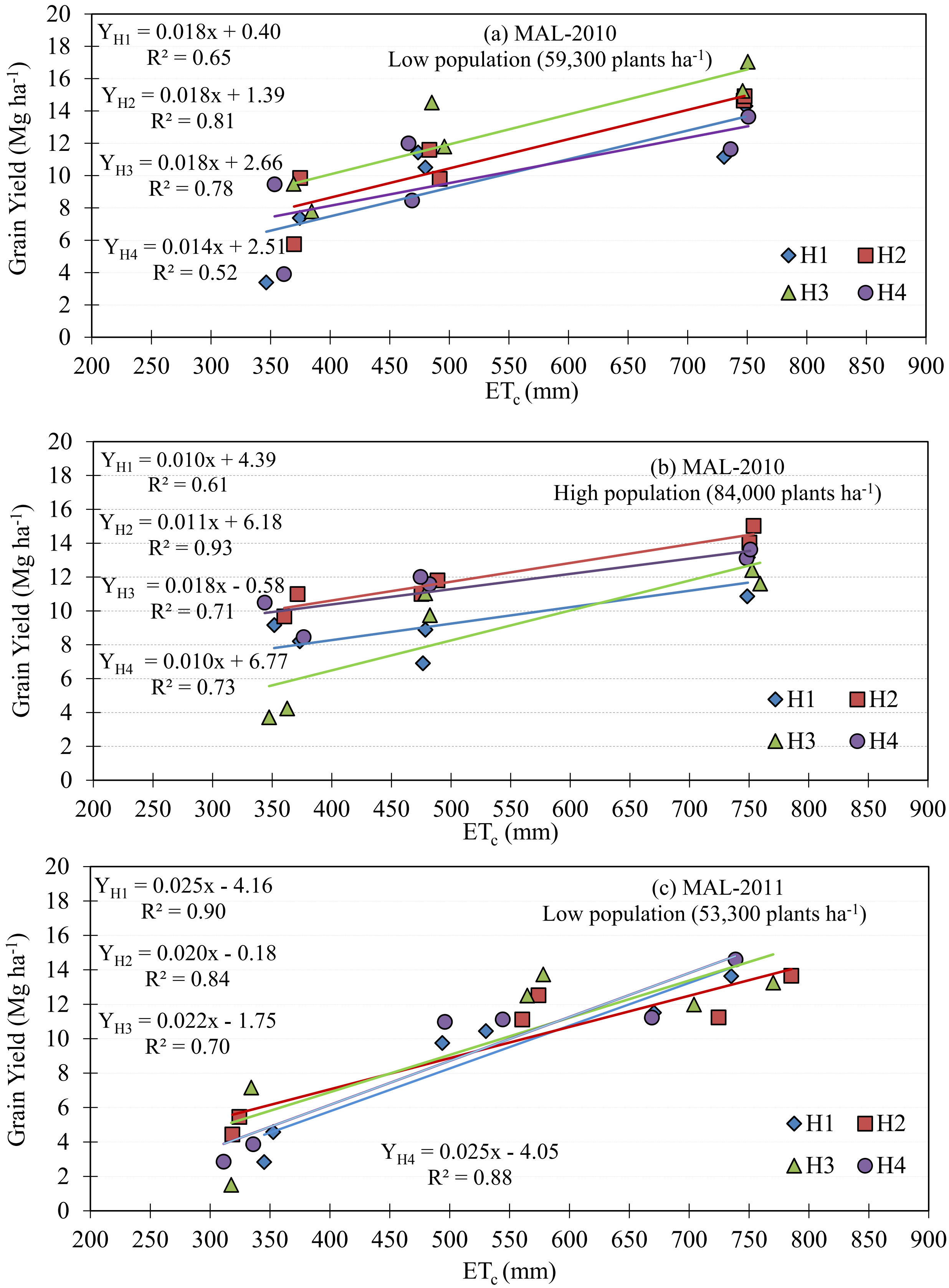
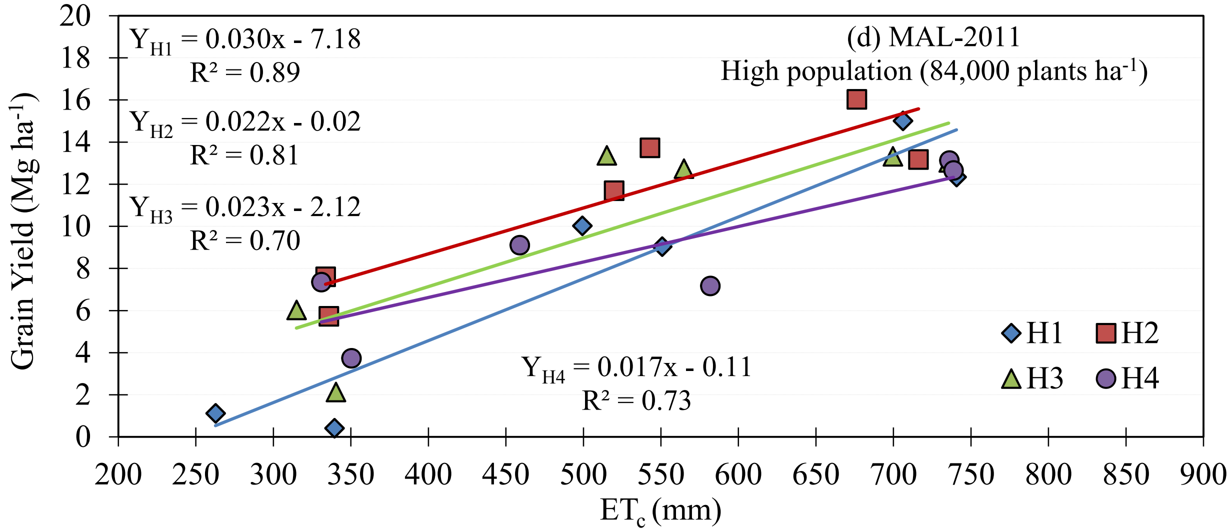
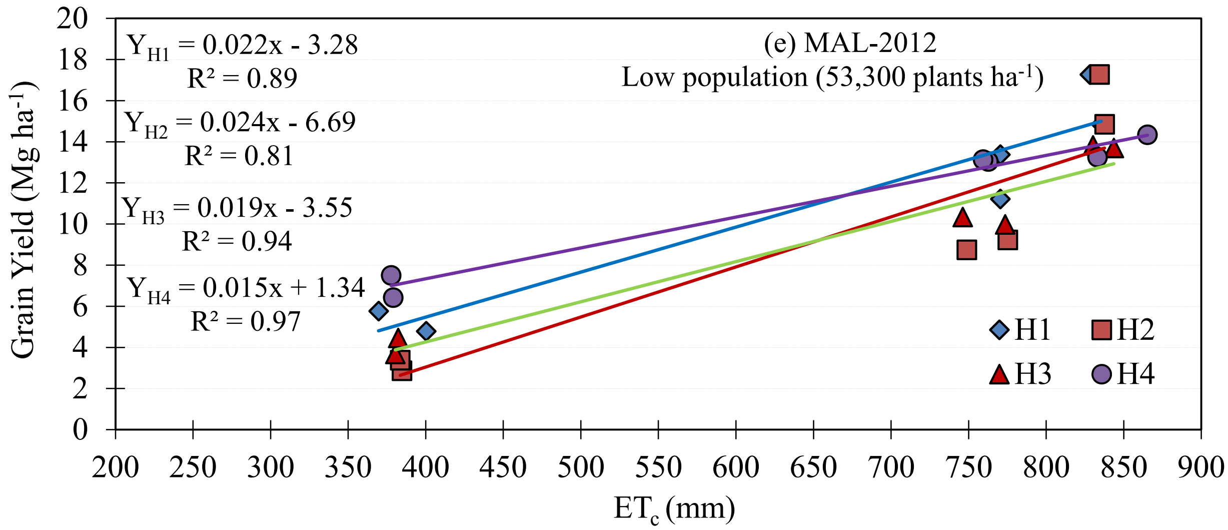


Figure 2. Relationships between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: low population-2010 (a), high population-2010 (b), low population-2011 (c), high population-2011 (d), low population-2012 (e), and high population-2012 (f) at the Mitchell Agricultural Laboratory (MAL) site at Scottsbluff, Neb. H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) hybrids. The ET_c values were from two replications of each treatment, which were correlated to the grain yield values from the same replications from which the ET_c values were used.





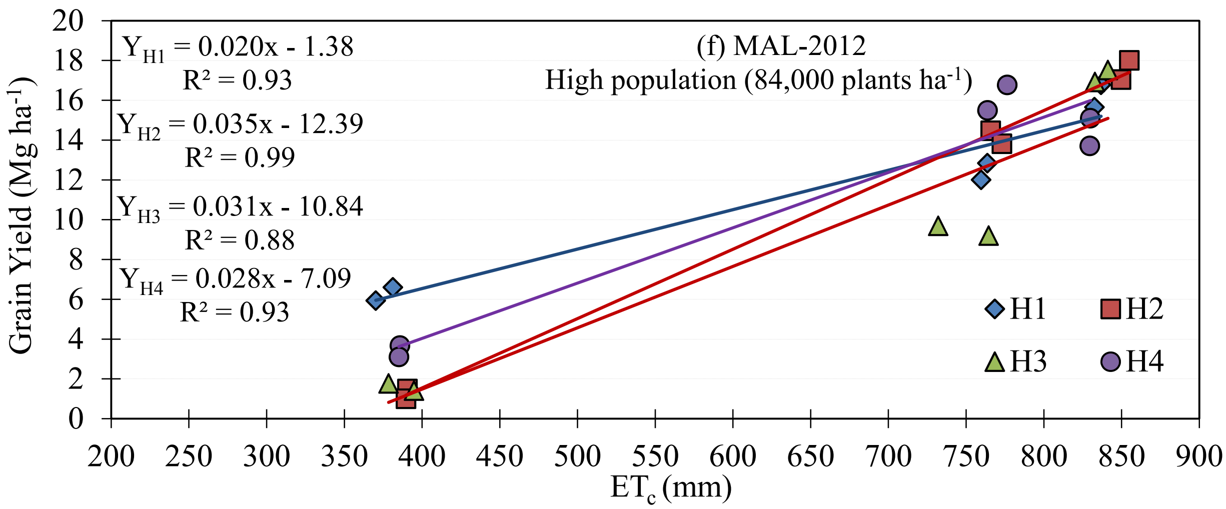


Figure 2 (continued). Relationships between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: low population-2010 (a), high population-2010 (b), low population-2011 (c), high population-2011 (d), low population-2012 (e), and high population-2012 (f) at the Mitchell Agricultural Laboratory (MAL) site at Scottsbluff, Neb. H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) hybrids. The ET_c values were from two replications of each treatment, which were correlated to the grain yield values from the same replications from which the ET_c values were used.

DT H3, DT H4, and pooled data for DT H2, DT H3, and DT H4, respectively. Generally, slopes were not significantly different (P>0.05) between the NDT and DT hybrids and all slopes were within 5% of each other. The NDT H1 had least amount of scattering of data points (fig. 3a) and the scatter of data points around the regression line was similar for all three DT hybrids (figs. 3b, c, and d).

BASAL EVAPOTRANSPIRATION (ET_B)

The ET_b values were quantified for individual NDT and DT hybrids under both low and high PPDs, both locations and all years (table 10). ET_b values exhibited a wide range of variation not only for the same hybrid within the same year for different PPDs, but also between the years and locations. Generally, DT hybrids had lower ET_b values than the NDT H1 in both PPD levels. For example, at WCREC, the average ET_b values (average of all three years) for the high PPDs were 299, 294, 277, and 259 mm for NDT H1, DT H2, DT H3, and DT H4, respectively, with as much as 40 mm difference between NDT and DT hybrids (H1 vs. H4). When the average of all DT hybrids was considered, the NDT H1 had 22 mm more ET_b than the averaged ET_b for DT hybrids with high PPD. Similar results with a greater difference in ET_b between NDT and DT hybrids were observed with the low PPDs. For example, the average ET_b values (average of all years) for the low PPDs were 256, 198, 154, and 267 mm for NDT H1, DT H2, DT H3, and DT H4 hybrids, respectively, with as much as 102 mm difference between NDT and DT hybrids (H1 vs. H3). When the average of all DT hybrids was considered, the NDT H1 hybrid had 50 mm more ET_b than the DT hybrids with low PPD. While it varied with year and location, among DT hybrids, in general, H4 had more ET_b than other DT hybrids.

Table 8. Regression analyses for the individual linear equations between grain yield and crop evapotranspiration (ET_c) for individual hybrids at two planting population densitites (PPDs), all irrigation treatments and years at WCREC.

Year	Site	Hybrid	PPD	Slope	P-Value	Standard Error
2010	WCREC	1	High	0.061	0.0033[a]	0.00973
2010	WCREC	2	High	0.084	0.0642	0.02233
2010	WCREC	3	High	0.067	0.159	0.03067
2010	WCREC	4	High	0.010	0.0516	0.00339
2010	WCREC	1	Low	0.051	0.0136[a]	0.01217
2010	WCREC	2	Low	0.010	0.1284	0.00499
2010	WCREC	3	Low	0.036	0.0687	0.01442
2010	WCREC	4	Low	0.024	0.046[a]	0.00742
2011	WCREC	1	High	0.032	0.0012[a]	0.00399
2011	WCREC	2	High	0.032	0.1903	0.01658
2011	WCREC	3	High	0.034	0.0166[a]	0.00692
2011	WCREC	4	High	0.036	0.0907	0.01627
2011	WCREC	1	Low	0.022	0.1167	0.00996
2011	WCREC	2	Low	0.022	0.08	0.00941
2011	WCREC	3	Low	0.023	0.0571[a]	0.00887
2011	WCREC	4	Low	0.041	0.1095	0.01809
2012	WCREC	1	High	0.017	0.0056[a]	0.00308
2012	WCREC	2	High	0.015	0.0408[a]	0.00515
2012	WCREC	3	High	0.022	0.0041[a]	0.0036
2012	WCREC	4	High	0.018	<0.0001[a]	0.00081
2012	WCREC	1	Low	0.016	0.0029[a]	0.00231
2012	WCREC	2	Low	0.017	0.0326[a]	0.0052
2012	WCREC	3	Low	0.015	0.0344[a]	0.00471
2012	WCREC	4	Low	0.019	0.0403[a]	0.00385
2010	MAL	1	High	0.010	0.064	0.00383
2010	MAL	2	High	0.011	0.0018[a]	0.00151
2010	MAL	3	High	0.018	0.0335[a]	0.00556
2010	MAL	4	High	0.010	0.0285[a]	0.00269
2010	MAL	1	Low	0.018	0.0504[a]	0.00639
2010	MAL	2	Low	0.018	0.013[a]	0.00425
2010	MAL	3	Low	0.018	0.0194[a]	0.0049
2010	MAL	4	Low	0.014	0.1037	0.00669
2011	MAL	1	High	0.030	0.0047[a]	0.00516
2011	MAL	2	High	0.022	0.0132[a]	0.00513
2011	MAL	3	High	0.023	0.0352[a]	0.00739
2011	MAL	4	High	0.017	0.0298[a]	0.00509
2011	MAL	1	Low	0.025	0.0036[a]	0.00405
2011	MAL	2	Low	0.020	0.0089[a]	0.00381
2011	MAL	3	Low	0.022	0.0363[a]	0.00698
2011	MAL	4	Low	0.025	0.0048[a]	0.0045
2012	MAL	1	High	0.020	0.0016[a]	0.0026
2012	MAL	2	High	0.035	<0.0001[a]	0.00105
2012	MAL	3	High	0.031	0.005[a]	0.00551
2012	MAL	4	High	0.028	0.0018[a]	0.00376
2012	MAL	1	Low	0.022	0.0038[a]	0.0038
2012	MAL	2	Low	0.024	0.0138[a]	0.00581
2012	MAL	3	Low	0.019	0.0011[a]	0.00234
2012	MAL	4	Low	0.015	0.0002[a]	0.00109

[a] Slope values are statistically different (α=0.05) in a given year.

Table 9. Regression analyses for the pooled data linear equations between grain yield and crop evapotranspiration (ET_c) for a given hybrid at WCREC and MAL.[a]

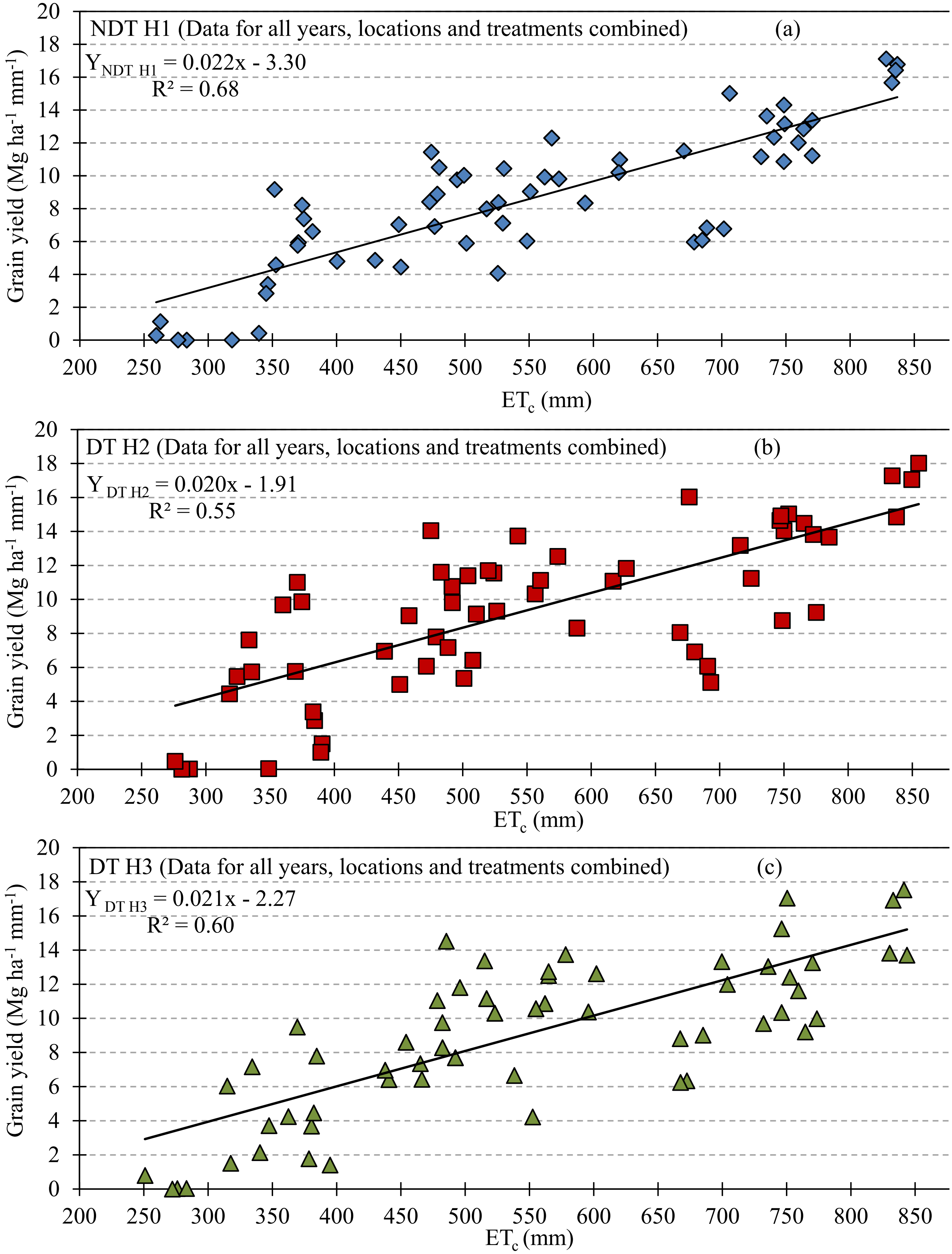
Hybrid	Slope	P-Value	Standard Error	95% Confidence Limits	
1 (NDT)	0.022	<0.0001[b]	0.00174	0.01814	0.02507
2 (DT)	0.020	<0.0001[b]	0.00223	0.01603	0.02495
3 (DT)	0.021	<0.0001[b]	0.00206	0.01660	0.02484
4 (DT)	0.019	<0.0001[b]	0.00190	0.01522	0.02282

[a] All years and all treatments (irrigation and PPDs) are combined.
[b] Slope values are statistically different (α=0.05) in a given year.

Table 10. Basal evapotranspiration (ET_b) for all individual NDT and DT hybrids under both high and low PPDs, two locations at WCREC (a) and MAL (b).

Year	Site	Hybrid	PPD	Basal Evapotranspiration (ET_b)
2010	WCREC	H1	High	334
2010	WCREC	H2	High	371
2010	WCREC	H3	High	342
2010	WCREC	H1	Low	303
2010	WCREC	H3	Low	138
2011	WCREC	H1	High	294
2011	WCREC	H2	High	263
2011	WCREC	H3	High	233
2011	WCREC	H4	High	251
2011	WCREC	H4	Low	302
2012	WCREC	H1	High	269
2012	WCREC	H2	High	247
2012	WCREC	H3	High	257
`2012	WCREC	H4	High	267
2012	WCREC	H1	Low	210
2012	WCREC	H2	Low	198
2012	WCREC	H3	Low	169
2012	WCREC	H4	Low	232
2011	MAL	H1	Low	166
2011	MAL	H4	Low	162
2012	MAL	H2	High	354
2012	MAL	H3	High	350
2012	MAL	H4	High	253
2012	MAL	H1	Low	149
2012	MAL	H2	Low	279
2012	MAL	H3	Low	187

[a] H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) hybrids; WCREC: West Central Research and Extension Center, North Platte, Neb.; MAL: Mitchell Agricultural Laboratory (MAL), Scottsbluff, Neb.


NDT H1 (Data for all years, locations and treatments combined)
(a)
$Y_{NDT\ H1} = 0.022x - 3.30$
$R^2 = 0.68$
DT H2 (Data for all years, locations and treatments combined)
(b)
$Y_{DT\ H2} = 0.020x - 1.91$
$R^2 = 0.55$
DT H3 (Data for all years, locations and treatments combined)
(c)
$Y_{DT\ H3} = 0.021x - 2.27$
$R^2 = 0.60$
Grain yield (Mg ha^{-1} mm^{-1})
ET_c (mm)
0
2
4
6
8
10
12
14
16
18
20
200
250
300
350
400
450
500
550
600
650
700
750
800
850

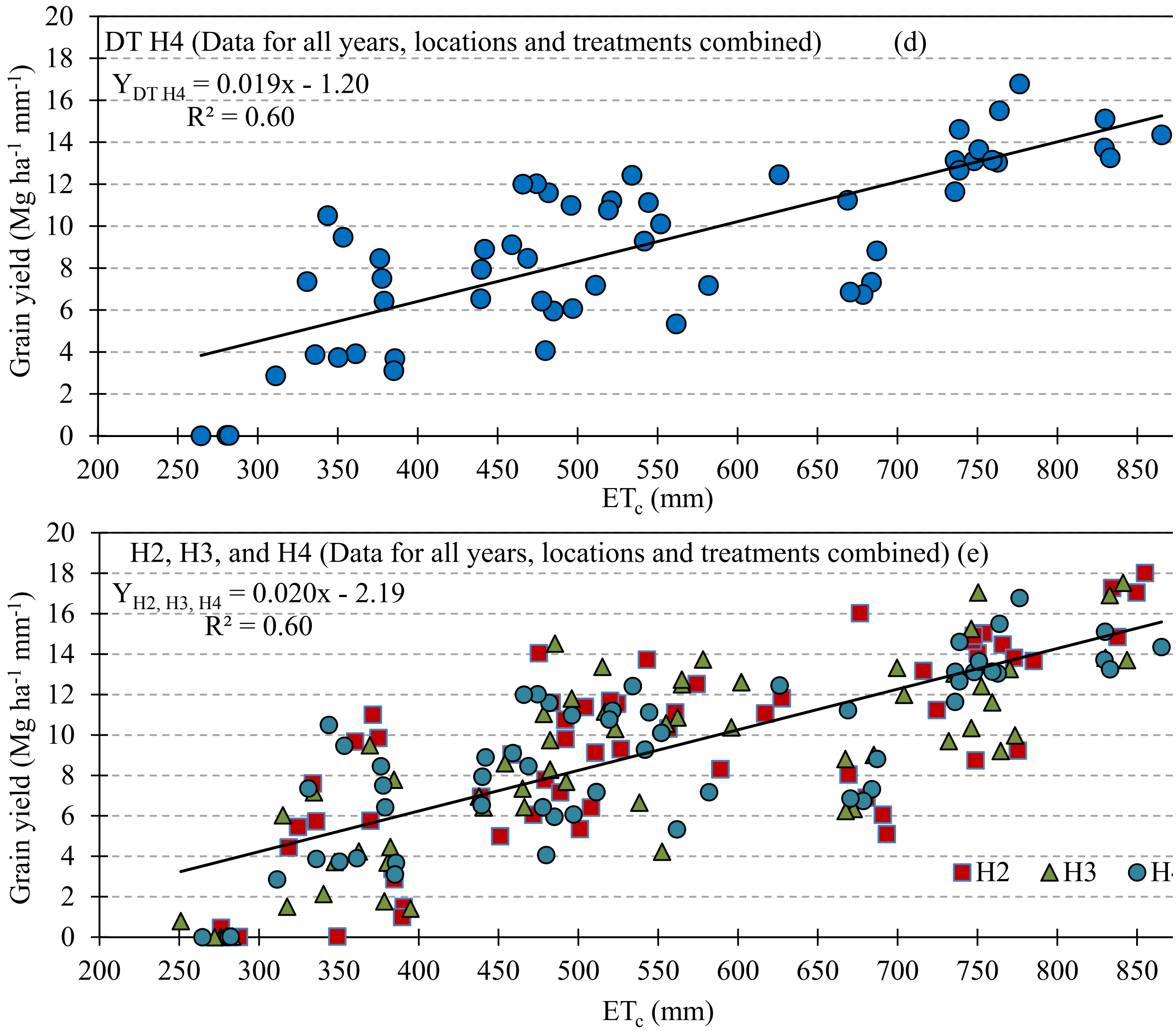


Figure 3. Relationships between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: NDT H1 (a), DT H2 (b), DT H3 (c), DT H4 (d), and all DT hybrids (H2, H3, and H4) combined (e). Data from all three years, two locations, and all treatments are combined for each case, H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) hybrids. WCREC: West Central Research and Extension Center, North Platte, Neb.; MAL: Mitchell Agricultural Laboratory (MAL), Scottsbluff, Neb.

At MAL in driest conditions in 2012, the ET_b values for DT hybrids were greater than at WCREC for the high PPDs (table 10). When averaging the ET_b values across all treatments, years, locations by hybrid (figs. 3a, b, c, and d) and by averaging all DT hybrids (H2, H3 and H4; fig. 3e), the NDT H1 had 150 mm of ET_b and DT H2, DT H3, and DT H4 had 95, 108, and 63 mm of ET_b, respectively. When all DT hybrids are pooled together, the ET_b value was 109 mm. Thus, when hybrids were pooled for three years, two locations, and both PPDs to obtain a general assessment, the DT hybrids had 41 mm less ET_b than the NDT hybrid, but this difference can be as much as 87 mm (ET_b of H1 vs. H4; figs. 3a vs. 3d). It is important to note that the DT hybrids showed less ET_b requirement than the NDT hybrid in both PPD levels at the WCREC as this may indicate that the DT hybrids can maintain high grain yield production with lower ET_b at both PPD levels in comparison to NDT hybrid. However, findings at MAL indicate that the DT H3 and H4 hybrids may perform superior (in terms of yield and water productivity as well as ET_b) when planted at low PPD. The DT hybrids can also be grown with low PPD (59,300 plants ha^{-1}) and planting the DT hybrids at high PPD (84,000 plants ha^{-1}) may reduce production efficiency in terms of ET_b, which should be considered in water-limiting environments (similar to semi-arid conditions of Scottsbluff). The results from this research point towards the assessment that the DT hybrids perform well with both low and high PPD in a transition zone in North Platte and they perform superior only with low PPD in drier semi-arid climate conditions in Scottsbluff.

Crop Water Use Efficiency (CWUE)

Another variable that can provide invaluable information about the performance of DT hybrids in comparison with NDT hybrid is CWUE, which indicates the grain production per unit of ET_c. There were differences in CWUE response between the treatments at the WCREC. In most cases, DT hybrids had greater CWUE values than the NDT hybrid at both locations. The CWUE values increased as the ET_c increased; however, across the three years the ECOT had the highest CWUE of 2.71 kg m^{-3} for the DT H3 (low PPD) at WCREC in 2010 (table 6), and 2.54 kg m^{-3} for the H2 (high PPD) at MAL in 2011 (table 7). Crops grown under rainfed conditions usually utilize less water than irrigated conditions, but with lower production, that can result in higher CWUE values than FIT and RFT (Howell and Hiler, 1975). At WCREC, the CWUE values ranged from 1.83 to 2.71, 1.43 to 2.27 kg m^{-3} and from near 0 to 1.26 kg m^{-3} in 2010, 2011, and 2012, respectively (table 6). The three-year average CWUE value, including both PPDs, was greater for DT hybrids (1.72 kg m^{-3}) than NDT hybrid (1.55 kg m^{-3}).

At MAL, the CWUE values ranged from 1.3 to 2.46, 1.11 to 2.54 kg m^{-3}, and 0.32 to 2.15 kg m^{-3} in 2010, 2011, and 2012, respectively (table 7). The three-year average CWUE value, including both PPDs, was greater for DT hybrids (1.81 kg m^{-3}) at MAL than DT hybrids (1.72 kg m^{-3}) at WCREC. In drier conditions (2012), when averaging the CWUE values for DT hybrids across all treatments, years, by location, the DT hybrids at MAL had higher CWUE of 1.43 kg m^{-3} than the DT hybrids at WCREC (0.72 kg m^{-3}). The CWUE pattern for the three irrigation treatments, PPDs, years, and locations showed that the highest CWUE values were recorded for DT H3 and H4 than other DT and NDT hybrids. The greatest CWUE values were recorded for DT H4, H3, and H2 with 1.87, 1.70, and 1.70 kg m^{-3} at MAL, respectively. When averaging CWUE for all DT hybrids, years and locations, the DT H2, H3, and H4 had 1.74, 1.75, and 1.79 kg m^{-3} of CWUE, respectively. It is important to note that the DT hybrids showed greatest CWUE at both locations for average years (2010 and 2011) and for drier conditions in 2012. This may indicate that the DT hybrids may maintain high yield production under varied environmental conditions such as a transition zone in North Platte and drier semi-arid climate conditions in Scottsbluff by ET_c reduction without affecting grain yield or higher grain production while maintaining similar ET_c.

SUMMARY AND CONCLUSIONS

Grain yield, ET_c, ET_b, ETYPF, and CWUE response of DT (H2, H3, and H4) and NDT (H1) maize hybrids to two PPDs and three irrigation levels were researched at two semi-arid locations (WCREC at North Platte and MAL at Scottsbluff) in Nebraska in 2010, 2011, and 2012. Year 2010 had above-average precipitation, 2011 was an average year, and 2012 was one of the driest and hottest years in Nebraska's recorded history. Specific findings and conclusions are summarized as:

- Generally, DT hybrids performed superior to the NDT hybrid not only in dry years, but also in average and above average rainfall years. The performances of the DT hybrids were stronger in drier years; and much stronger, especially with low PPD in the driest year in 2012 at the driest location (Scottsbluff).
- ET_c exhibited inter-annual variation for the same hybrid within the same location and between the two locations and with the PPD and irrigation treatments. There were significant differences ($P<0.05$) between the ET_c values for some hybrids across three irrigation treatments.
- The grain yield response to hybrids and treatments also exhibited substantial variation for the same hybrid between the PPDs and had inter-annual variation within the same location. The greatest grain yields of 14.6 and 18.0 Mg ha^{-1} were observed with 548 and 837 mm of ET_c, which was recorded for the DT H3 (high PPD) at WCREC and MAL, respectively. There were significant differences in performance among the DT hybrids as well in terms of performance variables (ET_c, ET_b, ETYPF, CWUE). In most cases, DT H3 resulted in greater grain yield than the NDT H1 and other DT hybrids; and, DT hybrids had lower ET_c in different irrigation levels and PPDs than the NDT hybrid in both locations.
- In terms of ETYPF response for individual hybrids, the slope of the production functions exhibited an inter-annual variation between the hybrids and for the same hybrids between the years and location for both high and low PPDs. All hybrids exhibited a linear and strong yield response to increasing ET_c in all years at both locations with positive slopes in all cases. Generally, DT hybrids produced more grain yield per unit of ET_c in drier conditions at MAL.
- The ET_b values also exhibited variations between the hybrids, years, locations, and PPDs. Generally, DT hybrids had lower ET_b than the NDT H1 in both PPD levels. For example, at WCREC, the average ET_b values (average of all three years) for the high PPDs were 299, 294, 277, and 259 mm for NDT H1, DT H2, DT H3, and DT H4 hybrids, respectively, with as much as 40 mm difference between NDT and DT hybrids (H1 vs. H4). For the DT hybrids having lower ET_b values than NDT hybrid in both PPD levels at the WCREC is an important finding as this may indicate that the DT hybrids can be grown at both PPD levels with good yields and lower ET_b. In drier conditions at Scottsbluff (in comparison to North Platte), the ET_b values were greater at MAL than at WCREC for both PPDs.
- There were differences in CWUE response between the treatments at both locations with DT hybrids generally having greater CWUE values than the NDT hybrid at both locations.

It was concluded that DT hybrids increase grain yield production per unit of ET_c in semi-arid regions of North Platte and Scottsbluff. Our research findings at MAL indicate that the DT hybrids may perform better (in terms of yield and water productivity as well as ET_b) when planted at low PPD (59,300 plants ha^{-1}) and planting the DT hybrids at high PPD (84,000 plants ha^{-1}) may reduce production efficiency in terms of ET_b in dry climates. The results and findings of this research should not be extrapolated beyond the boundaries of these and similar experimental conditions.

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