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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, population densities and environments: Part II. In south-central and northeast Nebraska's transition zone and sub-humid environments

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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, POPULATION DENSITIES, AND ENVIRONMENTS: PART II. IN SOUTH-CENTRAL AND NORTHEAST NEBRASKA'S TRANSITION ZONE AND SUB-HUMID ENVIRONMENTS

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ABSTRACT. *Information and data on newer drought-tolerant maize hybrid response to water in different climates are extremely scarce. This research quantified the performance of non-drought-tolerant (NDT) (H1) and drought-tolerant (DT) (H2, H3, and H4) maize (*Zea mays *L.) hybrids response to grain yield, crop evapotranspiration (ET_c), basal evapotranspiration (ET_b), ET_c-yield production functions (ETYPF), and crop water use efficiency (CWUE) at three irrigation levels and two plant population densities (PPDs) at two locations (transition zone between sub-humid and semi-arid climates at Clay Center (SCAL), Nebraska, in 2010 and 2012; and in a sub-humid climate at Concord (HAL), Nebraska, in 2010, 2011, and 2012). Irrigation treatments were: fully irrigated (FIT), early cutoff (ECOT) (i.e., no irrigation after blister stage), and rainfed (RFT) under two PPDs of 59,300 plants ha^{-1} (low PPD), and 84,000 plants ha^{-1} (high PPD). Generally, DT hybrids performed superior to NDT hybrid consistently at both locations, treatments, and years. DT H3 and DT H4 had highest grain yield consistently at SCAL and HAL, respectively. DT H3 and H4 hybrids' productivity was not only superior in the RFT, but also in FIT. The highest yield of 16.3, and 15.3 Mg ha^{-1} were achieved by DT H3 (high PPD) and DT H2 (high PPD), respectively, associated with 471 and 590 mm of ET_c in the FIT in 2012 at SCAL, and HAL, respectively. In most cases, all hybrids had highest grain yield under low PPD than high PPD at the RFT. All hybrids exhibited a linear yield response to increasing ET_c in all years at both locations with positive slopes in all cases. The individual ETYPF response for individual hybrids had inter-annual variation in slopes between the hybrids and for the same hybrids between the years and location for both low and high PPDs. The ETYPF slopes ranged from 0.004 to 0.102 Mg ha^{-1} mm^{-},^{1} including all treatments (i.e., irrigation and PPDs) at SCAL for 2010 and 2012; and they ranged from 0.008 to 0.057 Mg ha^{-1} mm^{-1} including all treatments at HAL for 2010, 2011, and 2012. The ET_b values exhibited inter-annual variation for the same hybrid between the irrigation levels, PPDs, and locations and they also exhibited an inner-annual variation between the hybrids and treatments in a given year with DT hybrids having consistently lower ET_b values than the NDT hybrid. The greatest CWUE values were found in DT hybrids consistently at both locations. The DT hybrids can significantly increase yield productivity as well as crop water productivity per unit of ET_c with respect to conventional hybrids not only in dry conditions, but also in average or above average years in terms of precipitation.*

Keywords. *Basal evapotranspiration, Crop evapotranspiration, Drought-tolerance, Efficiency, Maize, Production functions.*

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Water scarcity in many regions of the world, including Midwestern United States and Nebraska, is imposing increased pressure on water supplies in agriculture as food, fiber, feed, and fuel demand of a rapidly growing world's population increases. Changes in climate variables add further complications to optimize sufficient production of food, fiber, feed, and fuel. Short-term water shortages could be addressed by irrigation, which can make agricultural production possible in many regions otherwise unproductive areas (Kramer and Boyer, 1995). Crop species produced can have a substantial influence on water demand vs. productivity dynamics due to differences in crops' response and sensitivity to water stress. Maize (*Zea mays* L.) is considered as one of the crops with relatively high-water demand and is one of the major commodity crops grown globally. Drought can negatively and substantially affect crop yields and water availability. For example, year 2012 was one of the driest years in the United States and national crop yields decreased by 21% as compared with the previous 5-year period country average yield of 7.7 Mg ha^{-1} (Boyer et al., 2013). The impact of drought on crop productivity is heavily influenced on the timing, duration, and severity of drought and the sensitivity of crops to water stress. Shaw (1977) reported that maize during early vegetative growth stages is insensitive to water stress since the demand for the water is relatively low and the crop can adapt to water stress and may be adapted better if subsequent stress occurs. Roth et al. (2013) stated that the yield of traditional Corn Belt of the United States could be negatively influenced if maize experienced limiting soil-water conditions at the critical reproductive crop growth stages (tasseling, silking, pollination, and grain filling). In Nebraska, the reproductive stages of maize in many cases coincide with the peak air temperature, vapor pressure deficit, and in turn, crop water use (ET_c). Water stress can reduce crop yield through reduction in CO_2 assimilation, leaf area index, leaf numbers, rate of net assimilation, in turn, various plant and yield productivity components, such as number of kernels per ear and kernel size and weight, can be negatively influenced (Eck, 1986; Singh and Singh, 1995; Earl and Davis, 2003).

One of the viable alternatives to counter water stress vs. productivity challenges is the cultivation of new drought-tolerant (DT) hybrids/varieties/cultivars at adequate/optimum plant population density (PPD) coupled with effective water management strategies. Recently, new DT maize hybrids have been developed by major seed companies to optimize yield under non-optimal crop growth conditions. In general, DT hybrids can be defined as the hybrids that can sustain physiological functions during the drought with low internal water content (Levitt, 1972) or could tolerate the limiting soil-water conditions at the critical stages and achieve a higher yield than conventional hybrids under the same conditions. Among very limited studies that investigate the performance of newer DT maize hybrids under various conditions, Lindsey et al. (2015) showed that the DT hybrids had 3% to 11% greater yields than conventional hybrids. Lindsey and Thomison (2016) reported that two DT hybrids at three locations in Ohio had greater yield response as compared with two conventional maize hybrids at lower PPD. However, Cooper et al. (2014) reported 0.3 to 1.0 Mg ha^{-1} lower yields with DT maize hybrids than conventional hybrids across multiple locations in the United States, but they also reported that DT hybrids had 1.0 to 3.0 Mg ha^{-1} greater yields than conventional hybrids under very dry conditions. In a 3-yr study across more than 2,000 locations, Gaffney et al. (2015) reported 6.5% greater yields with DT maize hybrids than conventional ones under dry conditions and observed that DT hybrid yield was also 1.9% greater than conventional hybrids across 8,725 locations under favorable growing conditions. They concluded that DT hybrids provide greater yield stability under water-limited conditions with no yield penalty when the water limitations are relieved and growing conditions are favorable.

In addition to grain yield, ET_c and basal evapotranspiration (ET_b) are very important variables that can provide information in terms of hybrid's productivity response to water. ET_b is as an important variable that could provide invaluable information about the amount of ET_c that crop requires for the first increment for grain yield establishment. Researchers (Robins and Domingo, 1953; Hillel and Guron, 1973; Stewart et al., 1975; Musick and Dusek, 1980; Howell et al., 1995) reported conventional maize ET_b ranging from 147 to 300 mm. In a 3-yr research, Mohammed et al. (2019; companion article, this issue) quantified ET_b for the non-drought-tolerant (NDT) and three DT maize hybrids under three irrigation and two PPDs in semi-arid climatic conditions in North Platte and Scottsbluff, Nebraska. They reported that the ET_b values exhibited a substantial variation between the hybrids, years, locations, and PPDs. In their research, ET_b values ranged from 138 mm for DT H3 in 2010 with low PPD to 371 mm for DT H2 in 2010 with high PPD at North Platte. Generally, DT hybrids had substantially lower ET_b values than the NDT hybrid in both PPDs.

Crop yield response to water as well as related indices may exhibit variation as a function of location; soil, crop, and water management practices; irrigation method; and other factors. Therefore, locally developed yield production functions to quantify yield productivity per unit of water used are critical for developing effective irrigation management strategies under full and limited irrigation settings. This is valid not only for conventional maize hybrids, but perhaps more important for the newer DT maize hybrids for which data and information are extremely scarce. In northeast and south central Nebraska's regions, most producers and their advisors continually seek information and data as to how the new hybrids respond to water and how their productivity compares with the productivity of conventional hybrids under sub-humid and transition zone environments and different PPDs. Thus, the objectives of this research were to measure and analyze crop evapotranspiration (ET_c); develop crop production functions, measure basal evapotranspiration (ET_b), grain yield and crop water use efficiency (CWUE) response of DT maize hybrids in comparison to conventional (NDT) hybrid under different irrigation levels and PPDs in northeast and south central Nebraska's sub-humid and transition zone environments to provide data and information to the scientific community, producers and agricultural professionals in terms DT hybrid productivity performance.

MATERIALS AND METHODS

SITE DESCRIPTION

Three DT hybrids and an NDT hybrid were planted at two University of Nebraska-Lincoln research sites that varied in soil properties and climate (table 1). The sites were: South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska; and Haskell Agricultural Laboratory (HAL) near Concord in northeast Nebraska. The research was conducted in two growing seasons (2010 and 2012) at SCAL, and in three growing seasons in 2010, 2011, and 2012 at HAL. SCAL is in a transition zone between sub-humid and semi-arid climatic regions with strong winds and high evaporative demand. In general, the south-central part of Nebraska's weather is influenced by cold dry continental air masses flowing from Canada in the winter and warm and moist air from the Gulf of Mexico during summer (Irmak, 2010). The long-term average annual rainfall is 680 mm yr^{-1}, with significant within-season and inter-annual variation in distribution and magnitudes. The frost-free dates are between 24 April and 19 October (NOAA Satellite and Information Service, 2017). The soil at the site is a Hastings silt loam; fine, montmorillonitic, mesic Udic Argiustoll with 0-1% slope. The soil has a 34% vol field capacity and 14% vol permanent wilting point with the particle size of distribution of 15% sand, 65% silt, and 20% clay with 2.5% organic matter content in the topsoil (Irmak, 2015a). HAL is located near Concord, Nebraska, approximately 40 km west of Sioux City, Iowa. The site has a sub-humid climate with a shorter growing season than Clay Center. The long-term average annual rainfall is 672 mm yr^{-1} and frost-free dates are between 30 April and 10 October (NOAA Satellite and Information Service, 2017). The soil at this site is Blendon sandy loam (coarse-loamy, mixed, superactive, mesic Pachic Haplustoll) with 0 to 3% slope. The soil has a 23% vol field capacity, 10% vol permanent wilting point with particle size distribution of 28% sand, 48% silt, and 24% clay.

GENERAL CROP AND FIELD MANAGEMENT PRACTICES

Four Pioneer maize hybrids [hybrid one (H1) was a conventional NDT hybrid and the other three hybrids (H2, H3, and H4) were DT hybrids were planted at both sites in 2010, 2011, and 2012 growing seasons (table 2). The hybrids were evaluated under two PPDs of 59,300 plants ha^{-1} (low PPD) and 84,000 plants ha^{-1} (high PPD) under three irrigation treatments at each site and year. These PPDs are commonly used for rainfed and irrigated maize production, respectively, in Nebraska and Midwestern region. Three irrigation management strategies were imposed in both sites: (i) fully-irrigated treatment (FIT) that received irrigation when 35-40% of the available water holding capacity was depleted, which avoided any potential crop water stress, (ii) early cut-off treatment (ECOT) that did not receive any irrigation at or beyond blister stage, and (iii) rainfed treatment (RFT) which did not receive any irrigation throughout the growing seasons. Due to the limited amount of seed availability for these hybrids to plant in large research plots, not all hybrids were planted in all years and locations. At HAL, the DT H2 was not planted in the RFT and ECOT in 2010. In 2012, NDT H1 was included only in the ECOT. In addition, the ECOT was initially included in the experiments, but because of the distribution and high amount of precipitation this treatment was not continued until the end of the experiment at SCAL and HAL in 2010. Also, at SCAL, the ET_c for NDT H1 and DT H4 (low PPD) hybrids were not quantified in 2011 due to experimental challenges (e.g., issues with the neutron probe access tubes).

The planting, emergence, and harvest dates differed between the sites, depending on each site's growing season length (table 3). The fertilizer and herbicide application dates, amounts, and method; etc. are provided in table 3. The experimental design at SCAL was a split-split plot design with 6 sub-plots for PPDs, hybrids and irrigation treatments nested within three water levels and four replications per treatment. Each plot was 8 rows wide and 30.4 m long with a north-south planting direction on 0.76 m row spacing and 0.05 m planting depth. The field was irrigated using a 7-span linear-move sprinkler irrigation system. The HAL site had a split-split-plot design with 6 sub-plots for PPDs and hybrids, three water levels, and three replications of each treatment. Each plot was 8 rows wide and 36.5 m long with 0.76 m row spacing with 0.05 m planting depth. The field was irrigated using a subsurface drip irrigation (SDI) system with drip lines installed on a 1.5 m spacing (every-other-row) between the laterals at a depth of 0.30 m below the soil surface and 0.30 m emitter spacing along the drip tape. 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. At SCAL, there were four irrigation events in 2010 for FIT; four and two irrigation applications in 2012 for FIT, and ECOT, respectively. At HAL, there were two irrigation

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

Research Site	Coordinates, (°)	Elev. (m)	Soil Type	Field Capacity, (m^3 m^{-3})	Wilting Point, (m^3 m^{-3})	Irrigation Method	Climate
SCAL, Clay Center, Nebraska	44.6° N 98.1° W	552	Hastings silt loam	0.34	0.14	Linear Move	Transition zone between sub-humid and semi-arid
HAL, Concord, Nebraska	42.6° N 97° W	445	Blenden Sandy loam	0.23	0.10	SDI[a]	Sub-humid

[a] SDI: subsurface drip irrigation.

Table 2. Characteristic and ratings of drought-tolerant (DT) and conventional (non-drought-tolerant, NDT) maize hybrids used in this research (Source: DuPont Pioneer®).

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 as well as disease and pest pressures. All products may exhibit reduced yield under water and heat stress. Individual results may vary.

RATINGS: 9 = Outstanding; **1** = Poor; Blank = Insufficient Data.

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.

Herculex® Insect Protection technology by Dow AgroSciences and Pioneer Hi-Bred. Herculex® and the HX logo are registered trademarks of Dow AgroSciences LLC.

YieldGard®, the YieldGard Corn Borer Design and Roundup Ready® are registered trademarks used under license from Monsanto Company.

Liberty®, LibertyLink® and the Water Droplet Design are trademarks of Bayer.

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.

Table 3. General field management practices, including planting and emergence date, fertilizer and herbicide application amount and method, harvest, etc. at the South-Central Agricultural Laboratory (SCAL) near Clay Center, Neb., in 2010 and 2012 and Haskell Agricultural Laboratory (HAL) in Concord, Neb., in 2010, 2011, and 2012 growing seasons.

Site	Year	Description	Date	Type	Amount per ha	Method
SCAL	2010	Planting	18 May	-	-	Planter
		Emergence	24 May	-	-	-
		Harvest	22 Oct	-	-	Combine
		Fertilizer	19 Apr	11-52-0	112.1 Kg	Pre-plant
		Fertilizer	14 Apr	28-0-0	626.7 L	Pre-plant
		Fertilizer	18 May	10-34-0	46.7 L	Pre-plant
		Herbicide	22 May	Roundup	1.7 L	Sprayer
		Herbicide	22 May	Lexar	1.3 L	Sprayer
SCAL	2012	Planting	09 May	-	-	Planter
		Emergence	15 May	-	-	-
		Harvest	04 Oct	-	-	Combine
		Fertilizer	15 Mar	11-52-0	112.1 Kg	Pre-plant
		Fertilizer	09 May	10-34-0	46 L	Pre-plant
		Fertilizer	06 July	32-0-0	1.7 L	Side dress
		Fertilizer	01 Nov	11-52-0	112.1 Kg	Sprayer
		Herbicide	21 May	Roundup	1.7 L	Sprayer
		Herbicide	21 May	Roundup	1.7 L	Sprayer
		Herbicide	20 Jun	Lexar	1.3 L	Sprayer
HAL	2010	Planting	09 May	-	-	Planter
		Emergence	22 May	-	-	-
		Harvest	15 Oct	-	-	Combine
		Fertilizer	19 Apr	46-0-0	246 Kg	Pre-plant
		Fertilizer	25 Jun	34-0-0	78.4	Side dress
		Herbicide	Roundup	1.97 L	-	Sprayer
HAL	2011	Planting	10 May	-	-	Planter
		Emergence	24 May	-	-	-
		Harvest	20 Oct	-	-	Combine
		Fertilizer	14 Apr	46-0-0	258 Kg	Pre-plant
		Fertilizer	10 May	10-34-0	11.2 Kg	Pre-plant
		Herbicide	02 May	Valor	0.14 L	Sprayer
HAL	2012	Planting	01 May	-	-	Planter
		Emergence	14 May	-	-	-
		Harvest	21 Sep	-	-	Combine
		Fertilizer	05 May	Urea	269 Kg	Pre-plant
		Herbicide	23 Mar	Lime	4100 Kg	Sprayer
		Herbicide	01 May	Aztec	0.4 L	Sprayer
		Herbicide	30 May	Glyphosate	2.11 L	Sprayer
		Herbicide	30 May	Atrazine	1.17 Kg	Sprayer

events in 2010 for FIT; fourteen and five in 2011 for FIT and ECOT, respectively; and thirty and seventeen in 2012 for FIT and ECOT, respectively. The number of irrigation applications at HAL is greater than those at SCAL, because irrigation was applied more frequently with smaller amounts with SDI at HAL. The increased number of irrigation events in 2012 was due to extreme dry and hot growing season conditions. 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, CWUE, and Statistical Analyses

Soil-water status was measured using neutron attenuation probe (Model 4302, Troxler Electronics Laboratories, Inc., Research Triangle Park, N.C.). Neutron probe access tubes were installed on the plant row between two healthy maize plants in each treatment after emergence and readings were taken on a weekly basis from 0.30, 0.60, 0.90, and 1.20 m soil depths. Irrigations were triggered when the soil-water was depleted by approximately 35% to 40% of the water holding capacity by calculating the average of the top two soil layer's (0.30 and 0.60 m) soil-water readings reached about 23% to 24% vol water content before the tassel stage, and the average of top three soil layers' (0.30, 0.60, and 0.90 m) readings were used after the tasselling stage (Irmak et al., 2010). Crop ET (ET_c) was calculated using a soil-water balance equation for each irrigation treatment under the two PPDs at each site based on the procedures outlined in Irmak (2015a, b). In addition to ET_c, the ET_b was used to assess the performance of the hybrids in terms of their initial stage water requirements before grain production begins in different irrigation levels, PPDs, years, and locations. ET_b is an important variable that can be used to estimate the amount of water required for the first increment for grain yield establishment and it is considered to be the X-axis intercept of the ETYPF when grain yield is zero. It can be another significant assessment tool/method of performance of NDT and DT hybrids. 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.

To identify any potential significant differences in grain yield and slope of production functions for each hybrid under three irrigation treatments and two PPDs for a given year at each site, statistical analyses were carried out using GLIMMIX procedure in SAS (2003). A Fisher's protected least significant differences (LSD) test was conducted at the 5% significance level to determine which treatments were significantly different. When applicable (i.e., in cases where there were three replications of ET_c data), the statistical analyses were performed for the ET_c to identify any potential differences in ET_c between the treatments. The PROC REG procedure was used in SAS (2003) to test the significance of slopes of production functions at the 5% signifance level (except at SCAL due to the insufficient number of ET_c).

RESULTS AND DISCUSSION

WEATHER CONDITIONS IN 2010 AND 2012 AT SCAL AND IN 2010, 2011, AND 2012 AT HAL

The average monthly weather conditions and the long-term averages at SCAL and HAL are presented in tables 4 and 5, respectively, as measured by the High Plains Regional Climate Center (HPRCC, http://www.hprcc.unl.edu/) automatic weather station network. In general, the 2010 growing season was cooler and wetter than 2012 at SCAL. Seasonal average temperatures of April through October were similar in both years (table 4). Although the seasonal average wind speed (U_2) during April-October period was similar in 2010 and 2012, it was greater during July-September (peak water use period) in 2010 than 2012. These high winds occurred during the critical stages associated with maize silking and grain-fill stages and led to increases in ET_c in 2010 as compared with 2012 (table 6). The seasonal average relative humidity (RH) in 2010 was 11.3% greater than in 2012. Seasonal precipitation was less in 2012 than in 2010 (figs. 1a, 1b). A total of 594 mm precipitation occurred during the 2010 growing season, which reduced the irrigation events to four events for FIT. In 2012 season, the total precipitation was 371 mm, which was 60% less than in 2010. At HAL, seasonal average air temperatures were warmer in 2012 than in 2010 and 2011 by 5% and 8%, respectively. The warmer temperatures in 2012 growing season stimulated the maturity and harvest in September as compared with 2010 and 2011 growing seasons (visual observations), which occurred in October (table 5). Seasonal average U_2 was similar for all three growing seasons (4.2 m s^{-1}) as well as the long-term average. Seasonal average RH was higher in 2010 and 2011 than in 2012 by 17%. Precipitation was substantially higher in 2010 than in 2011 and 2012 (figs. 1c, 1d). A total of 962 mm precipitation occurred during the 2010 growing season, which was 199 and 564 mm higher than the amounts occurred in 2011 and 2012 seasons, respectively.

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

Seasonal ET_c quantified from emergence to harvest along with maize yield under two PPDs and three irrigation treatments (FIT, ECOT, and RFT) for 2010, 2011, and 2012 are presented in tables 6 and 7. At SCAL, each grain yield is an average of four replications and each ET_c value was obtained from one replication that associated with a given treatment (table 6). At HAL, each grain yield is an

Table 4. Weather conditions during 2010 and 2012 growing seasons and long-term average values at the South-Central Agricultural Laboratory (SCAL) site, Clay Center, 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	19.5	4.9	12.2	4.8	16.4	65.1	69.4
	May	20.9	8.5	14.7	4.6	17.9	71.3	115.3
	June	29.0	16.0	22.5	3.7	22.4	73.9	205.8
	July	29.7	18.4	24.1	3.1	21.9	78.9	56.1
	August	31.1	17.1	24.1	3.2	21.5	73.7	88.6
	September	26.0	10.5	18.2	3.3	15.3	73.4	55.1
	October	21.8	3.5	12.6	3.5	13.5	57.5	4.3
	Average	**25.4**	**11.3**	**18.3**	**3.7**	**18.4**	**70.5**	**594**[e]
2012	April	20.5	5.0	12.7	4.5	17.1	64.6	43.9
	May	26.4	11.0	18.7	4.8	21.4	60.0	115.1
	June	30.4	15.9	23.1	4.2	24.2	66.1	73.7
	July	33.4	18.4	25.9	2.7	25.8	65.4	47.2
	August	29.4	14.4	21.9	2.8	21.0	67.6	45.5
	September	27.3	8.2	17.8	2.7	17.4	52.5	13.7
	October	17.2	1.5	9.3	4.3	11.3	61.3	32.8
	Average	**26.4**	**10.6**	**18.5**	**3.7**	**19.7**	**62.5**	**371**[e]
1983–2009 average	April	17.0	2.7	9.9	4.7	16.8	65.9	68
	May	22.0	9.6	16.2	4.2	19.5	69.9	111
	June	28.3	14.9	21.6	3.6	22.4	70.3	106
	July	30.5	17.5	24.0	2.9	22.4	73.4	88
	August	29.3	16.5	22.9	2.7	19.4	75.3	93
	September	25.3	10.7	18.0	3.1	15.8	69.3	71
	October	18.1	3.7	10.9	3.5	11.0	68.2	51
	Average	**24.4**	**10.8**	**17.6**	**3.5**	**18.2**	**70.3**	**588**[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] Rs = incoming shortwave radiation.
[d] RH = relative humidity.
[e] Seasonal total rainfall.

Table 5. Weather conditions during 2010, 2011, and 2012 growing seasons and long-term average values at the Haskell Agricultural Laboratory (HAL) site, Concord, 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	18.7	4.5	11.6	5.4	16.7	59.2	55.1
	May	21.1	7.5	14.3	5.1	19.2	61.2	58.7
	June	27.0	14.9	21.0	3.9	21.3	72.1	325.6
	July	28.4	17.1	22.7	3.4	21.7	80.3	278.4
	August	28.5	16.8	22.6	3.5	20.2	79.4	129.4
	September	23.1	9.8	16.4	3.9	15.0	75.7	77.5
	October	19.5	3.5	11.5	4.1	13.0	59.3	37.8
	Average	**23.8**	**10.6**	**17.2**	**4.2**	**18.2**	**69.6**	**962**[e]
2011	April	13.4	1.6	7.5	5.9	14.1	71.7	152.1
	May	20.5	8.2	14.4	5.6	19.6	65.5	212.3
	June	26.0	14.7	20.3	4.9	21.0	71.2	138.7
	July	30.5	20.2	25.4	3.2	21.9	80.0	58.7
	August	27.7	16.3	22.0	2.9	19.4	79.6	143.0
	September	22.1	8.1	15.1	2.9	16.2	68.2	18.8
	October	19.1	4.1	11.6	4.2	11.9	58.6	39.9
	Average	**22.8**	**10.5**	**16.6**	**4.2**	**17.7**	**70.7**	**763**[e]
2012	April	19.0	4.6	11.8	5.4	18.0	57.2	114.1
	May	25.3	10.6	17.9	5.5	21.4	58.7	157.5
	June	29.0	16.0	22.5	4.6	22.9	62.1	35.6
	July	33.9	19.2	26.6	3.1	24.8	60.2	0.5
	August	29.6	14.3	21.9	3.3	20.7	63.9	42.2
	September	26.5	8.4	17.5	3.2	17.5	46.2	15.0
	October	14.9	1.5	8.2	4.3	10.0	61.4	33.1
	Average	**25.5**	**10.7**	**18.1**	**4.2**	**19.3**	**58.5**	**398**[e]
1983-2009 average	April	15.4	2.1	8.8	5.2	16.2	64.4	78.8
	May	21.8	8.7	15.3	4.9	19.3	65.5	94.3
	June	27.0	14.6	20.8	4.2	21.4	67.9	104.3
	July	29.0	16.6	22.8	3.3	22.1	75.0	66.5
	August	27.8	15.4	21.6	3.2	19.0	78.1	74.8
	September	16.4	3.2	9.8	4.0	10.2	68.4	55.4
	October	23.7	9.9	16.8	3.6	14.9	71.2	71.8
	Average	**23.0**	**10.1**	**16.6**	**4.1**	**17.6**	**70.1**	**545**[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] Rs = incoming shortwave radiation.
[d] RH = relative humidity.
[e] Seasonal total rainfall.

average of three replications and each ET_c value is an average of two replications in 2011 and three replications in 2010 and 2012 (table 7). The ET_c values varied between the NDT and DT hybrids under two PPDs and three irrigation treatments across two locations. The ET_c statistical analysis was not included in the 2010 and 2012 at SCAL due to the fact that ET_c values were obtained from one replication of each treatment. There were statistically significant differences (P<0.05) between the ET_c values for some hybrids across the three irrigation treatments at HAL; and in most cases, there were significant differences between the hybrids in FIT and RFT in the three growing seasons (table 7). In general, grain yields varied between the irrigation and PPD treatments for the same hybrids and between different hybrids. The PPD influence on the grain yield of all hybrids was mostly statistically negligible; however, there were differences in grain yield response of a given hybrid to the irrigation treatment. Thus, inter-annual variability existed in grain yield response to treatments for the same maize hybrid in the same location and between the locations. High PPD under FIT and ECOT usually resulted in the highest grain yield. In most cases, DT H3 resulted in the highest yield and usually had lower ET_c than other hybrids, especially at SCAL, under both PPDs in 2010 and irrigation treatments in 2012. However, at HAL, the grain yield results were not as consistent between the hybrids as those observed at SCAL. DT H4 had the highest grain yield at HAL with lower ET_c, in most cases. Inconsistent grain yield response to treatments between the two locations may be attributed to the climate differences, differences in soil type, different irrigation methods, planting date, and potentially due to the differences in other management practices and site characteristics. Grain yields were higher at SCAL than HAL in 2012 and these differences may be related to soil type's impact during extreme dry year [i.e., greater soil-water holding capacity at SCAL (~60 mm/0.30 m soil layer) than HAL (~15 mm/0.30 m soil layer)]. ET_c values were higher in 2010 than 2011 and 2012 for all hybrids due to above average precipitation (tables 4 and 5) that resulted in higher evaporative losses (evaporation and transpiration). Higher precipitation amounts in 2010 also resulted in smaller differences between the FIT and RFT (tables 6 and 7).

At SCAL, the ET_c values, including the RFT and FIT in both PPDs, ranged from 373 to 563 mm in 2010 and from 359 to 490 mm in 2012. In 2010, the lowest ET_c of 373 and 525 mm were recorded for DT H2 (low PPD) and DT H3 (high PPD) that associated with the grain yield of 8.6 and 11.2 Mg ha^{-1} in RFT and FIT, respectively. In 2012, the lowest ET_c of 359, 415, and 448 mm were recorded for 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 South-Central Agricultural Laboratory (SCAL) site, Clay Center, Neb., during 2010 and 2012 growing seasons.[a]

Year	Treatment	H[b]	Population	Rainfall (mm)	Irrigation (mm)	Grain Yield[c] (Mg ha^{-1})	ET_c[c] (mm)	CWUE (kg m^{-3})
2010	RFT[d]	1	high	483	0	5.8 f	-	-
			low	483	0	8.2 de	-	-
		2	high	483	0	7.0 e	458	1.52
			low	483	0	8.6 dc	373	2.30
		3	high	483	0	7.7 de	399	1.91
			low	483	0	8.6 dc	377	2.27
		4	high	483	0	8.0 de	450	1.78
			low	483	0	8.0 de	-	-
	FIT	1	high	483	152	10.4 ab	-	-
			low	483	152	9.5 dc	-	-
		2	high	483	152	10.9 ab	536	2.04
			low	483	152	9.2 dc	535	1.72
		3	high	483	152	11.2 a	525	2.13
			low	483	152	10.4 abe	563	1.84
		4	high	483	152	11.1 ab	539	2.05
			low	483	152	10.3 bce	531	1.94
2012	RFT	1	high	219	0	5.6 j	382	1.47
			low	219	0	6.4ij	382	1.69
		2	high	219	0	6.6 hi	364	1.82
			low	219	0	8.1 g	360	2.24
		3	high	219	0	6.9 ghi	375	1.86
			low	219	0	7.4 gh	359	2.08
		4	high	219	0	6.1 ij	380	1.63
			low	219	0	7.4 gh	387	1.91
	ECOT[e]	1	high	219	67	10.9 def	440	2.49
			low	219	67	10.7 def	419	2.57
		2	high	219	67	9.8 ef	441	2.24
			low	219	67	9.5 f	425	2.10
		3	high	219	67	10.7 def	415	2.60
			low	219	67	10.3 def	455	2.26
		4	high	219	67	11.6 cd	431	2.70
			low	219	67	11.3 de	434	2.61
	FIT[f]	1	high	219	148	14.0 ab	477	2.95
			low	219	148	13.4 bc	450	2.97
		2	high	219	148	15.9 a	473	3.36
			low	219	148	14.6 ab	448	3.26
		3	high	219	148	16.3 a	471	3.46
			low	219	148	15.5 ab	470	3.29
		4	high	219	148	15.1 ab	475	3.18
			low	219	148	14.2 ab	490	2.90

[a] High PPD (84,000 plans ha^{-1}); Low PPD (59,300 plants ha^{-1}). Each grain yield is an average of four replications and each ET_c value was obtained from one replications.
[b] Hybrid type.
[c] Values within a column followed by the same letter are not statistically different (P>0.05) for the given year.
[d] Rainfed treatment.
[e] Early cut-off treatment.
[f] Fully-irrigated treatment.

H3 (low PPD), DT H3 (high PPD), and DT H2 (low PPD) that associated with the grain yield of 7.4, 10.7, and 14.6 Mg ha^{-1} at RFT, ECOT, and FIT, respectively.

At HAL, ET_c values were generally lower than those observed at SCAL, which may be attributed to the weather variable differences between the two locations. For example, the average air temperature was higher at SCAL than HAL. The ET_c ranged from 495 to 523 mm in 2010, from 355 to 536 mm in 2011 and from 220 to 614 mm in 2012, including the RFT, ECOT, and FIT in both PPDs. In 2011, the ET_c values of RFT were significantly lower than ET_c of ECOT and FIT, except for the DT H4 (low PPD) at ECOT. In 2012, there were significant differences (P<0.05) among the ET_c values for all hybrids across the three irrigation treatments. These results indicated that the lowest ET_c were recorded for the DT hybrids that associated with the highest grain yield in most cases in a comparison with the NDT hybrid in all treatments, years at both locations. The effect of PPD on ET_c was negligible with in the same hybrid and irrigation treatment. These results suggested that, compared to the NDT hybrid, the DT hybrids showed less ET_c with less yield reduction under RFT and ECOT, especially for DT H3 and H4 as compared with NDT H1.

EVAPOTRANSPIRATION-YIELD PRODUCTION FUNCTIONS (ETYPF) FOR INDIVIDUAL HYBRIDS AND POOLED DATA

The ETYPFs for individual hybrids are presented in figures 2a-2d for SCAL for 2010 and 2012 and in figures 3a-3f for HAL for 2010, 2011, and 2012. At SCAL, due to some experimental challenges in some of the years, locations, and replications, the following replication data points were not included in the ETYPF regression analyses:

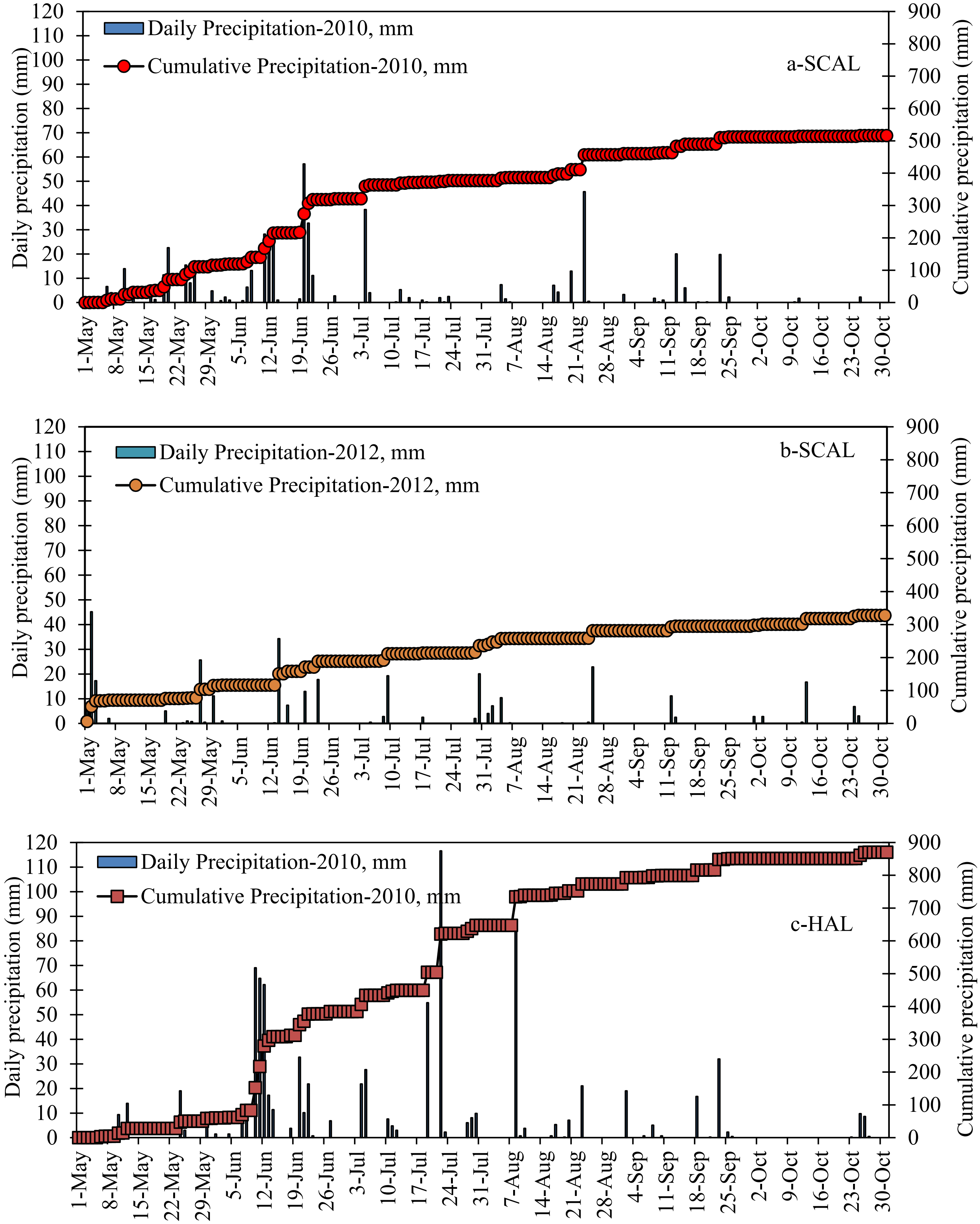


Figure 1. Daily and cumulative precipitation: (a) 2010-SCAL, (b) 2012-SCAL, (c) 2010-HAL, (d) 2011-HAL, and (e) 2012-HAL.

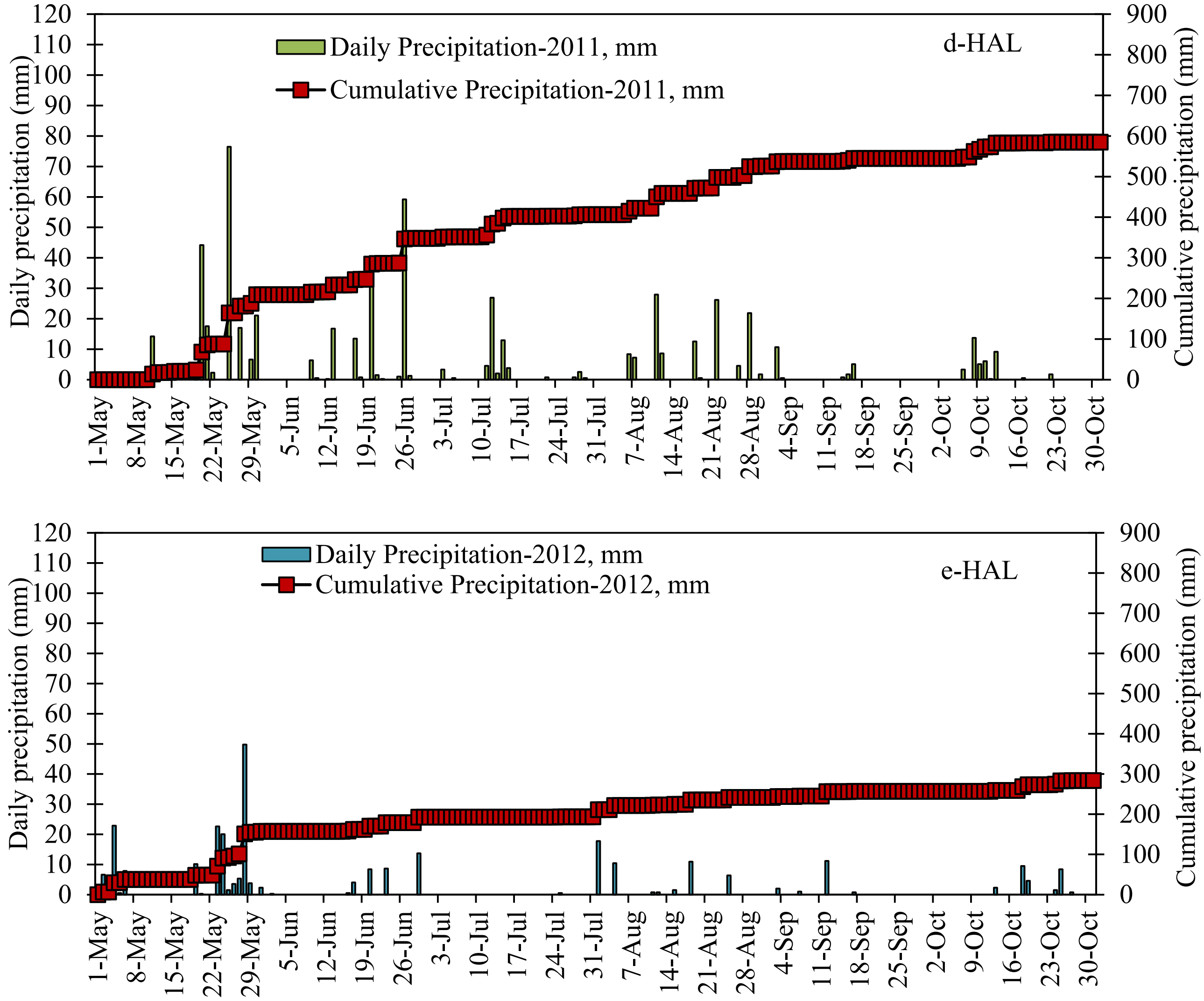


Figure 1 (continued). Daily and cumulative precipitation: (a) 2010-SCAL, (b) 2012-SCAL, (c) 2010-HAL, (d) 2011-HAL, and (e) 2012-HAL.

2010-DT H2 (low PPD) in FIT, ECOT, and RFT; 2011-DT H3 (low PPD) in ECOT and RFT; 2011-DT H4 (low PPD) in FIT, ECOT and RFT; 2011-NDT H1 (high PPD) in RFT; 2011-DT H2 (high PPD) in RFT; 2011-DT H4 (high PPD) in RFT. At HAL, the ET_c values were from two or three replications of each treatment, which were correlated to the grain yield values from the same replications from which values were obtained. Two data points (for NDT H1 at low PPD at HAL in 2011 with 353 mm of ET_c and 0.5 Mg ha^{-1} grain yield; and for DT H4 at both low and high PPDs at SCAL in 2010 in RFT with 0.0 mm ET_c and 8.0 Mg ha^{-1} of grain yield) were excluded from ETYPFs due to experimental challenges. Generally, the ETYPF response for individual hybrids at both locations exhibited a strong and linear response with a positive slope in all cases. All pooled ETYPF slopes were significant ($P<0.05$) (table 8). The slopes of the production functions exhibited inter-annual variation between the hybrids and for the same hybrids and location for both high and low PPDs. Generally, the slope values in this case indicate the amount of potential yield production per each unit of used ET_c. The intercept value, in this case, refers to the amount of ET_c required for production of the first increment of grain yield establishment (Irmak, 2015a, 2015b). The statistical analysis for an individual regression equation did not show any statistical significance ($P>0.05$) of the slopes in 2010 at HAL (table 9). However, all maize hybrids had significant ($P<0.05$) yield response per unit of ET_c in 2011 and 2012 at HAL, except NDT H1 under low PPD in 2011. This statistical analysis was not included at SCAL due to the aforementioned reasons. In this research, the intercept values of the ETYPFs also exhibited inter-annual variations between the hybrids and locations as well as PPDs and between the locations for the same hybrid within the same year (intra-annual variation). Also, in some cases, some hybrids resulted in greater grain yield with less ET_c as compared with the other hybrids. In both years, the ETYPFs had greater slopes with high PPDs than the low PPD. The two-year average (average of all hybrids) slopes for low and high PPDs were 0.045 and 0.068 Mg ha^{-1} mm^{-1},

Table 7. 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 Haskell Agricultural Laboratory (HAL) site, Concord, Neb., during 2010, 2011, and 2012 growing seasons.[a]

Year	Treatment	H[b]	Population	Rainfall (mm)	Irrigation (mm)	Grain Yield[c] (Mg ha^{-1})	ET_c[c] (mm)	CWUE (kg m^{-3})
2010	RFT[d]	1	high	618	0	10.9 b	514 abc	2.13
			low	618	0	12.8 ab	519 abc	2.48
		2	high	618	0	-	-	-
			low	618	0	-	-	-
		3	high	618	0	11.4 ab	501 c	2.28
			low	618	0	11.2 ab	503 c	2.22
		4	high	618	0	12.9 a	497 c	2.61
			low	618	0	12.9 a	521 a	2.49
	ECOT[e]	1	high	618	0	12.3 ab	499 c	2.46
			low	618	0	11.7 ab	506 abc	2.30
		2	high	618	0	-	-	-
			low	618	0	-	-	-
		3	high	618	0	11.2 ab	495 c	2.26
			low	618	0	11.7 ab	504 bc	2.33
		4	high	618	0	12.7 ab	511 abc	2.48
			low	618	0	11.7 ab	504 bc	2.33
	FIT[f]	1	high	618	30	12.8 ab	520 ab	2.47
			low	618	30	12.4 ab	523 a	2.37
		2	high	618	30	11.9 ab	510 abc	2.33
			low	618	30	12.7 ab	508 abc	2.50
		3	high	618	30	11.3 ab	511 abc	2.22
			low	618	30	12.6 ab	514 abc	2.44
		4	high	618	30	13.0 a	516 abc	2.52
			low	618	30	12.6 ab	521 a	2.43
2011	RFT	1	high	190	0	10.7 a	396 fg	2.71
			low	190	0	6.5 bc	386 fg	1.69
		2	high	190	0	7.4 abc	387 fg	1.90
			low	190	0	11.1 a	369 gh	3.01
		3	high	190	0	9.4 ab	391 fg	2.41
			low	190	0	11.1 a	389 fg	2.63
		4	high	190	0	6.2 c	355 h	1.76
			low	190	0	11.1 a	370 gh	3.01
	ECOT	1	high	190	76	10.3 a	478 bcd	2.16
			low	190	76	12.3 a	482 abcd	2.55
		2	high	190	76	11.6 a	439 ed	2.64
			low	190	76	12.2 a	439 ed	2.75
		3	high	190	76	12.1 a	454 d	2.67
			low	190	76	12.3 a	458 cd	2.61
		4	high	190	76	12.3 a	446 d	2.76
			low	190	76	13.4 a	409 ef	3.27
	FIT	1	high	190	190	12.7 a	514 ab	2.47
			low	190	190	12.7 a	536 a	2.36
		2	high	190	190	12.5 a	494 ab	2.53
			low	190	190	12.7 a	494 abc	2.33
		3	high	190	190	12.7 a	504 ab	2.51
			low	190	190	12.0 a	515 ab	2.33
		4	high	190	190	13.0 a	495 ab	2.62
			low	190	190	11.8 a	494 abc	2.39

[a] High PPD (84,000 plans ha^{-1}); Low PPD (59,300 plants ha^{-1}). Each grain yield is an average of three 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 (P>0.05) for the given year.

[d] Rainfed treatment.

[e] Early cut-off treatment.

[f] Fully-irrigated treatment.

respectively, with high PPD having 34% higher slope. At SCAL, in 2010, slopes ranged between 0.004 and 0.051 Mg ha^{-1} mm^{-1}, including both PPDs (figs. 2a, 2b). All of the highest slope values were found under the high PPD treatments in 2010 and this might be attributed to the wet growing season conditions, which may have provided more favorable condition for the high PPD (figs. 2a, 2b) as compared with drier years. The greatest slope of 0.051 Mg ha^{-1} mm^{-1} was recorded for the DT H2 (high PPD) (fig. 2b).

In drier conditions in 2012, the slopes of the ETYPFs were mostly higher than those in 2010 and ranged between 0.057 and 0.102 Mg ha^{-1} mm^{-1} for the high PPD (fig. 2c). The highest slope of 0.102 Mg ha^{-1} mm^{-1} was observed for the NDT H1 (low PPD) (fig. 2c). At HAL, in 2010, the highest slope of 0.057 Mg ha^{-1} mm^{-1} was observed for the DT H3 (low PPD) (fig. 3a). In 2011, the slopes (including all hybrids at PPDs) were 19% lower than those in 2010

Table 7 (continued). 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 Haskell Agricultural Laboratory (HAL) site, Concord, Neb., during 2010, 2011, and 2012 growing seasons.[a]

Year	Treatment	H[b]	Population	Rainfall (mm)	Irrigation (mm)	Grain Yield[c] (Mg ha^{-1})	ET_c[c] (mm)	CWUE (kg m^{-3})
2012	RFT[d]	1	high	180	0	0.0 f	227 d	0.00
			low	180	0	3.6 b	220 d	1.64
		2	high	180	0	0.6 efd	220 d	0.28
			low	180	0	1.9 bc	227 d	0.82
		3	high	180	0	0.6 ef	224 d	0.28
			low	180	0	1.8 bcd	230 d	0.78
		4	high	180	0	1.1 cefd	226 d	0.48
			low	180	0	1.4 bced	234 d	0.61
	ECOT[e]	1	high	180	227	-	-	-
			low	180	227	-	-	-
		2	high	180	227	13.3 a	436 c	3.05
			low	180	227	12.9 a	441 c	2.92
		3	high	180	227	11.5 a	433 c	2.66
			low	180	227	12.2 a	455 c	2.68
		4	high	180	227	12.0 a	444 c	2.69
			low	180	227	11.7 a	441 c	2.64
	FIT[f]	1	high	180	440	13.9 a	602 ab	2.31
			low	180	440	13.7 a	614 a	2.23
		2	high	180	440	15.3 a	590 ab	2.59
			low	180	440	14.2 a	591 ab	2.39
		3	high	180	440	14.5 a	607 ab	2.39
			low	180	440	14.4 a	610 ab	2.36
		4	high	180	440	14.1 a	588 ab	2.39
			low	180	440	13.9 a	562 b	2.48

[a] High PPD (84,000 plans ha^{-1}); Low PPD (59,300 plants ha^{-1}). Each grain yield is an average of three 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 (*P*>0.05) for the given year.
[d] Rainfed treatment.
[e] Early cut-off treatment.
[f] Fully-irrigated treatment.

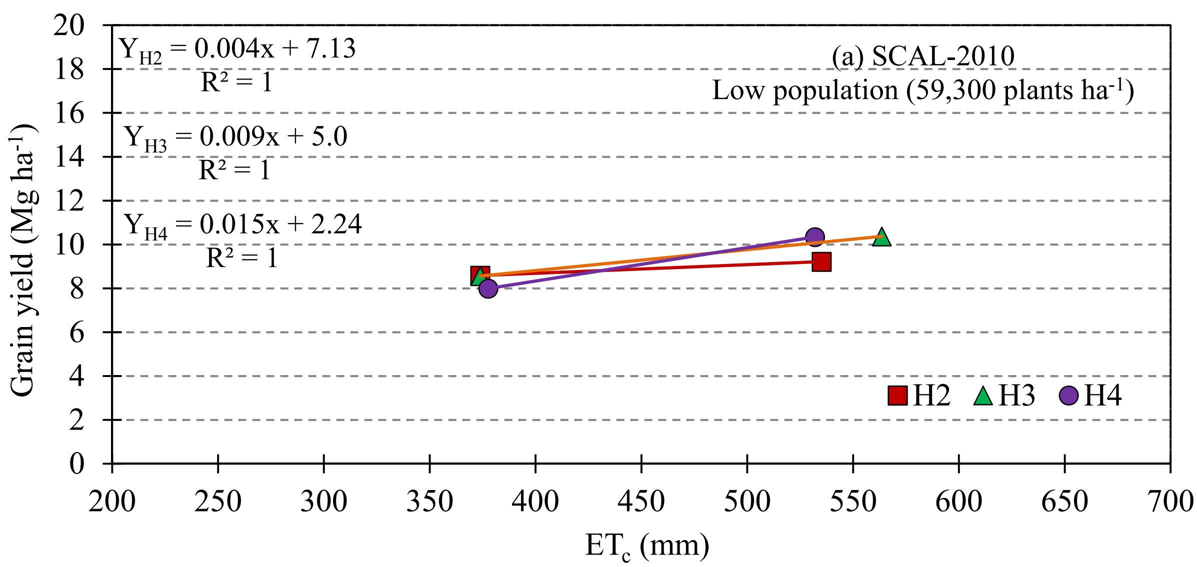


Figure 2. Relationship between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: (a) low population-2010, (b) high population-2010, (c) low population-2012, and (d) high population-2012 at the South Central Agricultural Laboratory (SCAL) site near Clay Center, Neb. H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) maize 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.

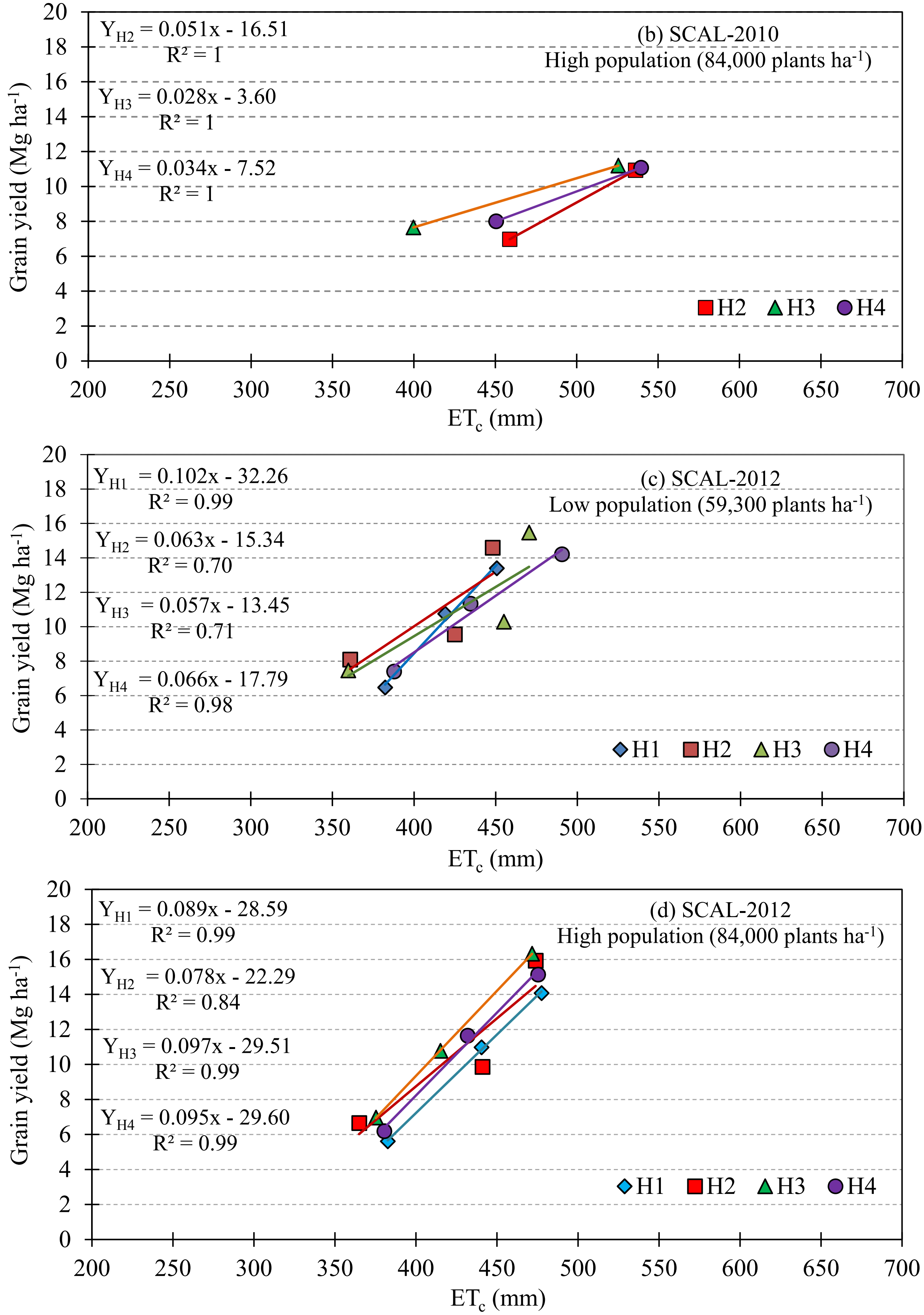


Figure 2 (continued). Relationship between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: (a) low population-2010, (b) high population-2010, (c) low population-2012 and (d) high population-2012 at the South Central Agricultural Laboratory (SCAL) site near Clay Center, Neb. H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) maize 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.

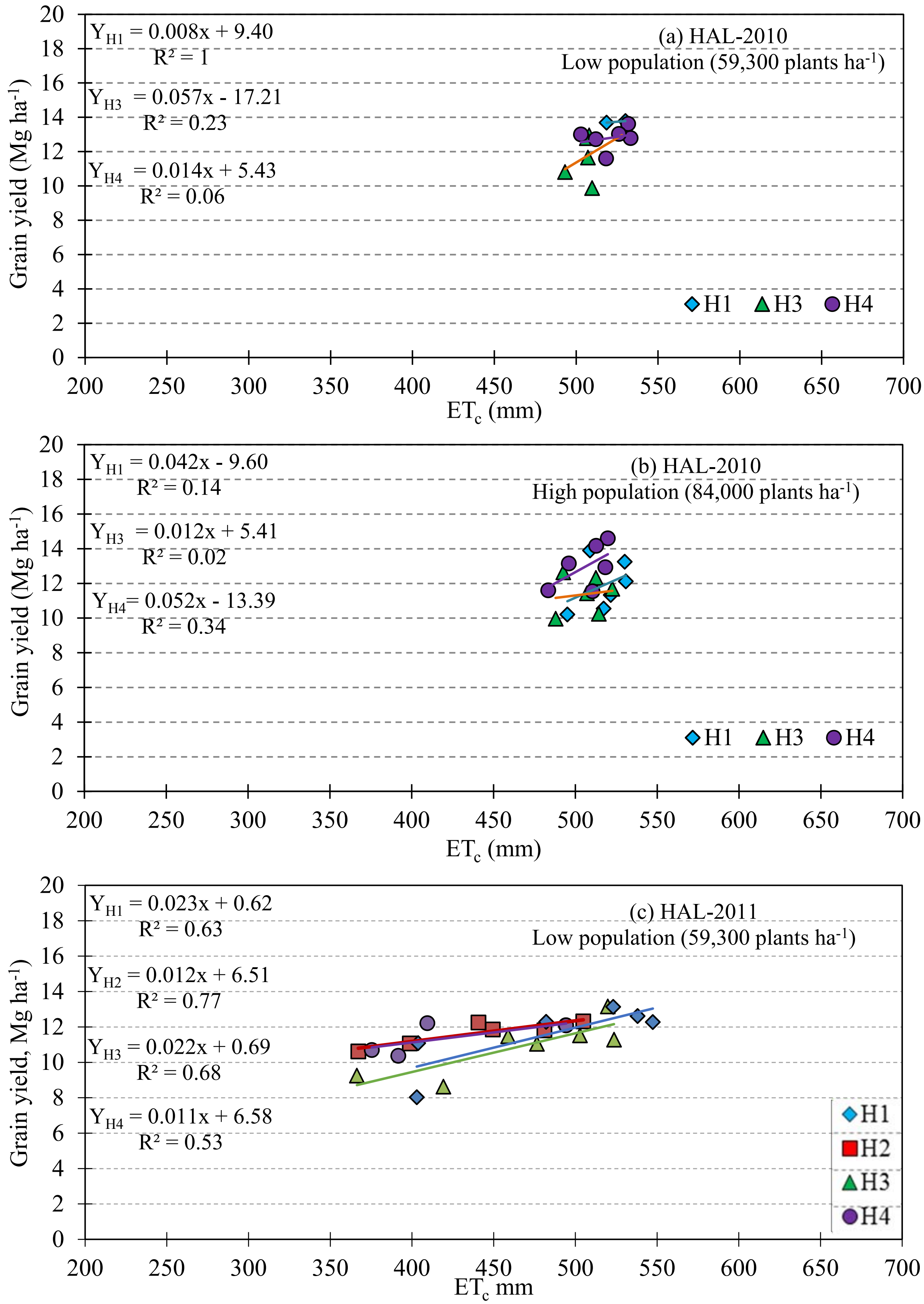


Figure 3. Relationship between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: (a) low population-2010, (b) high population-2010, (c) low population-2011, (d) high population-2011, (e) low population-2012, and (f) high population-2012 at the Haskell Agricultural Laboratory (HAL) site at Concord, Neb. H1: non-drought-tolerant (NDT); H2, H3, and H4: drought-tolerant (DT) maize 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.

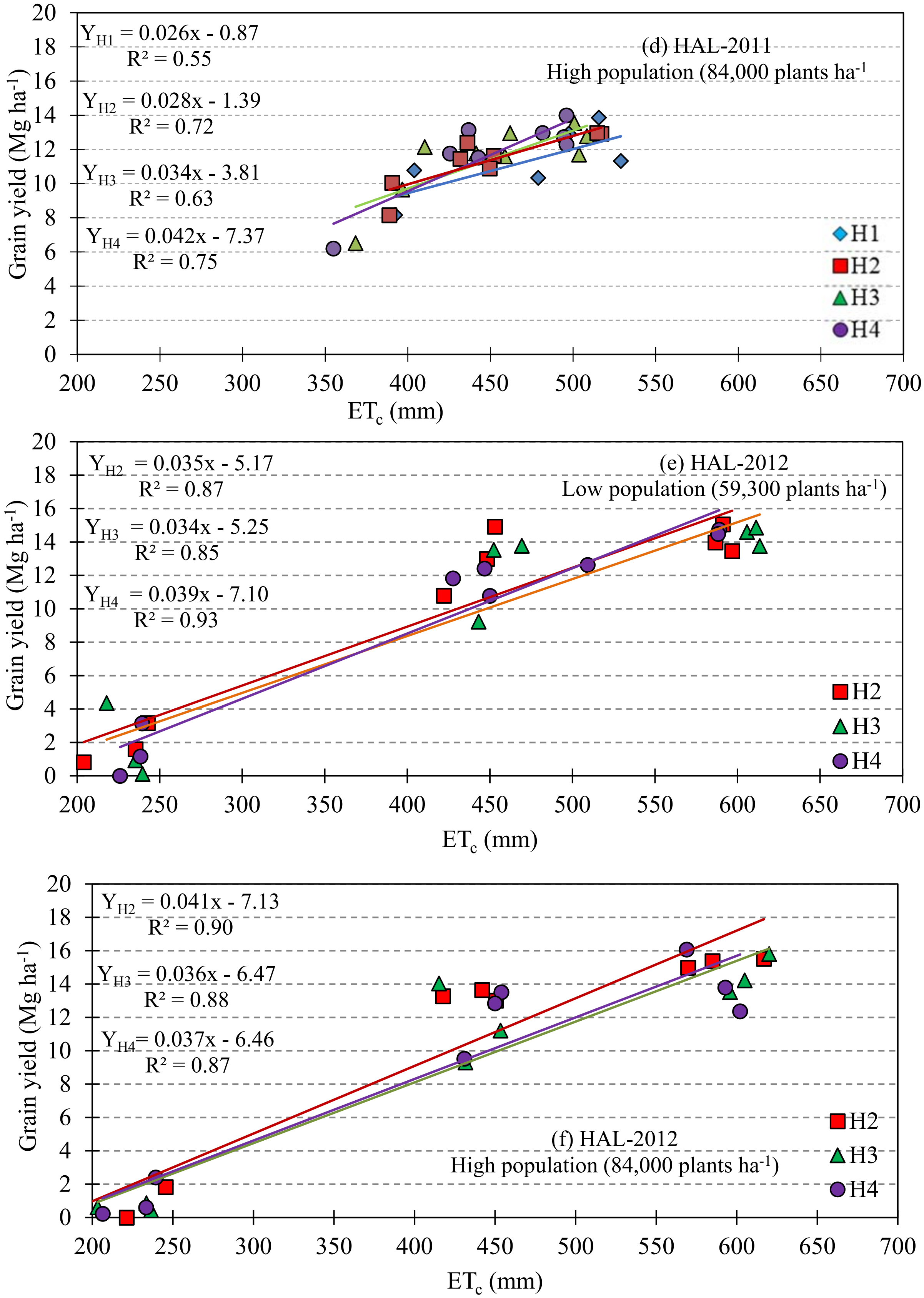


Figure 3 (continued). Relationship between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: (a) low population-2010, (b) high population-2010, (c) low population-2011, (d) high population-2011, (e) low population-2012 and (f) high population-2012 at the Haskell Agricultural Laboratory (HAL) site at Concord, Neb. H1: non-drought-tolerant (NDT); H2, H3 and H4: drought-tolerant (DT) maize 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.

Table 8. Statistical analyses of the evapotranspiration-yield production functions (ETYPF) for the pooled data for all treatments (irrigation and PPDs) at the South-Central Agricultural Laboratory (SCAL) and Haskell Agricultural Laboratory (HAL) in 2010, 2011, and 2012 growing seasons.

Hybrid	Slope	P-Value	Standard Error	95% Confidence Limits	
1	0.037	<0.0001[a]	0.00290	0.03076	0.04241
2	0.034	<0.0001[a]	0.00294	0.02778	0.03964
3	0.033	<0.0001[a]	0.00258	0.02826	0.03860
4	0.034	<0.0001[a]	0.00301	0.02838	0.04042

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

and ranged between 0.011 Mg ha^{-1} mm^{-1} for the DT H4 in low PPD and 0.042 Mg ha^{-1} mm^{-1} for the DT H4 in high PPD (figs. 3c and 3d). In 2012, slopes ranged between 0.034 Mg ha^{-1} mm^{-1} for the DT H3 in low PPD and 0.041 Mg ha^{-1} mm^{-1} for the DT H2 in high PPD (figs. 3e and 3f). The standard deviations (SD) in slopes for the same hybrids between the years in the low PPD category were 0.0102, 0.017, 0.018, and 0.015 Mg ha^{-1} mm^{-1}, for the NDT H1, DT H2, DT H3, and DT H4 hybrids, respectively. The hybrid performance in terms of ETYPF slope was more consistent (smaller inter-annual variation in slope for the same hybrid) with lower SD values for all hybrids in the high PPD category (the SD values were 0.011, 0.009, 0.014, and 0.007 Mg ha^{-1} mm^{-1}, for the NDT H1, DT H2, DT H3, and DT H4, respectively). When the average of the same hybrid for three years and for low PPDs was considered, the average slopes for the NDT H1, DT H2, DT H3, and DT H4 hybrids were 0.015, 0.023, 0.034, and 0.021 Mg ha^{-1} mm^{-1}, respectively, with the DT H3 hybrid having the highest slope. The NDT H1, DT H2, and DT H4 hybrids had 54%, 30%, and 36% lower slopes than the DT H3 hybrid, respectively, with low PPD. When the average of the same hybrid for three years and for high PPDs was considered, the average slopes for the NDT H1, DT H2, DT H3, and DT H4 hybrids were 0.034, 0.035, 0.027, and 0.044 Mg ha^{-1} mm^{-1}, respectively, with the DT H4 having the highest average slope. The three-year average slopes of all hybrids for low and high PPDs were 0.025 and 0.035 Mg ha^{-1} mm^{-1}, respectively, with high PPD having 29% higher slope. Generally, DT H3 and DT H4 hybrids had higher slopes than the NDT H1 and DT H2 for both PPDs. In general, DT hybrids produced more grain yield per unit of ET_c in driest year in the 2012 than in 2010 and 2011. The ETYPF slope (average of all DT hybrids) at SCAL was 47% higher than the slope observed at HAL. The DT hybrids not only performed well in the driest year in 2012, but their performance was stronger in the drier environment at SCAL than at HAL (which had higher growing season precipitation). The pooled ETYPFs (average of all three years, both PPDs, and both locations for a given hybrid; figs. 4a-e) were not similar to the ETYPFs that were developed for an individual hybrid and treatment by year.

All pooled ETYPFs resulted in strong and linear yield response to ET_c with positive slopes and negative intercepts in all cases and with high R^2 values (0.76, 0.74, 0.72, 0.68, and 0.71 for the NDT H1, DT H2, DT H3, DT H4 hybrids and pooled DT H2, DT H3, and DT H4 hybrids, respectively). The pooled ETYPFs had the slopes of 0.037, 0.034, 0.033, 0.034, and 0.034 Mg ha^{-1} mm^{-1} for the NDT H1, DT H2, DT H3, and DT H4 hybrids (figs. 4a-4d), and pooled DT H2, DT H3, and DT H4 hybrids (fig. 4e), respectively. In a companion research, Mohammed et al. (2018) evaluated several performance indices for the same NDT and DT hybrids in semi-arid locations (North Platte and Scottsbluff) of Nebraska and observed that, generally, DT hybrids performed better than the NDT hybrid, not only in dry years, but also in average and above average years. The performances of the DT hybrids were stronger in the driest year; especially with low PPD in the driest location (Scottsbluff). They also observed that 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.

Table 9. Regression analyses for the evapotranspiration-yield production functions (ETYPF) for the individual hybrids at each plant population density (PPD) and all irrigation treatments at the Haskell Agricultural Laboratory (HAL) in 2010, 2011, and 2012.

Year	Site	Hybrid	PPD	Slope	P-Value	Standard Error
2010	HAL	1	High	0.042	0.4524	0.04999
2010	HAL	3	High	0.012	0.7832	0.04007
2010	HAL	4	High	0.052	0.2227	0.03610
2010	HAL	1	Low	0.008	N/A[a]	N/A
2010	HAL	3	Low	0.057	0.3301	0.05158
2010	HAL	4	Low	0.014	0.6288	0.02705
2011	HAL	1	High	0.026	0.0912[b]	0.01164
2011	HAL	2	High	0.028	0.0077[b]	0.00721
2011	HAL	3	High	0.034	0.0104[b]	0.00975
2011	HAL	4	High	0.042	0.0053[b]	0.00995
2011	HAL	1	Low	0.023	0.0570	0.00856
2011	HAL	2	Low	0.012	0.0048[b]	0.00154
2011	HAL	3	Low	0.022	0.0214[b]	0.00663
2011	HAL	4	Low	0.011	0.1574	0.00605
2012	HAL	2	High	0.041	<0.0001[b]	0.00498
2012	HAL	3	High	0.036	0.0002[b]	0.00505
2012	HAL	4	High	0.037	0.0002[b]	0.00516
2012	HAL	2	Low	0.035	0.0002[b]	0.00504
2012	HAL	3	Low	0.034	0.0003[b]	0.00521
2012	HAL	4	Low	0.039	<0.0001[b]	0.00383

[a] Insufficient number in the treatment replications.
[b] Slope values are statistically different (α=0.05) in a given year.

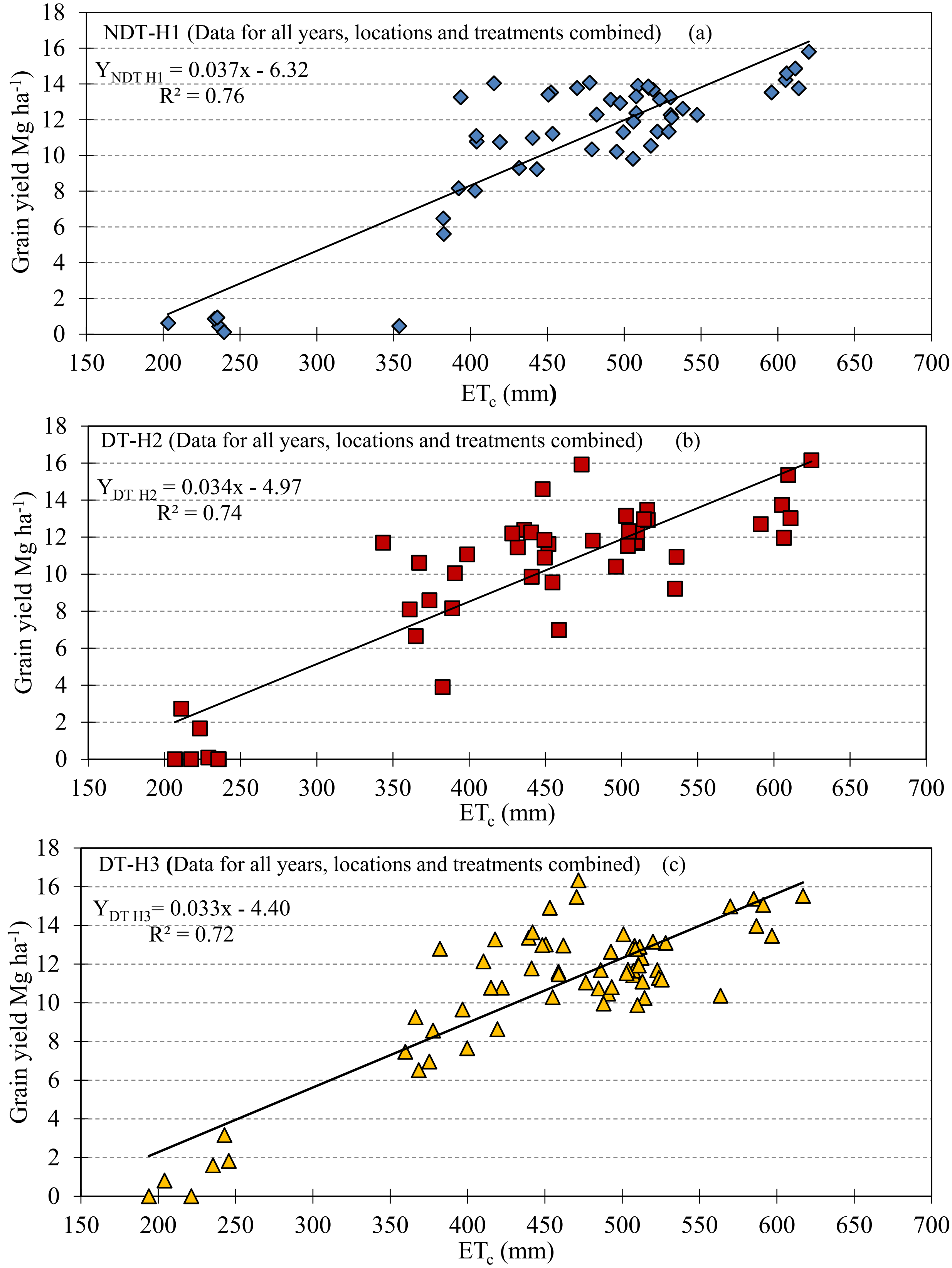
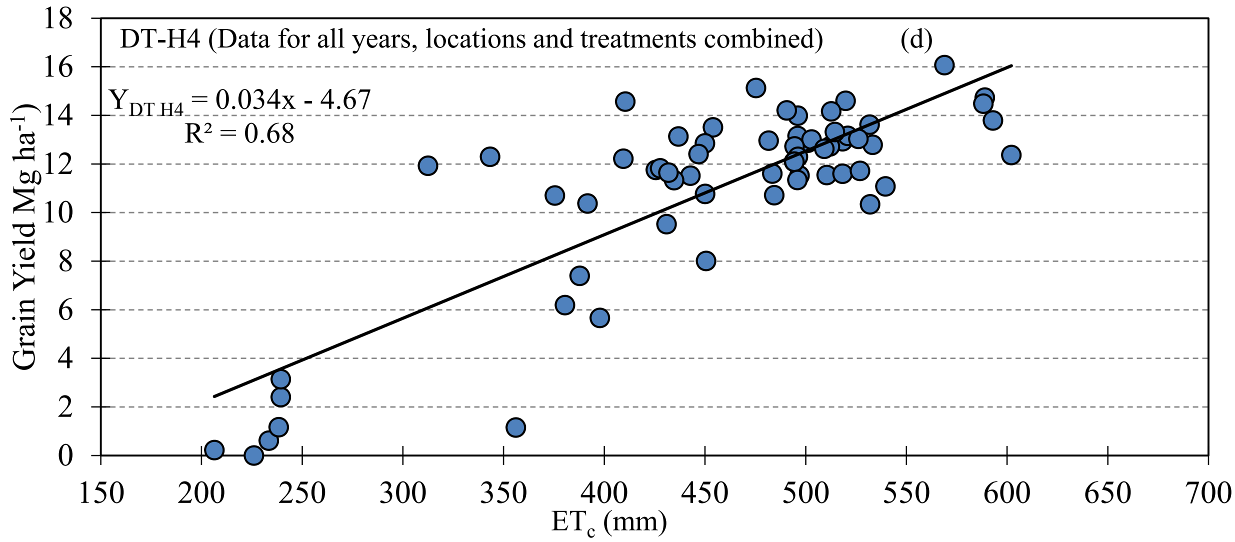


Figure 4. Relationship between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: NDT H1 (a), DT H2 (b), DT H3 (c), DT H4 (d) and all DT hybrids (H2, H3, and H4) combined (e). Data from all three years, two locations (SCAL and HAL) and all treatments are combined for each case. H1: non-drought-tolerant (NDT) and H2, H3, and H4: drought-tolerant (DT) maize hybrids. SCAL: South Central Agricultural Laboratory, Clay Center, Neb.; HAL: Haskell Agricultural Laboratory, Concord, Neb.



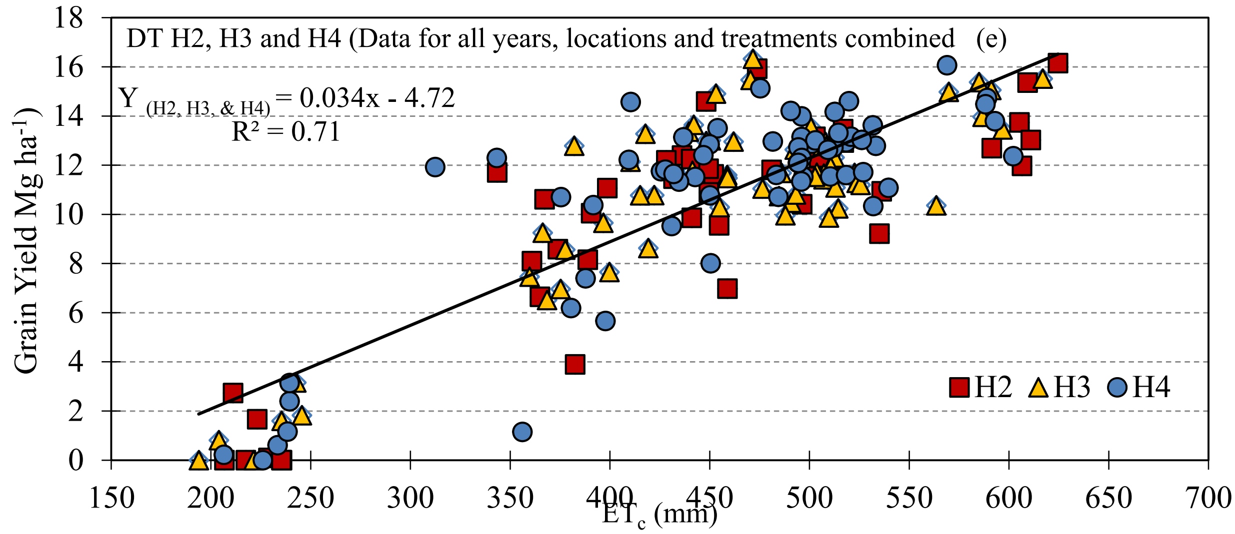


Figure 4 (continued). Relationship between grain yield and crop evapotranspiration (ET_c) for individual maize hybrids: NDT H1 (a), DT H2 (b), DT H3 (c), DT H4 (d) and all DT hybrids (H2, H3, and H4) combined (e). Data from all three years, two locations (SCAL and HAL) and all treatments are combined for each case. H1: non-drought-tolerant (NDT) and H2, H3, and H4: drought-tolerant (DT) maize hybrids. SCAL: South Central Agricultural Laboratory, Clay Center, Neb.; HAL: Haskell Agricultural Laboratory, Concord, Neb.

BASAL EVAPOTRANSPIRATION (ET_b)

The ET_b values exhibited inter-annual variation for the same hybrid between the irrigation levels, PPDs, and locations and they exhibited inner-annual variations between the hybrids and treatments (table 10). At SCAL, ET_b values ranged from 129 mm for the DT H3 hybrid with high PPD in 2010 to 324 mm for the DT H1 with high PPD in the 2010. Drier conditions in 2012 resulted in higher ET_b for all hybrids and both PPDs than in 2010. In addition, ET_b values were higher with the high PPD than low PPD for all hybrids (table 10). The NDT H1 had greater ET_b value than all DT hybrids under both PPDs. Also, the average ET_b values for the NDT H1, DT H2, DT H3, and DT H4 hybrids under low and high PPDs were 319, 274, 226, and 268 mm, respectively, with NDT H1 having the highest ET_b value. Thus, on average, the NDT H1 had 45, 93, and 51 mm more ET_b than DT H2, DT H3, and DT H4, respectively. Thus, the NDT H1 required substantially more ET_b for grain yield establishment than all the DT hybrids under both PPDs at SCAL. On average (taking the average ET_b for all DT hybrids), the NDT H1 required 59 and 67 mm more water for first increment for grain yield establishment than the DT hybrids under high and low PPDs, respectively, which can be a significant factor for planning, allocating and management decisions, especially in water-limiting areas.

At HAL, ET_b values were lower than those observed at SCAL with inter-annual variation for the same hybrid between the irrigation levels, PPDs (table 10). ET_b values ranged from 148 mm for the DT H2 with low PPD in 2012 to 302 mm for the DT H3 with low PPD in 2010. Opposite to observations made at SCAL, drier conditions in 2012 resulted in lower ET_b for all DT hybrids in both PPDs than in 2010 and 2011 at HAL, which could be attributed to the reduced surface evaporation losses with the SDI. On an average basis, the NDT H1 had 68, 25, and 37 mm more ET_b than DT H2, DT H3, and DT H4, respectively (table

Table 10. Basal evapotranspiration (ET_b) for all individual drought-tolerant (DT) and non-drought-tolerant (NDT) maize hybrids under high and low plant population density (PPD), irrigation levels two locations (SCAL and HAL).

Year	Site	Hybrid	PPD	Basal Evapotranspiration (ET_b)
2010	SCAL	H2	High	324
2010	SCAL	H3	High	129
2010	SCAL	H4	High	221
2012	SCAL	H1	High	321
2012	SCAL	H2	High	286
2012	SCAL	H3	High	304
2012	SCAL	H4	High	312
2012	SCAL	H1	Low	316
2012	SCAL	H2	Low	243
2012	SCAL	H3	Low	236
2012	SCAL	H4	Low	270
2010	HAL	H1	High	258
2010	HAL	H4	High	258
2010	HAL	H3	Low	302
2011	HAL	H4	High	175
2012	HAL	H2	High	174
2012	HAL	H3	High	180
2012	HAL	H4	High	175
2012	HAL	H2	Low	148
2012	HAL	H3	Low	154
2012	HAL	H4	Low	182

[a] H1: NDT; H2, H3, and H4: DT hybrids; SCAL: South-Central Agricultural Laboratory, Clay Center, Neb.; HAL: Haskell Agricultural Laboratory, Concord, Neb.

10). Thus, the NDT H1 required substantially more ET_b for grain yield establishment than all DT hybrids under both PPDs at HAL as well. On average (taking the average ET_b for all DT hybrids), the NDT H1 hybrid required 43 mm more water for the first increment for grain yield establishment than the DT hybrids under high PPD. These aforementioned values are, in general, with an agreement with those reported by other researchers. From six-year field research, Irmak (2015a, 2015b) reported six-year average maize ET_b of 279 mm. He also reported that the ET_b values had a substantial inter-annual variation ranging from 263 to 418 mm. The substantial variation on the ET_b was due to the climate dependency, irrigation method and strategy, soil type, hybrid characteristics, and management practices as reported by Irmak (2015b).

Crop Water Use Efficiency (CWUE)

The CWUE values, including all hybrids and all of the irrigation treatments under both PPDs, at SCAL, ranged from 1.52 to 2.30 kg m^{-3} in 2010, 1.47 to 3.46 kg m^{-3} in 2012 (table 6). At HAL, the values ranged from 2.13 to 2.61 kg m^{-3} in 2010, 1.69 to 3.27 kg m^{-3} in 2011, and 0.0 to 3.05 kg m^{-3} in 2012 (table 7) and CWUE increased with irrigation amounts. However, the above-average conditions in 2010 resulted in almost no differences between the two irrigation treatments of RFT and FIT in terms of CWUE; and, PPDs did not have impact on the hybrid CWUE response for a given irrigation treatment. In contrast differences in CWUE were observed between the irrigation treatments of RFT and FIT at SCAL in 2012 (drier conditions). At SCAL, the two-year average CWUE, including both PPDs, was greater for DT hybrids (2.45 kg m^{-3}) than NDT hybrid (2.35 kg m^{-3}). The two-year average CWUE across all treatments, and years, by hybrid, the NDT H1 had 2.35 kg m^{-3} and DT H2, H3, and H4 had 2.50, 2.43, and 2.48 kg m^{-3} of CWUE, respectively. At HAL, the three-year average CWUE, including both PPDs, was greater for DT hybrids (2.29 kg m^{-3}) than NDT hybrid (2.08 kg m^{-3}). When averaging the three-year CWUE across all treatments, and years, by hybrid, the DT H4 had the greatest CWUE of 2.33 kg m^{-3} while the other NDT and DT hybrids of H1, H2, and H3 had 2.08, 2.27, and 2.23 kg m^{-3} of CWUE, respectively. The evidence indicates that the DT hybrids performed superior at both locations and across the years, even though there were inconsistent greatest CWUE patterns for a given DT hybrid.

Summary and Conclusions

Grain yield, ET_c, ET_b, ETYPF, and CWUE response of NDT DT maize hybrids were quantified in different irrigation levels and rainfed conditions under two PPDs and two locations. The DT H3 and DT H4 hybrids performed superior than the NDT H1 and DT H2 consistently at both locations. Generally, DT H2, H3, and H4 resulted in higher yields than NDT H1 for three irrigation management strategies under low and high PPDs at both locations. Inter-annual variability existed in grain yield response to treatments for the same maize hybrid at the same location and between the locations. In most cases, DT H3 resulted in the highest yield and usually had lower ET_c than other hybrids, especially at SCAL, under both PPDs and irrigation. The DT H3 and H4 hybrids had stronger yield response to irrigation at both locations in all three years. The ETYPF response for individual hybrids at both locations exhibited a strong and linear response with positive slopes in all cases. The slope of the production functions exhibited an inter-annual variation between the hybrids and for the same hybrids between the years and locations for both high and low PPDs. At SCAL, in both years, the ETYPFs had higher slopes with high PPDs than the low PPD. The two-year average (average of all hybrids) slopes for low and high PPDs were 0.045 and 0.068 Mg ha^{-1} mm^{-1}, respectively, with high PPD having 34% higher slope. At HAL, the three-year average (average of all hybrids) slopes for low and high PPDs were 0.025 and 0.035 Mg ha^{-1} mm^{-1}, respectively, with high PPD having 29% higher slope. The ET_b values also exhibited inter-annual variations. The NDT H1 required substantially more ET for grain yield establishment than all of the DT hybrids under both PPDs at both locations. The CWUE values were greatest with the DT H3 at SCAL and DT H4 hybrid at HAL than other hybrids in all irrigation levels, both PPDs, and years. In general, DT hybrids' productivity responses to treatments were stronger than the NDT hybrid. DT hybrids not only perform well in extremely dry year, but they can also have greater production efficiency in average or above average year (in term of precipitation) as compared with NDT hybrid.

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