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Irrigation-Yield Production Functions and Irrigation Water Use Efficiency Response of Drought-Tolerant and Non-Drought-Tolerant Maize Hybrids under Different Irrigation Levels, Population Densities, and Environments

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Abstract: Irrigation-yield production functions (IYPFs), irrigation water use efficiency (IWUE), and grain production per unit of applied irrigation of non-drought-tolerant (NDT) and drought-tolerant (DT) maize (*Zea mays* L.) hybrids were quantified in four locations with different climates in Nebraska [Concord (sub-humid), Clay Center (transition zone between sub-humid and semi-arid); North Platte (semi-arid); and, Scottsbluff (semi-arid)] during three growing seasons (2010, 2011, and 2012) at three irrigation levels (fully-irrigated treatment (FIT), early cut-off (ECOT), and rainfed (RFT)) under two plant population densities (PPDs) (low-PPD; 59,300 plants ha^{-1}; and, high-PPD, 84,000 plants ha^{-1}). Overall, DT hybrids' performance was superior to NDT hybrid at RFT, ECT, and FIT conditions, as confirmed by the yield response, IYPF and IWUE when all locations, years, and PPDs were averaged. The yield response to water was greater with the high-PPD than the low-PPD in most cases. The magnitude of the highest yields for DT hybrids ranged from 7.3 (low-PPD) to 8.5% (high-PPD) under RFT, 3.7 (low-PPD) to 9.6% (high-PPD) under ECOT, and 3.9% (high-PPD) under FIT higher than NDT hybrid. Relatively, DT hybrids can resist drought-stress conditions longer than NDT hybrid with fewer penalties in yield reduction and maintain comparable or even higher yield production at non-stress-water conditions.

Keywords: drought-tolerant; maize; plant population; production function; irrigation water use efficiency; water–yield relations

1. Introduction

Supplying adequate amounts of food, feed, fuel, and fiber for the growing population while using effective and efficient resource management strategies has always been challenging. However, this challenge needs increased attention in the 21st century due to projected rapid global population growth, increasing demand for food, fiber, feedstock, and bioenergy. Additionally, climate change has impacted the growing season magnitude and distribution of rainfall, due to the uncertainty imposed due to changing climate's influence on agricultural productivity. Ultimately influencing the dynamics and availability of water resources, which, in turn, influences crop productivity and its variability. Especially in water-limiting regions, water stress due to insufficient irrigation and precipitation can cause a substantial reduction in yield quantity and quality. Water withdrawal by agricultural sector for irrigation from surface and groundwater resources is greater than any other industry/discipline segments in the U.S. and it accounts for approximately 80% of the nation's total water withdrawal [1]. The estimated total irrigation water that is extracted from surface and groundwater resources for irrigation in production agriculture on a global basis ranges from 75–90% of total water withdrawal [2]. With the projected substantial increase in the world's population to almost 10 billion by 2050 [3], the regions that already have water-limiting conditions may face further challenges and regions that do not currently have limitation may begin experiencing shortages. It may complicate national and global efforts to achieve water and food security and prevent food shortages in some regions of the world [4].

Among agricultural commodities, maize (*Zea mays* L.) is one of the world's most important grain crops. Originating in Mexico and Central America in the pre-Columbia era, maize production spread northward to Canada and southward to Argentina [5], and eventually to the entire world. Maize is a major source for food, feed, fiber, and fuel that requires a substantial amount of water and other agronomic inputs (e.g., fertilizers, pesticides, etc.) to achieve potential yield. Typically, the fully irrigated maize requires approximately 500–600 mm of irrigation water [6], but this amount varies substantially based on the maturity class and hybrid characteristics; climatic characteristics; soil and crop management conditions; fertilizer management; and, irrigation method, water management practices, and other factors. Maize yield is sensitive to water stress, particularly if it is exposed to stress during critical growth stages (i.e., VT through R2; blister) [7]. Additionally, water stress in early growth stages might cause reduced plant growth and development, which can negatively influence yield [8,9].

Meeting the growing population's demand for adequate food, fiber, feed, and fuel will likely impose additional stresses on the agricultural sector, necessitating improved crop production efficiency in water-limited and non-water-limited areas. However, meeting the demand will require effective and multi-faceted measures, including effective soil, crop and water management strategies and techniques, and the adoption of new hybrids with drought-tolerance (DT). DT hybrid is the crop's ability to tolerate lower tissue water content by adaptive traits and crop technologies [4,10]. Where sufficient irrigation cannot be applied and/or in-season rainfall is insufficient or not-uniformly distributed, which results in an increased risk of water stress, DT hybrids have been considered to be a viable cropping system strategy for reducing the risk and negative effect(s) of water-limiting conditions on crop yields, which have been considered as a research topic in this work. In response to these potential forecasted challenges, as well as existing resource limitations in many regions, scientists and major seed companies have been developing DT hybrids to optimize yield production and efficiency per unit of water applied and/or used by the plant. Currently, three maize hybrid technologies are being marketed as DT hybrids, which include Pioneer Optimum AQUAmax^{TM} (DuPont Pioneer, Johnston, IA, USA); Syngenta Artesian^{TM} (Syngenta Seeds, Minnetonka, MN, USA), both being promoted as achieving drought-tolerance through traditional breeding. The third DT technology is Monsanto's Genuity^{TM} Drought Gard^{TM} (Monsanto Co., St. Louis, MO, USA), which is promoted as conferring drought-tolerance through both traditional plant breeding and the introduction of a transgenic trait [11]. However, there is a significant lack of data and information regarding irrigation water use efficiency (IWUE), irrigation-yield production functions (IYPF), and yield performance of these new DT maize hybrids in response to different irrigation management in various climatic conditions in comparison to non-drought-tolerant (NDT) maize hybrids.

Among the limited number of studies existing in the literature, Chen et al. [12] evaluated a selection of maize inbred lines for drought and heat stress tolerance under field conditions in Lubbock, Texas, USA. They found that the DT inbred lines had relatively high leaf water content when they were exposed to drought stress when compared with NDT lines. The DT hybrids showed significant tolerance to maintain vegetative growth and alleviate damage to reproductive tissues when compared with NDT lines. Gaffney et al. [13] reported that DT hybrids yielded 6.5% more under limited water environments, while NDT hybrids yielded 1.9% more under water-favorable environments. Some other studies also reported more yield with DT maize hybrids than NDT hybrids under water-limiting environments [14–18]. Hao et al. [19] found that the DT hybrids did not consistently have greater yield than NDT hybrid at 100% evapotranspiration (ET) in a three-year field study near Etter, Texas, USA;

however, DT hybrids consistently had greater yield than NDT at 75% ET and 50% ET. Additionally, they reported that greater plant population density (PPD) resulted in greater yield at 100% ET and 75% ET, but PPD did not affect yield at 50% ET. Lindsey and Thomison [20] fount that the DT hybrids yielded greater than NDT hybrids in low yielding environment in the US Corn Belt. Roth et al. [21] reported that grain yields declined as the PPD increased for both DT and NDT hybrids. Cooper et al. [18] reported positive grain yield response of DT hybrids when the PPD increased from 30,000 to 80,000 plants ha^{-1}.

The productivity response of maize hybrid to PPD can vary from one location to another as a function of numerous factors. Two of the indices for evaluating crop response to water/irrigation are IYPF and IWUE [4,22,23]. The term IWUE is the ratio of differences between the irrigated yield production and rainfed or dryland grain yield production to the total amount of applied irrigation. IWUE has not been sufficiently investigated for DT hybrids. The IWUE can be an important indicator, particularly in dry climates, where most of the irrigation water is used to meet ET requirements and can provide an assessment of crop performance under different irrigation strategies. The main objectives of this research were to: (i) investigate the potential differences in IYPFs or IWUE response of DT and NDT hybrids and how they potentially change with locations (climates), years, PPDs, and water levels, (ii) measure three DT and one NDT maize hybrids' yield response to seasonal irrigation under different irrigation treatments and PPDs in different climatic conditions, (iii) develop IYPFs, and (iv) quantify IWUE and the variation in IWUE and IYPF under different irrigation levels, PPDs, and climatic conditions. Irmak et al. [22] and Mohammed et al. [23] presented the grain yield results of the same hybrids and locations and climate data for all sites in the context of crop evapotranspiration and yield relationships and yield data are presented here in the context of only irrigation and yield relationships. The IYPFs and IWUE responses of DT and NDT hybrids and their variations have not been investigated or previously reported for the hybrids studied in this research.

2. Materials and Methods

2.1. Site Description

Field experiments were conducted in 2010, 2011, and 2012 growing seasons at four research sites across the state of Nebraska, USA. that are over 675 km apart with different climatic and environmental conditions, as well as soil properties (Figure 1, Table 1). The research sites were: Haskell Agricultural Laboratory (HAL) in northeast NE near Concord; South Central Agricultural Laboratory (SCAL) in south central NE near Clay Center; West Central Research and Extension Center (WCREC) in west central NE near North Platte; and, Mitchell Agricultural Laboratory (MAL) in western NE near Scottsbluff. HAL has a sub-humid climate and the soil classification is Blendon sandy loam (coarse-loamy, mixed, superactive, mesic Pachic Haplustoll), with 28% sand, 48% silt, and 24% clay. SCAL is located in a transition zone between sub-humid and semi-arid climatic zones with strong winds. The soil classification at this site is a Hastings silt loam; fine, montmorillonitic, mesic Udic Argiustoll and the particle size of distribution is 15% sand, 65% silt, and 20% clay with 2.5% organic matter content in the topsoil [4,10]. The WCREC has a semi-arid climate with a soil classification of Cozad silt loam (fine-silty, mixed, mesic Fluventic Haplustoll, with slope 0–1% slope). The MAL site has a semi-arid climate with a soil classification of Tripp fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls).

Table 1. Research site description, including coordinates, elevation (Elev.), long-term average rainfall, frost-free dates, soil type, field slope, field capacity, permanent wilting point, irrigation method, and climate type [22,23].

Research Site	Coordinates (Degrees)	Elev. (m)	Long-Term Average Annual Rainfall [1] (mm yr^{-1})	Frost-Free Dates [1]	Soil Type	Percent Slope	Field Capacity (m^3 m^{-3})	Wilting Point (m^3 m^{-3})	Irrigation Method	Climate
HAL [2], Concord, NE	42.6° N 97° W	445	672	30 Apr–10 Oct	Blenden sandy loam	0–3	0.23	0.10	SDI [6]	Sub-humid
SCAL [3], Clay Center, NE	44.6° N 98.1° W	552	680	24 Apr–19 Oct	Hastings silt loam	0–1	0.34	0.14	Linear Move	Transition zone between sub-humid and semi-arid
WCREC [4], North Platte, NE	41.1° N 100.8° W	861	510	30 Apr–05 Oct	Cozad silt loam	0–1	0.29	0.11	SDI	Semi-arid
MAL [5], Scottsbluff, NE	41.9° N 103.7° W	1098	340	08 May–07 Oct	Fine sandy loam	0–1	0.21	0.10	SDI	Semi-arid

[1] Source: NOAA Satellite and Information Service, 2017. [2] HAL: Haskell Agricultural Laboratory. [3] SCAL: South-Central Agricultural Laboratory. [4] WCREC: West Central Research and Extension Center. [5] MAL: Mitchell Agricultural Laboratory. [6] SDI: subsurface drip irrigation.

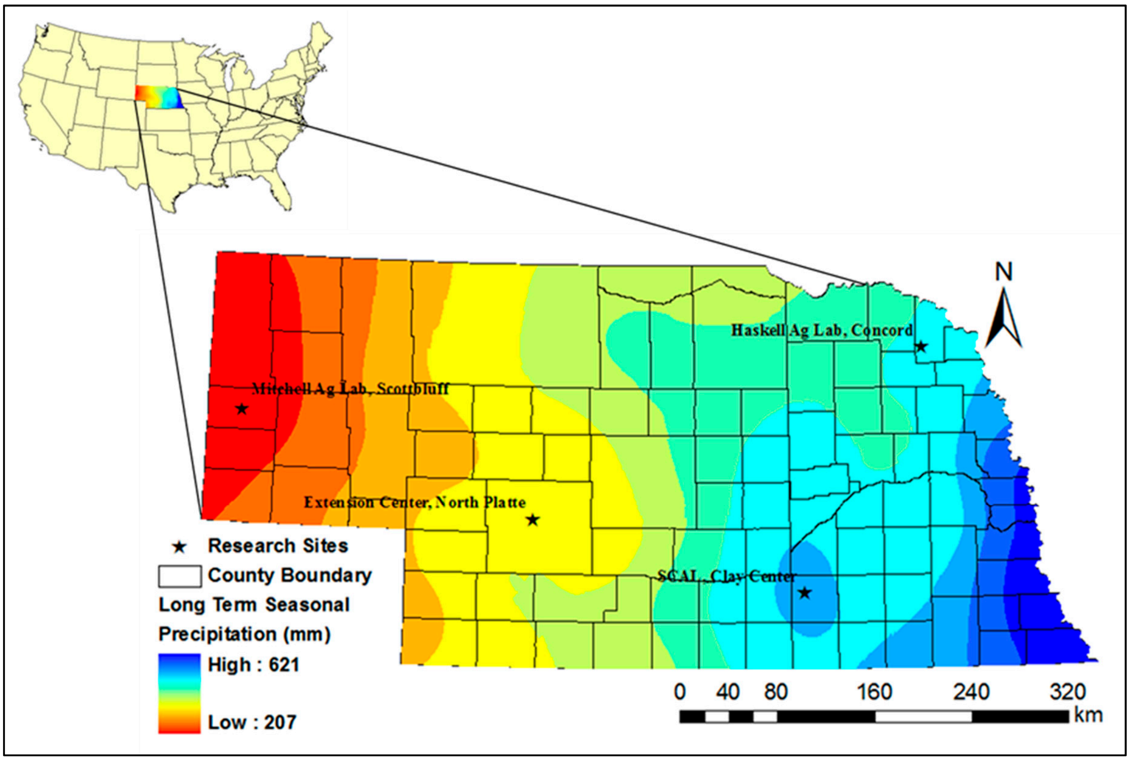

Figure 1. Locations of research sites with the long-term average growing season (1 May–30 September) rainfall (mm) on the background.

2.2. General Crop and Field Management Practices

Three irrigation management strategies were implemented in each site and year at two plant population densities (PPDs) to quantify crop productivity response to water. The hybrids were H1, a non-drought-tolerant (NDT) hybrid, and H2, H3, and H4 that were drought-tolerant (DT) hybrids (Table 2). Two PPDs were used at all locations: 59,300 plants ha^{-1} (low-PPD) and 84,000 plants ha^{-1} (high-PPD) with a 0.05 m planting depth. While these PPDs were referred to as low and high, this was only based on their numeric magnitudes. In real production fields in Nebraska and Midwest, the low-PPD is representative of typical rainfed maize production and high-PPD is commonly practiced for irrigated maize production [22]. The irrigation management strategies were: (i) fully-irrigated treatment (FIT), triggering 25.4 mm of irrigation at 35–40% depletion of the soil-water holding capacity and (ii) early cut-off treatment (ECOT), which was managed as a FIT up to the blister kernel stage and thereafter received no irrigation up to the time of harvesting. A rainfed treatment (RFT), which did not receive any irrigation throughout the season, was also included. The quantity of the rainfall at each site and year varied among the sites for a given year and between the years (Table 3). In general, 2010 was above average in terms of rainfall in Nebraska; therefore, ECOT was not included at SCAL or HAL. The amount of irrigation that was applied at each event to each treatment varied with year and location (Table 3). The fertilizer and pesticide applications type, application amount, and other management practices were based on the University of Nebraska–Lincoln Extension recommendations. The nitrogen (N) rate for each site was calculated while using the University of Nebraska–Lincoln N algorithm based on soil samples taken each year from each site [24].

$$\begin{aligned} \text{N need}\left(\frac{\text{lb}}{\text{ac}}\right) = \; & [35 + (1.2*\text{EY}) - (8 * \text{NO}_3 - \text{Nppm}) - (0.14 * \text{EY} * \text{OMC}) \\ & -\text{other N credits}]*\text{Price}_{\text{adj}} * \text{Timing}_{\text{adj}} \end{aligned} \tag{1}$$

where, EY = expected yield (bu/ac)

Nitrate-N ppm = average nitrate-N concentration in the root zone (2–4 foot depth) n partsper million (ppm)
OM = percent organic matter
Other N credits include N from legumes, manure, other organic materials, and from irrigation water.
$Price_{adj}$ = adjustment factor for prices of maize and N
$Timing_{adj}$ = adjustment factor for fall, spring and split applications

Each experimental site had a different statistical/experimental layout that was a function of irrigation system design. The experimental design at HAL site had a split-split-plot design with irrigation treatments as a main plot, six sub-plots for PPD and maize hybrids (sub-subplot), three irrigation levels, and three replications of each treatment. Each plot was eight rows wide and 36.5 m long. The field was irrigated while using a subsurface drip irrigation (SDI) system with drip lines installed on a 1.5 m spacing (every other interrow) at a depth of 0.30 m below the soil surface and 0.30 m of emitter spacing along the drip line. The SCAL field had a split-split plot design with the irrigation treatment as a main plot with six sub-plots for PPD and maize hybrids (sub-subplot) nested within three irrigation levels and four replications per treatment. Each plot was eight rows wide and 30.4 m long with a north-south planting direction. The field was irrigated using a seven-span linear-move sprinkler irrigation system with a 47.8 m span length, a 2.5 m sprinkler space along the spans with a 2.4 m sprinkler height. The experimental design at the WCREC site was a split-plot design with four replications for each treatment irrigated while using an SDI system, which has eight irrigation valves that irrigate 32 plots. Each valve controls four plots (one plot in each replication). Drip line spacing was 1.52 m and the lines were installed at a depth of 0.40 m below the soil surface in every other interrow and the emitters were spaced every 0.46 m on the drip lines. Each irrigation treatment (main plot) in each replication has eight subplots to randomly assign the eight hybrid-population combinations (subplot) and each main plot was divided into four subplots (hybrids) and each irrigation level replication was randomly assigned to one of eight subplots. Each subplot was six rows wide and 18 m long. The experimental design at the MAL site was a split-plot with irrigation treatments (main plot) and hybrid-population combinations as a subplot randomized in blocks and replicated four times. Within each irrigation treatment or strip, a combination of four hybrids and two PPDs were randomized and the field was irrigated while using an SDI system. This system allows for independent irrigations of 122 m long strips that are twelve 0.55 m rows wide. Each subplot was 8.2 m long and six rows wide. The emitters were spaced 0.61 m apart and the driplines were installed at every other interrow with 1.12 m dripline spacing at a depth of 0.28 m. There was a six-row border between each irrigation water treatment strip. At all locations, the row spacing was 0.76 m.

Table 2. Characteristic and ratings of drought-tolerant (DT) and conventional (non-drought-tolerant, NDT) maize hybrids used in this research (Source: DuPont Pioneer®) [22,23].

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 1/2 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 that 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; and, 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. Cumulative applied irrigation amount for each irrigation treatment, seasonal total rainfall, and long-term average total rainfall at the Haskell Agricultural Laboratory (HAL) in Concord, NE; South-Central Agricultural Laboratory (SCAL) in Clay Center, NE; West Central Research and Extension Center (WCREC) in North Platte, NE; and, Mitchell Agricultural Laboratory (MAL) in Scottsbluff, NE, in 2010, 2011, and 2012 growing seasons [22,23].

Year	HAL				SCAL			
	FIT [1]	ECOT [2]	Seasonal Total Rainfall	Long-Term Average Total Rainfall	FIT [1]	ECOT [2]	Seasonal Total Rainfall	Long-Term Average Total Rainfall
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
2010	30	-	869	395	152	-	521	469
2011	190	76	571		-	-	-	
2012	440	227	250		148	67	295	
Year	WCREC				MAL			
	FIT [1]	ECOT [2]	Seasonal Total Rainfall	Long-Term Average Total Rainfall	FIT [1]	ECOT [2]	Seasonal Total Rainfall	Long-Term Average Total Rainfall
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
2010	211	50	374	231	513	140	206	213
2011	223	79	402		595	325	252	
2012	555	279	84		830	680	74	

[1] Fully-irrigated treatment. [2] Early cut-off treatment.

2.3. Soil-Water Measurements, Quantification of IWUE and Statistical Analyses

The soil-water content was measured while using two different sensors: neutron attenuation soil moisture probe (Model 4302, Troxler Electronics Laboratories, Inc., Research Triangle Park, NC, USA) and Watermark Granular Matrix sensors (Irrometer, Co., Inc., Riverside, CA, USA). Irrigation was scheduled while using a neutron attenuation soil moisture probe (Model 4302, Troxler Electronics Laboratories, Inc., Research Triangle Park, NC, USA). Neutron probe and Watermark soil matric potential readings were taken every 0.30 m down to 1.5 m soil depth throughout each growing season in each research site. The Watermark sensors were connected to a Watermark Monitor data logger (Irrometer Co., Inc., Riverside, CA, USA). The grain yield was determined while using a two-row plot combine and all grain yields are reported in Mg per hectare at 15.5% grain moisture content. The IWUE was calculated as the ratio of difference between the irrigated and rainfed yield to the amount of applied irrigation to account for yield increase due to irrigation:

$$\mathrm{IWUE} = (\mathrm{Yi} - \mathrm{Yr})/\mathrm{Ii}, \quad (2)$$

where, IWUE, Y and I are in kg m^{-3}, g m^{-2} and mm, respectively. Yi is grain yield under irrigated treatments, Yr is rainfed grain yield, and I is applied irrigation water, while the subscript i represents irrigation treatment. Statistical analyses were carried out using the GLIMMIX procedure in SAS [25] to determine whether any treatments were significantly different than each other at the 5% significance level. A Fisher's protected least significant differences test was conducted to identify which treatments were different.

3. Results and Discussion

3.1. Weather Conditions

On average, the rainfall amounts during May through September substantially differed between the locations (Table 3). The 2010 growing season was above long-term average year in terms of precipitation at SCAL, HAL, and WCREC; and, similarly, in the 2011 growing season for HAL, WCREC, and MAL (Table 3). Year 2012 was one of the driest years in Nebraska's recorded weather history and the total rainfall was substantially lower than the long-term average across the four sites. It influenced Midwest agricultural production, especially the western and west-central part of Nebraska, which caused a substantial reduction in grain yield productions, even in well-watered conditions. The average air temperatures were generally warmer than the long-term average in all locations and years (Table 4).

3.2. Yield Response to Irrigation and Plant Population Density

The grain yields varied among the sites and years, but, generally, the lowest grain yield results were recorded in 2012, especially in the RFT, due to extremely dry and warm conditions (Tables 5–8). However, some of the highest yields were also obtained in 2012 under irrigation. There were no significant differences ($p > 0.05$) on the three-way interaction (irrigation amount × PPD × hybrid) at any of the four locations or years. However, irrigation treatments had significant ($p < 0.05$) effects on the grain yields. Some hybrids' yields' did not significantly differ between ECOT and FIT and between ECOT and RFT. However, the grain yields in the FIT were significantly greater ($p < 0.05$) than the RFT yields in all cases, except in 2010 at HAL, due to above average rainfall. PPD did not affect the performance of any hybrid in any irrigation treatments, or even sites. However, all of the hybrids performed better under the RFT low-PPD than the RFT high-PPD and the opposite was observed under FIT. The fact that maize competition for the inadequate soil moisture per unit area throughout the season was higher under RFT high-PPD than RFT low-PPD could partially explained this result and it led to lack of maize nutrient uptake coupled with insufficient soil moisture.

Table 4. Average growing seasonal air temperatures during 2010, 2011, and 2012 growing seasons and long-term average values at the Haskell Agricultural Laboratory (HAL) in Concord, NE; South-Central Agricultural Laboratory (SCAL) in Clay Center, NE; West Central Research and Extension Center (WCREC) in North Platte, NE; and Mitchell Agricultural Laboratory (MAL) in Scottsbluff, NE. T_{max}, T_{min}, and T_{avg} = maximum, minimum, and average air temperature, respectively.

Year	HAL						SCAL					
	Average Growing Seasonal Air Temperatures (01 May–30 Sep)			Long-Term (1983–2009) Average Growing Seasonal Air Temperatures (01 May–30 Sep)			Average Growing Seasonal Air Temperatures (01 May–30 Sep)			Long-Term (1997–2009) Average Growing Seasonal Air Temperatures (01 May–30 Sep)		
	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)
2010	25.6	13.2	19.4	24.4	11.7	18.0	27.3	14.1	20.7	27.1	13.8	20.5
2011	25.4	13.5	19.4				-	-	-			
2012	28.9	13.7	21.3				29.4	13.6	21.5			
	WCREC						**MAL**					
Year	**Average Growing Seasonal Air Temperatures (01 May–30 Sep)**			**Long-Term (1983–2009) Average Growing Seasonal Air Temperatures (01 May–30 Sep)**			**Average Growing Seasonal Air Temperatures (01 May–30 Sep)**			**Long-Term (1983–2009) Average Growing Seasonal Air Temperatures (01 May–30 Sep)**		
	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)
2010	27.5	12.4	19.9	27.3	11.7	19.5	26.7	10.4	18.6	27.2	10.7	18.9
2011	27.0	11.6	19.3				26.7	10.7	18.7			
2012	30.7	12.3	21.5				29.6	12.0	20.8			

Table 5. Hybrid (Hyb.), irrigation treatment (IRR), grain yield (Mg ha^{-1}) and irrigation water use efficiency (IWUE; kg m^{-3}) at two planting population densities (PPD; plants ha^{-1}) at the Haskell Agricultural Laboratory (HAL) in Concord, NE in 2010, 2011, and 2012 growing seasons.

Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE	Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE
			HAL						HAL		
2010	1	RFT	high	10.9 b	-	2011	3	ECOT	high	12.1 a	3.51
2010	1	RFT	low	12.8 ab	-	2011	3	ECOT	low	12.3 a	2.28
2010	2	RFT	high	-	-	2011	4	ECOT	high	12.3 a	8.0
2010	2	RFT	low	-	-	2011	4	ECOT	low	13.4 a	2.98
2010	3	RFT	high	11.4 ab	-	2011	1	FIT	high	12.7 a	1.04
2010	3	RFT	low	11.2 ab	-	2011	1	FIT	low	12.7 a	3.23
2010	4	RFT	high	12.9 a	-	2011	2	FIT	high	12.5 a	2.7
2010	4	RFT	low	12.9 a	-	2011	2	FIT	low	12.7 a	0.2
2010	1	ECOT	high	12.3 ab	-	2011	3	FIT	high	12.7 a	1.7
2010	1	ECOT	low	11.7 ab	-	2011	3	FIT	low	12.0 a	0.93
2010	2	ECOT	high	-	-	2011	4	FIT	high	13.0 a	3.55
2010	2	ECOT	low	-	-	2011	4	FIT	low	11.8 a	0.38
2010	3	ECOT	high	11.2 ab	-	2012	1	RFT	high	0.0 f	-
2010	3	ECOT	low	11.7 ab	-	2012	1	RFT	low	3.6 b	-
2010	4	ECOT	high	12.7 ab	-	2012	2	RFT	high	0.6 def	-
2010	4	ECOT	low	11.7 ab	-	2012	2	RFT	low	1.9 bc	-
2010	1	FIT	high	12.8 ab	6.14	2012	3	RFT	high	0.6 ef	-
2010	1	FIT	low	12.4 ab	−1.6	2012	3	RFT	low	1.8 bcd	-
2010	2	FIT	high	11.9 ab	-	2012	4	RFT	high	1.1 cdef	-
2010	2	FIT	low	12.7 ab	-	2012	4	RFT	low	1.4 bcde	-
2010	3	FIT	high	11.3 ab	−0.32	2012	1	ECOT	high	-	-
2010	3	FIT	low	12.6 ab	4.63	2012	1	ECOT	low	-	-
2010	4	FIT	high	13.0 a	0.18	2012	2	ECOT	high	13.3 a	5.59
2010	4	FIT	low	12.6 ab	−0.96	2012	2	ECOT	low	12.9 a	4.86
2011	1	RFT	high	10.7 a	-	2012	3	ECOT	high	11.5 a	4.79
2011	1	RFT	low	6.5 bc	-	2012	3	ECOT	low	12.2 a	4.57
2011	2	RFT	high	7.4 abc	-	2012	4	ECOT	high	12.0 a	4.79
2011	2	RFT	low	11.1 a	-	2012	4	ECOT	low	11.7 a	4.51
2011	3	RFT	high	9.4 ab	-	2012	1	FIT	high	13.9 a	3.16
2011	3	RFT	low	11.1 a	-	2012	1	FIT	low	13.7 a	2.29
2011	4	RFT	high	6.2 c	-	2012	2	FIT	high	15.3 a	3.33
2011	4	RFT	low	11.1 a	-	2012	2	FIT	low	14.2 a	2.79
2011	1	ECOT	high	10.3 a	−0.52	2012	3	FIT	high	14.5 a	3.15
2011	1	ECOT	low	12.3 a	7.57	2012	3	FIT	low	14.4 a	2.86
2011	2	ECOT	high	11.6 a	5.53	2012	4	FIT	high	14.1 a	2.95
2011	2	ECOT	low	12.2 a	1.28	2012	4	FIT	low	13.9 a	2.84

[1] Values within a column followed by the same letter are not statistically different ($p > 0.05$) for a given year.

Table 6. Hybrid (Hyb.), irrigation treatment (IRR), grain yield (Mg ha^{-1}), and irrigation water use efficiency (IWUE; kg m^{-3}) at two planting population densities (PPD; plants ha^{-1}) at the South-Central Agricultural Laboratory (SCAL) in Clay Center, NE in 2010, 2011, and 2012 growing seasons.

Year	Hyb	IRR	PPD	Grain [1] Yield	IWUE	Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE
			SCAL						SCAL		
2010	1	RFT	high	5.8 f	-	2012	3	RFT	high	6.9 ghi	-
2010	1	RFT	low	8.2 de	-	2012	3	RFT	low	7.4 gh	-
2010	2	RFT	high	7.0 e	-	2012	4	RFT	high	6.1 ij	-
2010	2	RFT	low	8.6 cd	-	2012	4	RFT	low	7.4 gh	-
2010	3	RFT	high	7.7 de	-	2012	1	ECOT	high	10.9 def	7.95
2010	3	RFT	low	8.6 cd	-	2012	1	ECOT	low	10.7 def	6.34
2010	4	RFT	high	8.0 de	-	2012	2	ECOT	high	9.8 ef	4.75
2010	4	RFT	low	8.0 de	-	2012	2	ECOT	low	9.5 f	4.56
2010	1	FIT	high	10.4 ab	3.02	2012	3	ECOT	high	10.7 def	5.64
2010	1	FIT	low	9.5 cd	0.85	2012	3	ECOT	low	10.3 def	4.18
2010	2	FIT	high	10.9 ab	2.60	2012	4	ECOT	high	11.6 cd	8.07
2010	2	FIT	low	9.2 cd	0.41	2012	4	ECOT	low	11.3 de	5.83
2010	3	FIT	high	11.2 a	2.33	2012	1	FIT	high	14.0 ab	5.69

Table 6. *Cont.*

Year	Hyb	IRR	PPD	Grain [1] Yield	IWUE	Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE
			SCAL						**SCAL**		
2010	3	FIT	low	10.4 ab	1.19	2012	1	FIT	low	13.4 bc	4.66
2010	4	FIT	high	11.1 ab	2.01	2012	2	FIT	high	15.9 a	6.23
2010	4	FIT	low	10.3 bc	1.54	2012	2	FIT	low	14.6 ab	4.37
2012	1	RFT	high	5.6 j	-	2012	3	FIT	high	16.3 a	6.29
2012	1	RFT	low	6.4ij	-	2012	3	FIT	low	15.5 ab	5.38
2012	2	RFT	high	6.6 hi	-	2012	4	FIT	high	15.1 ab	6.01
2012	2	RFT	low	8.1 g	-	2012	4	FIT	low	14.2 ab	4.58

[1] Values within a column followed by the same letter are not statistically different ($p > 0.05$) for a given year.

Table 7. Hybrid (Hyb.), irrigation treatment (IRR), grain yield (Mg ha^{-1}), and irrigation water use efficiency (IWUE; kg m^{-3}) at two planting population densities (PPD; plants ha^{-1}) at the West Central Research and Extension Center (WCREC) in North Platte, NE in 2010, 2011, and 2012 growing seasons.

Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE	Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE
			WCREC						**WCREC**		
2010	1	RFT	high	8.7 l	-	2011	3	ECOT	high	9.5 cdef	2.27
2010	1	RFT	low	9.9 k	-	2011	3	ECOT	low	10.8 abc	2.80
2010	2	RFT	high	10.7 jk	-	2011	4	ECOT	high	11.0 ab	4.20
2010	2	RFT	low	10.9 jk	-	2011	4	ECOT	low	10.3 bcd	2.75
2010	3	RFT	high	10.8 jk	-	2011	1	FIT	high	10.8 abc	2.08
2010	3	RFT	low	11.2 ij	-	2011	1	FIT	low	10.8 abc	1.38
2010	4	RFT	High	10.8 jk	-	2011	2	FIT	high	11.1 ab	1.16
2010	4	RFT	low	10.9 jk	-	2011	2	FIT	low	12.0 a	1.70
2010	1	ECOT	high	11.9 ghij	6.40	2011	3	FIT	high	12.1 a	1.97
2010	1	ECOT	low	12.4 efgh	4.94	2011	3	FIT	low	10.7 abc	0.95
2010	2	ECOT	high	12.4 fghi	3.50	2011	4	FIT	high	11.0 abc	1.50
2010	2	ECOT	low	12.6 cdefgh	3.40	2011	4	FIT	low	12.4 a	1.91
2010	3	ECOT	high	12.7 cdefgh	3.78	2012	1	RFT	high	0.2 b	-
2010	3	ECOT	low	13.6 abcde	4.70	2012	1	RFT	low	0.0 bcd	-
2010	4	ECOT	high	11.6 hij	1.55	2012	2	RFT	high	0.1 bc	-
2010	4	ECOT	low	12.5 defgh	3.35	2012	2	RFT	low	0.0 cd	-
2010	1	FIT	high	13.9 abc	2.48	2012	3	RFT	high	0.2 bc	-
2010	1	FIT	low	13.4 abcdef	1.67	2012	3	RFT	low	0.0 cd	-
2010	2	FIT	high	13.7 abcd	1.46	2012	4	RFT	High	0.1 bcd	-
2010	2	FIT	low	13.9 abcd	1.40	2012	4	RFT	low	0.0 d	-
2010	3	FIT	high	14.6 a	1.80	2012	1	ECOT	high	6.3 a	2.18
2010	3	FIT	low	14.1 ab	1.38	2012	1	ECOT	low	5.5 a	1.97
2010	4	FIT	high	12.9 bcdef	0.98	2012	2	ECOT	high	5.8 a	2.05
2010	4	FIT	low	12.9 cdefg	1.02	2012	2	ECOT	low	5.2 a	1.85
2011	1	RFT	high	6.2 g	-	2012	3	ECOT	high	5.4 a	1.87
2011	1	RFT	low	7.7 f	-	2012	3	ECOT	low	5.0 a	1.79
2011	2	RFT	high	8.5 def	-	2012	4	ECOT	high	6.6 a	2.33
2011	2	RFT	low	8.2 ef	-	2012	4	ECOT	low	5.4 a	1.94
2011	3	RFT	high	7.7 f	-	2012	1	FIT	high	6.6 a	1.15
2011	3	RFT	low	8.6 def	-	2012	1	FIT	low	6.4 a	1.15
2011	4	RFT	High	7.7 f	-	2012	2	FIT	high	7.3 a	1.29
2011	4	RFT	low	8.1 f	-	2012	2	FIT	low	5.8 a	1.04
2011	1	ECOT	high	9.2 def	3.85	2012	3	FIT	high	6.9 a	1.21
2011	1	ECOT	low	10.0 bcde	2.82	2012	3	FIT	low	7.1 a	1.28
2011	2	ECOT	high	10.9 abc	2.95	2012	4	FIT	high	6.7 a	1.20
2011	2	ECOT	low	11.7 ab	4.36	2012	4	FIT	low	7.5 a	1.34

[1] Values within a column followed by the same letter are not statistically different ($p > 0.05$) for a given year.

Table 8. Hybrid (Hyb.), irrigation treatment (IRR), grain yield (Mg ha^{-1}), and irrigation water use efficiency (IWUE; kg m^{-3}) at two planting population densities (PPD; plants ha^{-1}) at the Mitchell Agricultural Laboratory (MAL) in Scottsbluff, NE in 2010, 2011, and 2012 growing seasons.

Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE	Year	Hyb.	IRR	PPD	Grain [1] Yield	IWUE
			MAL						MAL		
2010	1	RFT	high	7.4 ijk	-	2011	3	ECOT	high	13.3 a	2.27
2010	1	RFT	low	8.5 fghi	-	2011	3	ECOT	low	13.0 a	2.08
2010	2	RFT	high	4.7 l	-	2011	4	ECOT	high	10.5 abc	0.99
2010	2	RFT	low	7.8 ghij	-	2011	4	ECOT	low	10.2 abc	1.52
2010	3	RFT	high	7.6 hij	-	2011	1	FIT	high	14.6 a	1.84
2010	3	RFT	low	5.6 kl	-	2011	1	FIT	low	13.0 a	1.23
2010	4	RFT	high	7.0 jkl	-	2011	2	FIT	high	14.8 a	1.28
2010	4	RFT	low	7.6 hijk	-	2011	2	FIT	low	12.3 ab	1.06
2010	1	ECOT	high	9.9 defghi	1.73	2011	3	FIT	high	14.3 a	1.40
2010	1	ECOT	low	9.4 efghi	0.65	2011	3	FIT	low	13.1 a	1.16
2010	2	ECOT	high	10.9 bcdefg	4.43	2011	4	FIT	high	13.7 a	1.08
2010	2	ECOT	low	9.4 efghi	1.13	2011	4	FIT	low	12.8 a	1.26
2010	3	ECOT	high	11.8 abcdef	3.00	2012	1	RFT	high	5.9 i	-
2010	3	ECOT	low	10.8 bcdefg	3.76	2012	1	RFT	low	5.1 i	-
2010	4	ECOT	high	11.4 bcdef	3.16	2012	2	RFT	high	1.3 l	-
2010	4	ECOT	low	10.6 cdefgh	1.73	2012	2	RFT	low	3.3 k	-
2010	1	FIT	high	15.1 ab	2.13	2012	3	RFT	high	1.2 l	-
2010	1	FIT	low	13.9 abc	1.01	2012	3	RFT	low	4.0 j	-
2010	2	FIT	high	13.9 abcd	0.89	2012	4	RFT	high	3.2 k	-
2010	2	FIT	low	12.4 abcde	0.57	2012	4	RFT	low	7.1 h	-
2010	3	FIT	high	15.9 a	0.58	2012	1	ECOT	high	11.6 ef	0.84
2010	3	FIT	low	12 abcde	0.79	2012	1	ECOT	low	12.6 de	1.10
2010	4	FIT	high	13.2 abcd	0.23	2012	2	ECOT	high	14.5 bcd	1.95
2010	4	FIT	low	13.2 abcd	0.36	2012	2	ECOT	low	9.5 g	0.91
2011	1	RFT	high	3.7 e	-	2012	3	ECOT	high	9.1 g	1.15
2011	1	RFT	low	5.7 d	-	2012	3	ECOT	low	10.1 fg	0.89
2011	2	RFT	high	7.2 cd	-	2012	4	ECOT	high	15.9 abc	1.86
2011	2	RFT	low	5.9 d	-	2012	4	ECOT	low	12.6 de	0.81
2011	3	RFT	high	6.0 d	-	2012	1	FIT	high	17.3 a	1.38
2011	3	RFT	low	6.2 d	-	2012	1	FIT	low	16.7 ab	1.40
2011	4	RFT	high	7.3 bcd	-	2012	2	FIT	high	16.3 abc	1.81
2011	4	RFT	low	5.3 d	-	2012	2	FIT	low	15.8 abc	1.5
2011	1	ECOT	high	11.4 abc	2.36	2012	3	FIT	high	18.0 a	2.02
2011	1	ECOT	low	10.8 abc	1.55	2012	3	FIT	low	14.0 dc	1.20
2011	2	ECOT	high	13.4 a	1.89	2012	4	FIT	high	15.5 abc	1.48
2011	2	ECOT	low	12.3 ab	1.94	2012	4	FIT	low	14.0 dc	0.83

[1] Values within a column followed by the same letter are not statistically different ($p > 0.05$) for a given year.

3.3. Irrigation-Yield Production Functions (IYPF)

The general trend in IYPFs of all hybrids was similar at all of the sites and years with an increasing trend in grain yield with increasing irrigation amounts to the point where the grain yield plateaued and did not respond to increase in irrigation amount (diminishing return) (Figures 2–5, for HAL, SCAL, WCREC, and MAL, respectively). In most of the IYPFs, the total amount of water applied is closer to the total crop water use (plateaued part of IYPFs figures) and increasing the amount of irrigation becomes less effective in converting water applied to grain yield. However, the magnitude of grain yield response to water applied exhibited substantial variation for the same hybrids between locations, as well as among the hybrids in the same location between the years. The irrigation amounts that were applied differed between the sites due to differences in climatic conditions and crop water demand. However, within the same site, all of the hybrids received the same amount of irrigation water in FIT and ECOT in each irrigation. The IYPFs were fitted to the treatment mean values by using the average of three replications in HAL and four replications in SCAL, WCREC, and MAL for each hybrid under each treatment, year and location (the number of replications varied between the sites; three replications in HAL and four in other locations). 22 IYPFs were developed and the IYPFs were explained with a second-order polynomial in all cases, with the exception of four cases. Linear functions were only fitted to two data points for the HAL data for 2010 (Figure 2a,b) and SCAL data for 2010 (Figure 3a,b). The primary objective with these linear relationships with two data points was to infer general trends in yield response to irrigation due to the absence of ECOT data, and the objective was not to analyze the significance of the relationship.

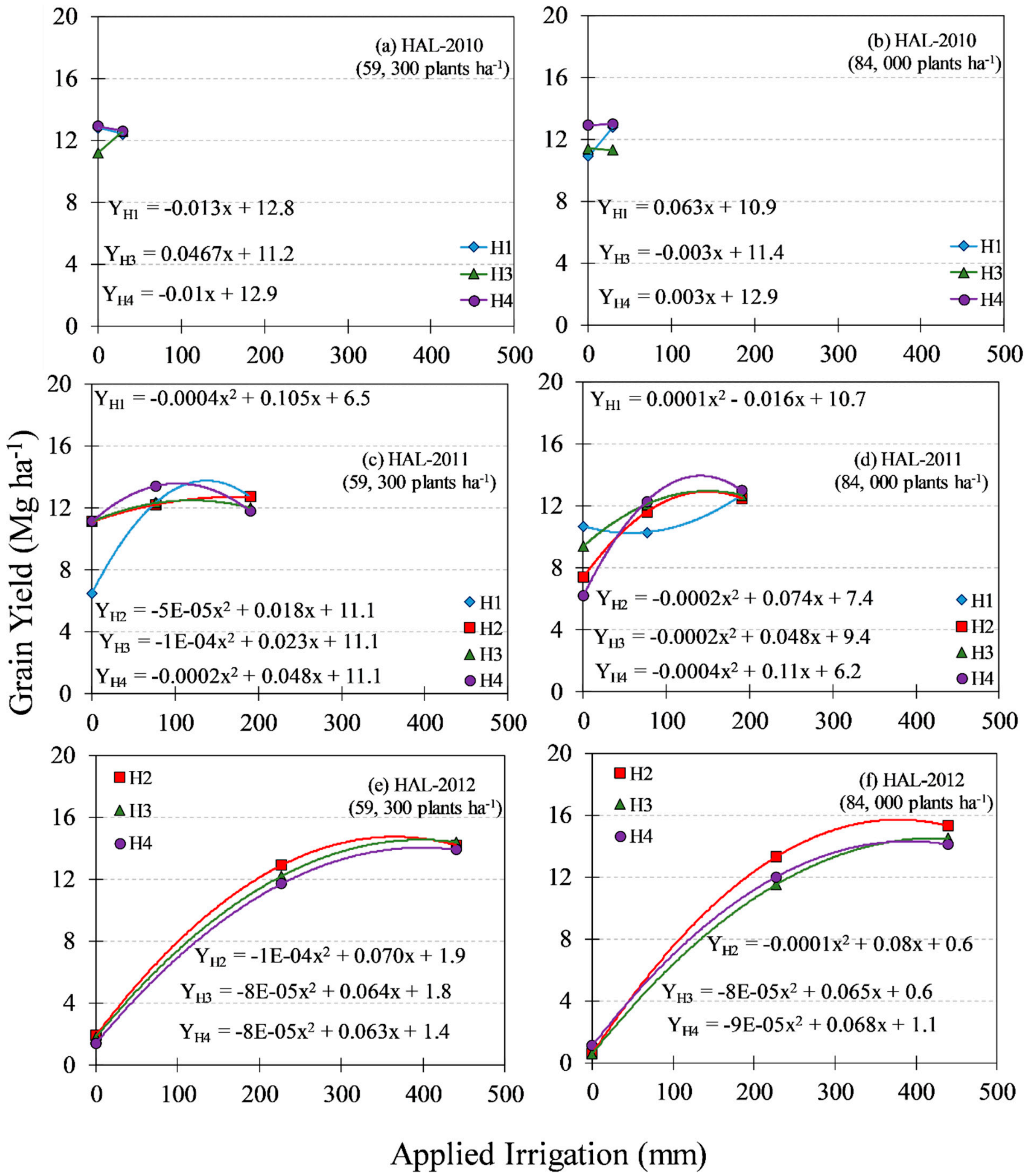

Figure 2. Relationships between grain yield and applied irrigation (irrigation-yield production function, IYPF) for individual maize hybrids: (**a**) low population-2010, (**b**) high population-2010, (**c**) low population-2011, (**d**) high population-2011, (**e**) low population-2012, and (**f**) high population-2012 at the Haskell Agricultural Laboratory (HAL) site at Concord, NE. H1: non-drought-tolerant (NDT); and, H2, H3, and H4: drought-tolerant (DT) hybrids.

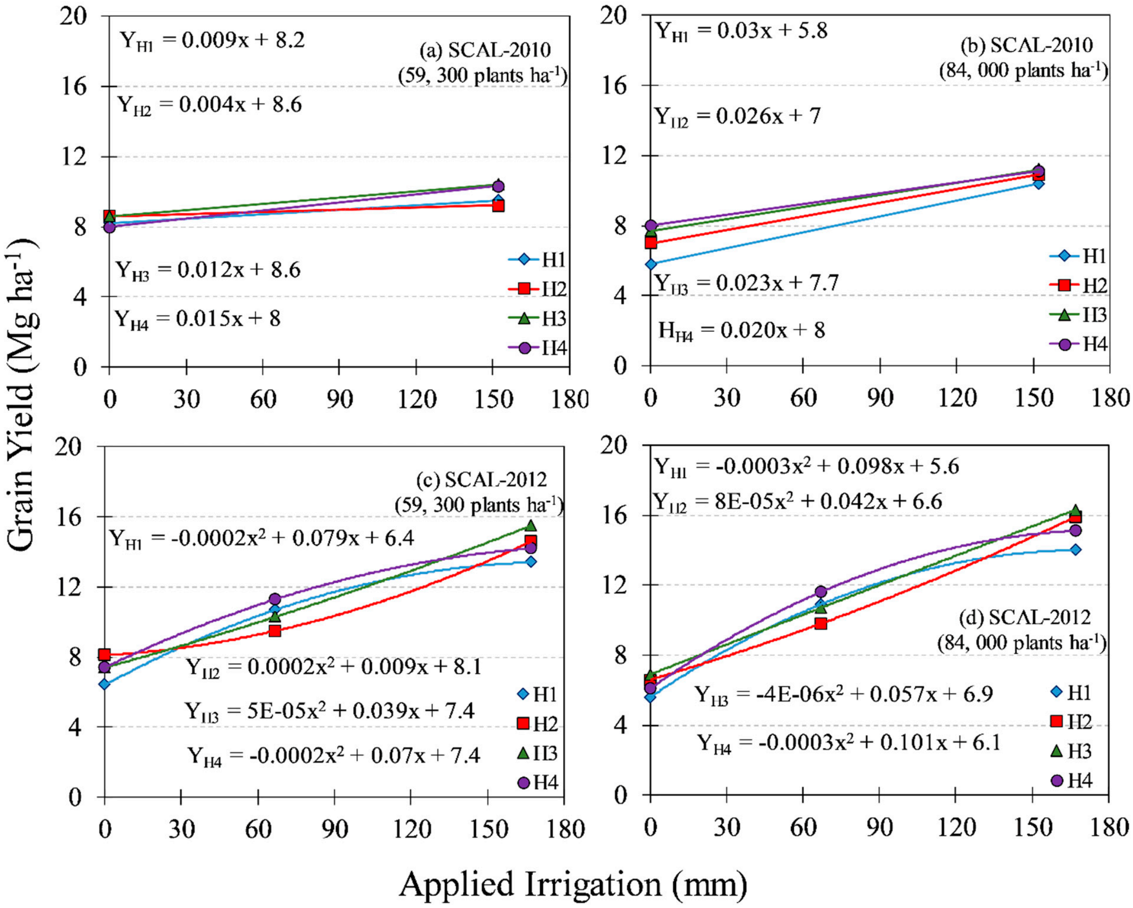

Figure 3. Relationships between grain yield and applied irrigation (irrigation-yield production function, IYPF) for individual maize hybrids: (**a**) low population-2010, (**b**) high population-2010, (**c**) low population-2012, and (**d**) high population-2012 at the South Central Agricultural Laboratory (SCAL) site at Clay Center, NE. H1: non-drought-tolerant (NDT); and, H2, H3, and H4: drought-tolerant (DT) hybrids.

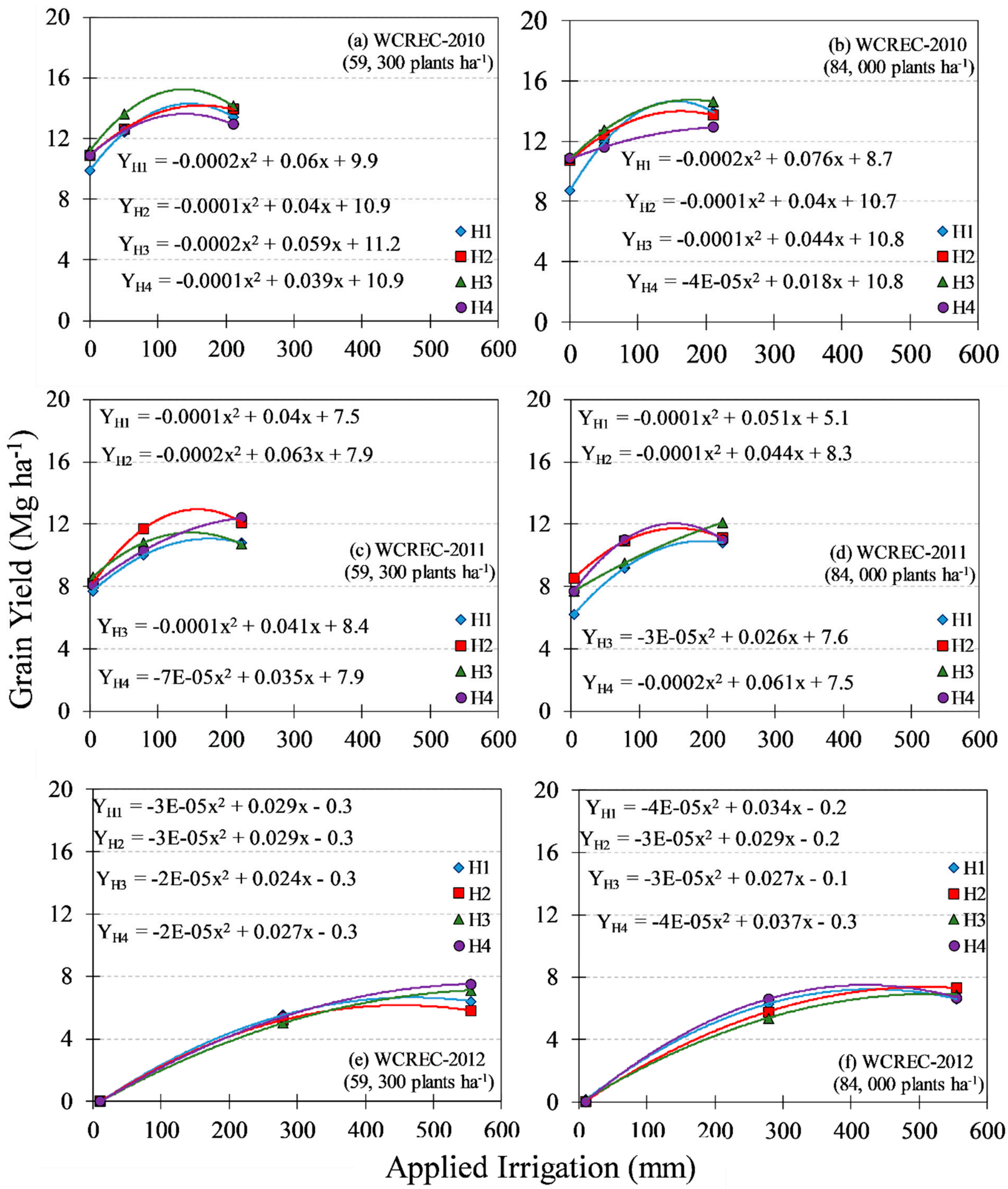

Figure 4. Relationships between grain yield and applied irrigation (irrigation-yield production function, IYPF) for individual maize hybrids: (**a**) low population-2010, (**b**) high population-2010, (**c**) low population-2011, (**d**) high population-2011, (**e**) low population-2012, and (**f**) high population-2012 at the West Central Research and Extension Center (WCREC) site at North Platte, NE. H1: non-drought-tolerant (NDT); and, H2, H3, and H4: drought-tolerant (DT) hybrids.

The productivity response (slope) of the IYPFs were positive, but there were some negative productivity responses, which is, in part, due to the rainfed yields being greater than some of the irrigated yields for some hybrids or yield reduction at the ECOT (Figures 2a,b,d, and 4e,f). DT and NDT hybrids' average productivity response (excluding negative productivity response values) across the sites and years was 21% higher at high-PPD than low-PPD. Additionally, generally, the yield response to water was stronger with the high-PPD than the low-PPD and this occurred because of the lower yield production under RFT at high-PPD. The average productivity response of NDT hybrid across years and sites was 19 and 16% greater than all of the combined DT hybrids at low and high-PPDs, respectively. The greater productivity response values for NDT hybrid at both PPDs may be explained by the fact that greater yields difference between RFTs and FITs for the NDT hybrid was obtained when compared with DT hybrids. This finding further supports that, in general, DT hybrids could produce greater yield under rainfed conditions than NDT hybrid. The grain yield response to irrigation amount was the strongest with higher productivity in the driest and warmest year in 2012 than other years at all locations and for all hybrids.

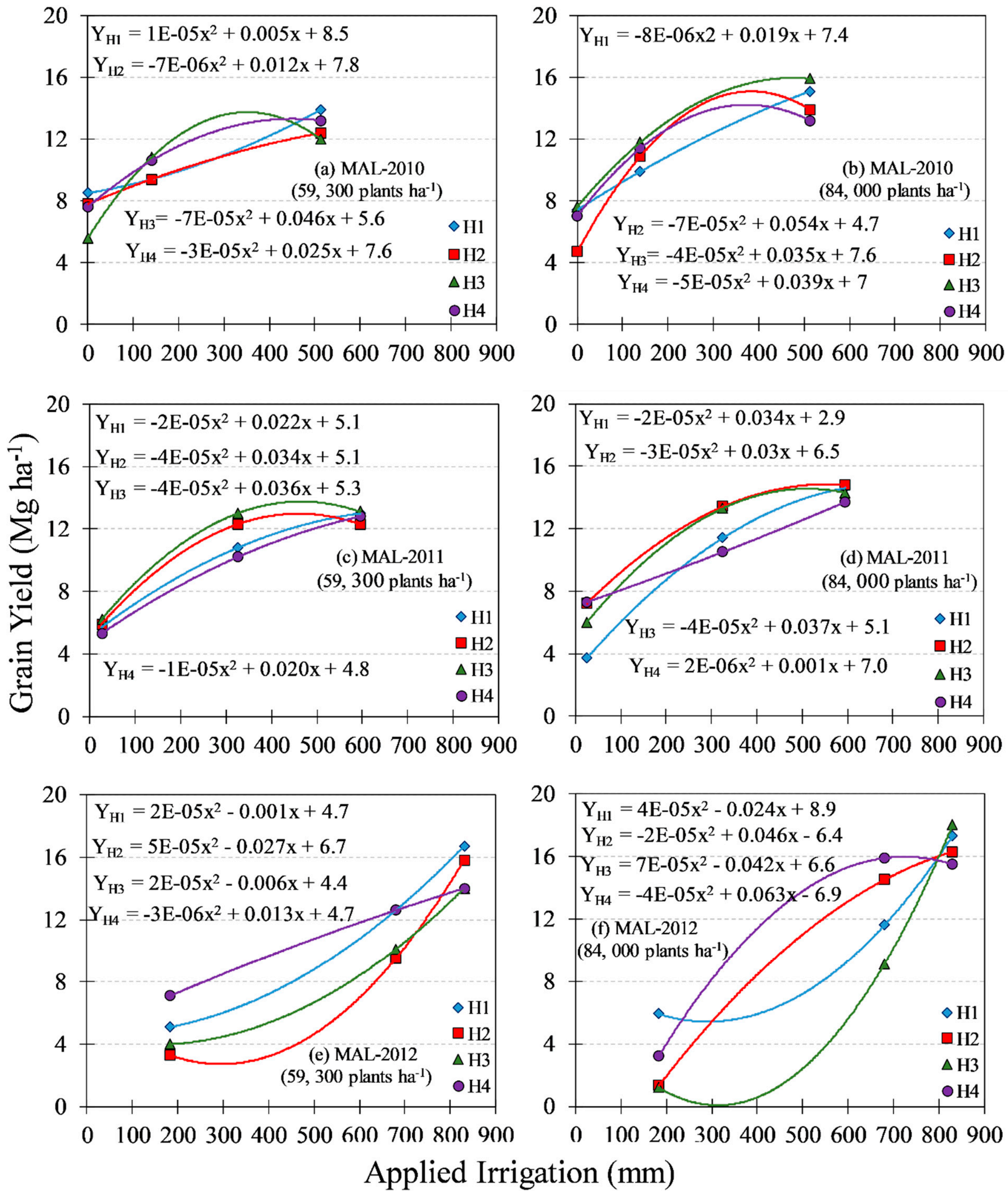

Figure 5. Relationships between grain yield and applied irrigation for individual maize hybrids: (**a**) low population-2010, (**b**) high population-2010, (**c**) low population-2011, (**d**) high population-2011, (**e**) low population-2012, and (**f**) high population-2012 at the Mitchell Agricultural Laboratory (MAL) site at Scottsbluff, NE. H1: non-drought-tolerant (NDT); and, H2, H3, and H4: drought-tolerant (DT) hybrids.

To be able to infer overall (average) assessments of DT and NDT hybrids response, the average grain yield production for NDT H1 hybrid and DT H2, H3, and H4 hybrids under three irrigation treatments (RFT, ECOT, and FIT) at low and high-PPDs for each year and for all years were graphed with standard deviations after specific analyses for each of the DT and NDT hybrids' response to irrigation levels under two PPDs, years, and locations (Figure 6). The average of the given DT hybrid's and NDT hybrid across the years and sites for the given PPD showed that the highest grain yields at each irrigation treatment were obtained with the DT hybrids, except for FIT low-PPD (Figure 6a). DT H3 and H4 consistently yielded greater than NDT H1 in all irrigation treatments under both PPDs (except DT H2 and H3 at FIT high-PPD). The magnitude of the highest yields for DT hybrids ranged from 7.3 (low-PPD) to 8.5% (high-PPD) under RFT, 3.7 (low-PPD) to 9.6% (high-PPD) under ECOT, and 3.9% (high-PPD) higher than NDT hybrid under FIT. This finding aligns with those that were reported by Adee et al. [11], who reported that the DT hybrids had superior performance in water-stressed and in high and medium evapotranspiration environments and yielded 5 to 7% more than NDT hybrids. Even though the average yield of DT hybrids and NDT hybrid varied with PPD and year, the DT hybrids of H3 and H4 yields were similar or even greater than the NDT hybrid, regardless of irrigation treatment or PPD (except RFT low-PPD in 2012) (Figure 6b–d). Furthermore, none of the specific DT hybrid consistently had the highest grain yields, which could be due to the fact that the weather variables, location, soil type, year, and the hybrid characteristics influenced DT hybrids' yields. These results suggest that some DT hybrids could produce greater yields than NDT hybrid under rainfed or water-stressed conditions at low PPD and equal or even greater yield under medium level water stress and well-watered conditions at high PPD.

The responses of each hybrid were pooled for all locations and years for both PPDs (Figure 7a), and for high PPDs (Figure 7b) and low PPDs (Figure 7c) separately, to further infer overall assessments of hybrids' grain productivity. This was intended to infer the expected performance of the DT and NDT hybrids under different locations that have different climatic conditions. In examining Figure 7a–c (excluded negative data points) from any of the research locations, years, or treatments and without the following replication data points at SCAL: 2010-DT H2 (low-PPD) in FIT; at WCREC: 2010-DT H4 (high-PPD) in ECOT and FIT) all hybrids' grain yield productivity responded strongly to seasonal irrigation. When all locations, years, and PPDs were considered by averaging DT H2, DT H3, and DT H4 hybrids' responses and compared to NDT H1 hybrid (Figure 7a), the average of all DT hybrids had a stronger grain productivity response to irrigation amount with greater slope and R^2 as compared with the NDT H1. For example, DT H2, DT H3, and DT H4 hybrids (average of all three hybrids) had 40% more grain yield productivity per 25 mm of irrigation application than the NDT H1 across all locations (0.046 Mg ha^{-1} for H1 vs. 0.076 Mg ha^{-1} for the average of DT H2, DT H3, and DT H4). Pooled data response curves differed when the crop yield responses to irrigation were separated by PPDs and hybrids, but were pooled with all locations and years. At high-PPD (Figure 7b), all of the hybrids responded to irrigation amounts marginally with R^2 values of 0.43, 0.54, 0.56, and 0.49 for NDT H1, DT H2, DT H3, and DT H4, respectively. DT H2 and DT H3 had the highest grain yield production per 25.4 mm of irrigation water (0.244 Mg ha^{-1} for DT H2 and 0.170 Mg ha^{-1} for DT H3) among all hybrids and NDT H1 only had higher yield response to irrigation than DT H4 (0.117 Mg ha^{-1} for NDT H1 and 0.030 Mg ha^{-1} for DT H4). When the hybrids' responses under high-PPDs were considered, the grain yield productivity was significantly higher for all of the hybrids than low-PPD (Figure 7c). The grain yield productions per 25.4 mm of irrigation water applied were 0.018, 0.066, 0.058, and 0.010 Mg ha^{-1} for the NDT H1, DT H2, DT H3, and DT H4, respectively, with DT H2 and DT H3 having greater grain production per unit of irrigation application than NDT H1 and DT H4. The NDT H1 only had higher yield response than DT H4. On average, under low-PPD, NDT H1 had about 15% more grain production per 25.4 mm of irrigation than under high-PPD; and, DT H2, DT H3, and DT H4 had 27, 34, and 33% more yield production under high-PPD than under low-PPD.

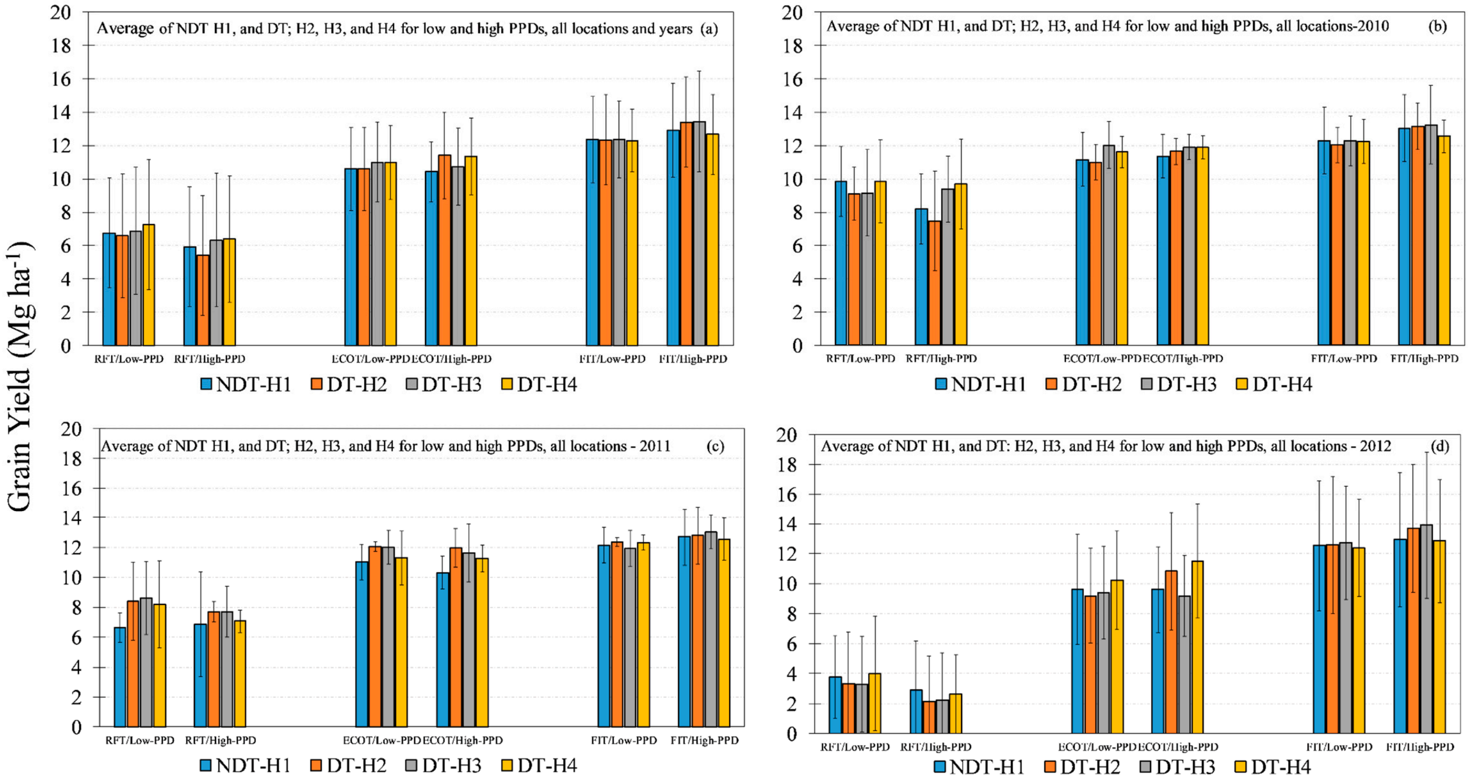

Figure 6. Average grain yield production for non-drought-tolerant (NDT) H1 hybrid and drought-tolerant (DT) H2, H3 and H4 hybrids under three irrigation treatments of RFT, ECOT, and FIT at low and high population density (PPD): (**a**) average grain production for NDT H1 hybrid and DT H2, H3, and H4 hybrids across the locations and years at low and high-PPD; (**b**) average grain production for NDT H1 hybrid and DT H2, H3, and H4 hybrids across the locations at low and high PPD for 2010; (**c**) average grain production for NDT H1 hybrid and DT H2, H3, and H4 hybrids across the locations at low and high PPD for 2011; and, (**d**) average grain production for NDT H1 hybrid and DT H2, H3, and H4 hybrids across the locations at low and high-PPD for 2012.

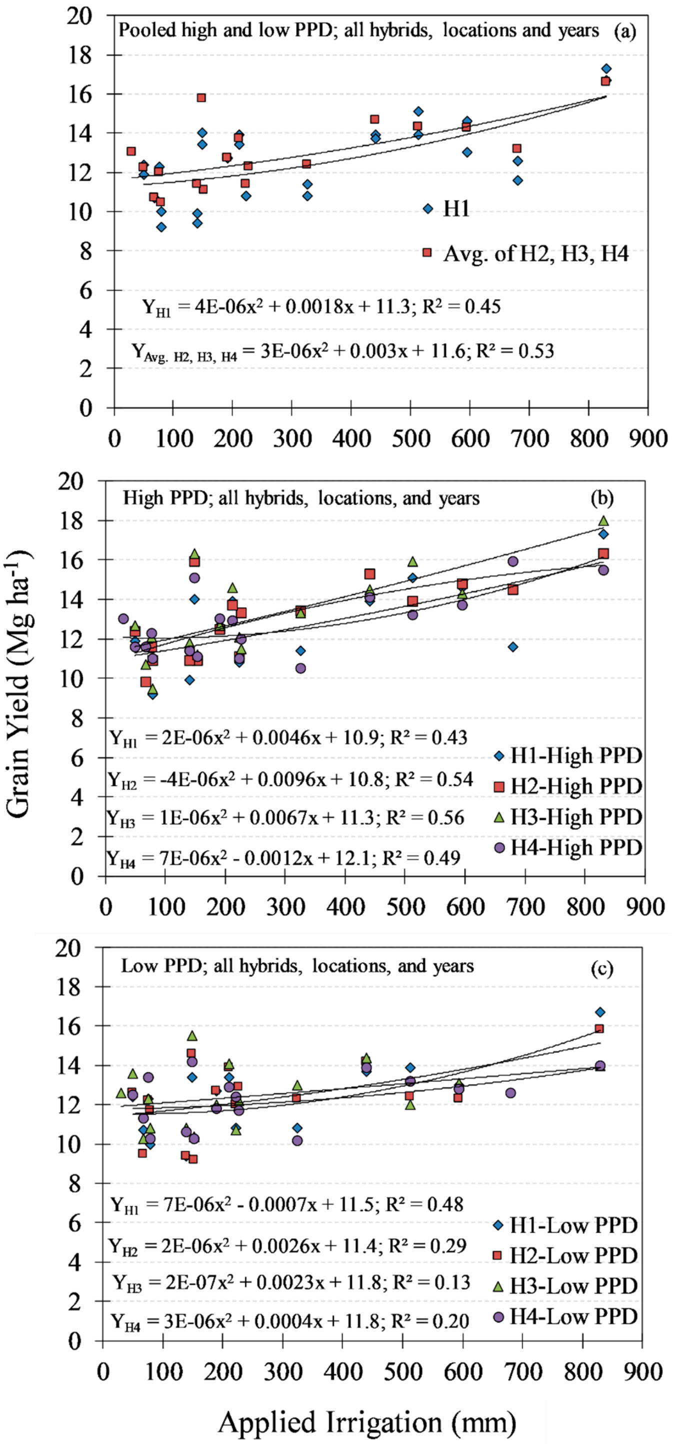

Figure 7. Grain yield response to seasonal irrigation amount for non-drought-tolerant (NDT) H1 hybrid and drought-tolerant (DT) H2, H3, and H4 hybrids under low and high population density (PPD). Figure 7a–c includes all data from all years, locations, and treatments with exclude data from years and treatments that had experimental issues as described in the text: (**a**) the grain yield response to irrigation of NDT H1 hybrid was compared to the average response of all drought-tolerant (DT) H2, H3 and H4 hybrids, (**b**), the grain yield response to irrigation of NDT H1 hybrid and all drought-tolerant (DT) H2, H3 and H4 hybrids at high population density, and (**c**) the grain yield response to irrigation of NDT H1 hybrid and all drought-tolerant (DT) H2, H3, and H4 hybrids at low population density.

3.4. Grain Productivity per Unit of Irrigation for Individual Hybrids, Locations, Years and PPDs

Figure 8 presents grain production per 25.4 mm of irrigation application for individual NDT H1 and DT of H2, H3, and H4 hybrids (excluded negative data points). Grain production for an individual NDT and DT hybrids exhibited inter-annual and intra-annual variation for the same hybrids between the locations and years as well as for the same hybrid between the PPDs. The grain yield productions also showed variation between the hybrids within the same year. Grain productivity per 25.4 mm of irrigation application in the low-PPD ranged from 0.03 Mg ha^{-1} for DT H3 in 2010 at SCAL to 1.73 Mg ha^{-1} for DT H2 in 2011 at HAL. The NDT H1 had the lowest grain production per 25.4 mm of irrigation application as 0.03 Mg ha^{-1} in 2010 at MAL and it had the highest value of 2.41 Mg ha^{-1}) in 2011 at HAL. The productivity of DT H2 ranged from 0.10 Mg ha^{-1} in 2010 at SCAL to 1.73 Mg ha^{-1} in 2012 at HAL. The grain productivity for the DT H3 ranged from 0.03 Mg ha^{-1} in 2010 at SCAL to 1.62 Mg ha^{-1} in 2012 at HAL. The DT H4 had its lowest value of 0.08 Mg ha^{-1} in 2012 at WCREC and the highest value of 1.62 Mg ha^{-1}) was observed in 2012 at SCAL. The DT H2 had the highest grain production per 25.4 mm of irrigation application among all of the hybrids, locations, and years in the low-PPD category. In general, the DT hybrids had greater grain production per 25.4 mm of irrigation application than the NDT H1 in the low-PPD treatment. In the driest year in 2012, the NDT H1 had greater productivity (1.88 Mg ha^{-1}) at SCAL than all of the DT hybrids (0.36, 0.99, and 1.62 Mg ha^{-1} for DT H2, DT H3, and DT H4, respectively). However, at the drier location at MAL, all of the DT hybrids had greater grain productivity than the NDT H1 per unit of irrigation. When all years and locations were averaged for each hybrid, DT H3 had the highest grain productivity (0.81 Mg ha$^{-1)}$ among all of the DT hybrids.

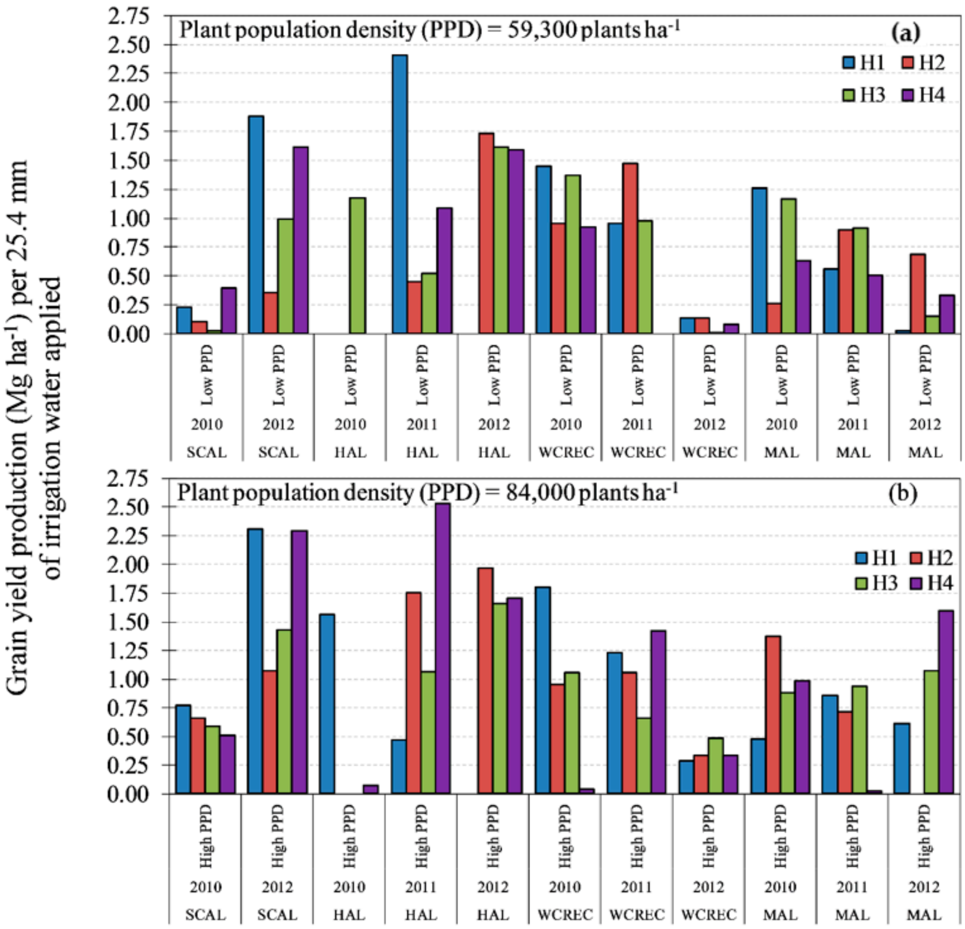

Figure 8. Grain yield production per 25.4 mm of irrigation water application for all hybrids, locations, and years under low (**a**) and high (**b**) plant population density (PPD).

The grain productivity of all of the NDT and DT hybrids was higher in the high-PPD treatment than the low-PPD. The productivity of the NDT H1 ranged from 0.29 Mg ha^{-1} in the driest year at WCREC to 2.31 Mg ha^{-1} also in 2012 at SCAL. DT H2 had its lowest value (0.33 Mg ha^{-1}) in 2012 at WCREC and the highest (1.97 Mg ha^{-1}) in 2012 at HAL. The DT H3 also had its lowest value (0.48 Mg ha^{-1}) in 2012 at WCREC. DT H4 hybrid's productivity ranged from 0.03 Mg ha^{-1} in 2011 at MAL to 2.53 Mg ha^{-1} in 2011 also at HAL and this hybrid had the highest productivity among all of the hybrids, locations and years in the high-PPD category. When the grain productivity was averaged among all years and locations, NDT H1 and DT H2, DT H3, and DT H4 hybrids had 5, 55, 21, and 31.2%, respectively, more productivity with high-PPD than low-PPD, which were associated with 0.05, 0.39, 0.17, and 0.25.4 Mg ha^{-1} of grain yield, for the same hybrids, respectively. There was a general trend of decreasing grain productivity per 25.4 mm of irrigation when moving from the sub-humid and transition zones in eastern and south-central Nebraska towards semi-arid climatic conditions in the west-central and western part of the state. The reduction in grain production per 25.4 mm of irrigation application when moving from sub-humid to western semi-arid part was more pronounced with the -PPD. For example, when the grain productivity values were averaged for all of the years for a given location, the amount of grain productivity per unit of irrigation application gradually decreased from sub-humid to semi-arid locations (from east to west) as 1.42, 1.20, 0.80, and 0.87 Mg ha^{-1} for HAL (eastern, sub-humid), SCAL (south central, transition zone between sub-humid and semi-arid), WCREC (west central, semi-arid), and MAL (western, semi-arid), respectively.

3.5. Irrigation Water Use Efficiency (IWUE)

The IWUE exhibited inter-annual variation among the hybrids, irrigation treatments, PPDs, locations, and years (Tables 5–8). The IWUE values were higher at both SCAL and HAL than WCREC and MAL for all DT and NDT hybrids. Among all 150 IWUE values that were quantified, there were numerous cases where the IWUE values were greater for the NDT H1 than the DT hybrids. The IWUE values were 3.75, 3.23, 2.98 and 3.17 kg m^{-3} for NDT H1, DT H2, DT H3, and DT H4, when the IWUE values were averaged across all years, locations, and irrigation treatments for the high-PPD treatment, respectively, with NDT H1 having the highest IWUE among all hybrids. The IWUE values for the low-PPD across all location, years, and irrigation treatments were 3.34, 2.22, 2.61, and 2.45 kg m^{-3} for the same hybrids, respectively, with NDT H1 having the highest IWUE among all of the hybrids. These findings indicate that the NDT hybrid showed greater yield difference between the given irrigated treatment (i.e., ECOT and FIT) and rainfed yield (rainfed yields were lower for the NDT H1 hybrid than DT hybrids in most cases), which reduced the yield deference between RFT vs. ECOT and RFT vs. FIT across locations and years. This result offers vital evidence that DT hybrids are more likely to produce more yields than NDT hybrid under RFT and/or water-stressed regions while maintaining higher/or comparable yield potential with NDT hybrid under FIT and/or non-stressed conditions. The average (across all years, locations, and irrigation treatments) IWUE values were higher in the high-PPD category than low-PPD for all hybrids, even though IWUE showed variation with years, locations, and irrigation treatments. On average, the IWUE values with the high-PPD were 11.1, 31.3, 12.5, and 22.8% greater than those that were observed with the low-PPD for NDT H1, DT H2, DT H3 and DT H4, respectively.

The PPD levels impacted the IWUE of NDT H1 to a lesser degree than all DT hybrids (3.75 kg m^{-3} with high-PPD vs. 3.34 kg m^{-3} with low-PPD when all years, locations, and treatments were averaged). When the IWUE values were averaged across locations and years, but separated by the PPDs and irrigation treatments (i.e., FIT and ECOT), the average IWUE values were 2.71, 2.28, 2.25, and 1.92 kg m^{-3} for NDT H1, DT H2, DT H3, and DT H4, respectively, for the FIT under high-PPD. While the IWUEs were higher than those in FIT as 3.62, 3.63, 3.14 and 3.90 kg m^{-3} for the same hybrids, respectively, for the ECOT under high-PPD. Similar observations (decrease in IWUE with increasing irrigation amounts) were also reported by other researchers [26–28]. On an all hybrids-average basis, the IWUE values were 21.1% (0.49 kg m^{-3}) and 16% (0.59 kg m^{-3}) higher for FIT and ECOT, respectively, under high-PPD than the low-PPD. There was no apparent trend in terms of any specific DT hybrid having higher IWUE than other DT hybrids.

4. Conclusions

The IYPFs, IWUE, and grain production per unit of applied irrigation of a NDT hybrid in comparison with three DT hybrids were quantified in four different climates, three years (2010, 2011, and 2012), three irrigation levels RFT, ECOT, and FIT under two PPDs. This research clearly identified that the grain yield response to irrigation was stronger with higher productivity in the driest and warmest year in the 2012 than other years at all locations and for all hybrids. The level of productivity not only varied substantially between the DT hybrids in the same location among the years, but also for the same hybrid among the locations and years, as well as with the PPDs. DT hybrids' performance was superior to a NDT hybrid at RFT, ECOT, and FIT conditions, as confirmed by the grain yield response, IYPF and IWUE, and when all locations, years and PPDs were averaged. Some of the DT hybrids had their highest and lowest grain productivity responses in the driest year in the 2012. The DT and NDT hybrids' average productivity response across sites and years were 21% higher at high-PPD than low-PPD. The magnitude of the highest yields for DT hybrids ranged from 7.3 (low-PPD) to 8.5% (high-PPD) under RFT, 3.7 (low-PPD) to 9.6% (high-PPD) under ECOT, and 3.9% (high-PPD) under FIT higher than NDT hybrid. The PPD levels impacted the IWUE of NDT H1 to a lesser degree than all DT hybrids with low-PPD when all years, locations, and treatments are averaged. Overall, the results indicated that DT hybrids could resist drought-stress conditions longer than NDT hybrid with fewer penalties in terms of yield reduction and maintain comparable and/or even higher yield production at non-stress-water conditions. These results can play a role in aiding in evaluating maize water productivity when planting DT hybrids under different PPDs and they can provide guidance in terms of expected crop productivity vs. water availability analyses and projections. The results of this research should be applicable to regions that have similar soil, climate, and management practices. However, the results should not be extrapolated beyond their boundaries.

Author Contributions: S.I. conceptualized and developed the ideas included in the manuscript. S.I. and A.T.M. worked on analyses, interpretation and writing the manuscript. A.T.M. worked on the field research and data collection under the supervision of S.I. S.I., W.K., S.v.D., and C.D.Y. provided resources to conduct field research. All authors have read and agreed to the published version of the manuscript.

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