ANALYSIS OF DROUGHT TOLERANT CORN PRODUCTION IN THE SOUTHERN HIGH PLAINS

by

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ABSTRACT

Corn (*Zea mays* L.) is an important crop in the Texas High Plains (THP). Chapter 1 of this study discusses why corn is such an important commodity for the THP as well as the challenges that farmers face when trying to produce a successful and profitable crop. These challenges include many stressors, both biotic and abiotic. Chapter 2 serves as a review of some of the stressors that corn producers face in the area, and reports production challenges that were observed in a two-year experiment, 2013-2014, conducted at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX. Corn earworms (*Helicoverpa zea*), spider mites (*Tetranychus urticea*), grasshoppers (*Caelifera*) and rust (Puccinia sorghi) were among the biotic stressors noted in the experiment. Abiotic stresses included heat stress, water stress, drought stress and severe weather events. A comparison of two corn hybrids is presented in Chapter 3. A drought tolerant and a conventional hybrid were planted in 2013 and 2014 at three different irrigation treatment levels (100%, 75% and 50%). The purpose of this study was to investigate the performance of a drought tolerant hybrid by comparing yields, crop water use (ET_c), water use efficiency (WUE), and harvest index (HI), with a common hybrid. Grain yields for the drought tolerant hybrid were similar to the conventional hybrid for all irrigation treatment levels, while ET_c was always numerically less. However, more research needs to be conducted on these drought tolerant hybrids in more extreme drought conditions.

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CHAPTER I

INTRODUCTION

Corn (*Zea mays* L.) is an important commodity in the Texas High Plains (THP). The Texas High Plains contains portions of both the Southern High Plains and the Central High Plains. Grain production is popular in these areas as the cattle feeding industry continues to grow. In recent years, corn production shifted upwards as it has become an increasingly important feedstock for ethanol, a fuel additive for vehicles (USDA-ERS, 2013). This change created competition in the industry and caused maize prices to skyrocket. With the introduction of ethanol plants in the area distillers' grains have become a popular feed for livestock due to its high nutrients, increased availability and lower cost compared to raw grain (Klopfenstein et al., 2014). The THP is responsible for approximately 3-5% of the total maize production in the United States (USDA-NASS, 2013). Although the potential for high yields and net returns make maize production attractive over other grain crops, global climate change, irrigation requirements and limited available water for irrigation make the sustainability of maize production questionable in this region.

Corn is a C4 crop, meaning that it is very efficient (Gowik and Westhoff, 2011). Although it uses water efficiently it still demands a lot of water to be productive which makes corn a difficult crop to grow in the area. Water is a limited resource in the THP and is becoming more scarce. Farmers are always looking for ways to continue growing corn and this can’t be done unless they are able to sustain profitable yields. New drought tolerant corn hybrids are an option that producers are turning to. Considering alternate irrigation methods or partitioning fields between corn and crops that demand less water are other options that are common practice (Scanlon et al., 2012).

Aside from water, area producers face other challenges that include abiotic and biotic stresses. Abiotic stressors include weather (drought, flooding, and hail), water stress and heat stress. Biotic stressors are organisms that cause damage, which include insects and disease. These stresses will be discussed in Chapter 2 of this thesis. Chapter 3 will present results from a two year study comparing the performance of a drought tolerant corn hybrid with a conventional corn hybrid grown under deficit irrigation at Bushland, Texas during the 2013 and 2014 cropping seasons.

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CHAPTER II

STRESSES IMPACTING CORN IN TEXAS HIGH PLAINS REGION

ABSTRACT

Corn (*Zea mays* L.) is an important crop in the Texas High Plains (THP). It serves as a feedstock for ethanol and livestock production. However, corn producers face many challenges when trying to produce a successful crop. These challenges include many stressors, both biotic and abiotic. This paper serves as a review of the stressors that corn producers face in the area, and reports production challenges that were observed in a two-year experiment, 2013-2014, conducted at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX. In the two-year experiment, two corn hybrids, one drought tolerant (P0876HR) and one conventional (33Y75), were grown side-by-side. Both hybrids were irrigated at a full, a mild deficit and a severe deficit irrigation amount. During both growing seasons, air temperatures were rather mild; however, corn biomass and grain yields in the severe deficit irrigation plots were reduced by 46% as compared with the fully irrigated plots. Corn earworms (*Helicoverpa zea*) were the main pest invading both hybrids during the two years, yet the destruction that they caused was determined to be less than 7% of total yield. Digital images were used to assess the damage to corn plants from hailstorms occurring in 2013, and results showed that the

P0876HR hybrid incurred less damage from this type of severe weather, but grain yields were similar to what was expected based on the seeding rate.

INTRODUCTION

Maize, commonly referred to as corn, has become an important commodity in the Texas High Plains (THP) regions in the last 50 years, despite its high water use and concerns of water withdrawals from the Ogallala Aquifer. This area of the High Plains consists of the southern portion of the Central High Plains as well as a majority of the Southern High Plains (Fig. 1). Grain production is widespread in this area as the cattle feeding industry continues to grow. In recent years, the popularity of corn shifted upwards as it has become an increasingly important feedstock for ethanol, a fuel additive for vehicles (USDA-ERS, 2013). This change created competition in the industry (Carter et al., 2012) and caused corn prices to skyrocket, whereas the price per bushel in May of 2013 was around $7.00 (NASS, 2015). With the introduction of ethanol plants in the area, distillers grains have become a popular feed for livestock due to its high nutrients, increased availability and lower cost compared to raw grain (Klopfenstein et al., 2008). Total corn production in the Texas High Plains combined is approximately 3-5% of the total corn production in the United States (USDA-NASS, 2013). Although the potential for high yields and net returns make corn production attractive over other grain crops, climate variability, abiotic stressors such as high temperatures, drought, and hail, biotic stressors such as disease and pestilence, irrigation requirements and limited groundwater availability impact the sustainability of profitable corn production in this region.

This paper focuses on the abiotic and biotic stressors that producers in the Texas High Plains region encounter, and provides specific data for stresses encountered at Bushland, Texas located near the southern edge of the Central High Plains (CHP) region (Fig. 1) during the cropping years of 2013 – 2014.

Abiotic Stressors

Water Stress

Lack of adequate soil water can affect yield quantity and quality. Supplemental irrigation is critical to profitable corn production and a deficit supply at any stage of growth can have a negative effect on total yield.

When soil moisture is reduced to the wilting point in the vegetative stage yield can be reduced by 25%. Physiological plant responses to water stress at the vegetative stage are reduced plant height (Denmead and Shaw, 1960; Gavloski et al., 1992; Payero et al., 2006; Traore et al., 2000), inability to produce ears or reduced cob length (Claassen and Shaw, 1970; Payero et al., 2006), reduced leaf area (NeSmith and Ritchie, 1992; Payero et al., 2006; Traore et al., 2000), leaf rolling (Sabrador, 1987), whiteness or greying of green tissue, and reduced elasticity due to reduced water content in the plant stem. Water stress affects the plants ability to take in nutrients, this inhibits the plants ability to accumulate biomass and eventually grain yield (Cakir, 2004).

Corn is most sensitive to water deficits during the flowering stage (Doorenbos and Kassam, 1979). Stress in the silking stage is more harmful to total grain yield than any other single stage because when soil moisture is depleted to the wilting point during silk a

50% reduction in grain yield can occur (Denmead and Shaw, 1960). When stress occurs during flowering, the anthesis-silking interval timing is thrown off causing poor pollination leading to reduced yield due to barrenness (Grant et al., 1989; Ribaut et al., 1996). Grain yield suffers most when water stress occurs near flowering stage due to reduced kernel size and increased barrenness caused by poor kernel set (Claassen and Shaw, 1970; Hall et al., 1981; Lorens et al., 1987).

The greatest loss in grain yield due to water stress occurs in the 25 day period following flowering (Campos et al., 2004). During ear growth (30 days after silking) yield can be reduced by 21% when soil moisture is depleted to wilting point (Denmead and Shaw, 1960). Water stress in the grain filling stages reduces grain yield by limiting kernel size, ear size, and weight per kernel (Campos et al., 2004; Claassen and Shaw, 1970). When a corn crop experiences stress before silking, pollination ear size and kernel number are reduced, when stressed after silk, weight per kernel is negatively affected or reduced (Claassen and Shaw, 1970). However, if irrigation is applied to the crop near the black layer stage (physiological maturity) an increase in grain yield may not occur since the crop can no longer take up the water that is in the soil, thus plant available water remains in the soil profile (Payero et al., 2006).

Stress during the ear development (silk to blister) causes loss of lower leaves, leading to decreased biomass as well as grain yield from loss of photosynthesis. Total dry matter accumulation was reduced up to 25% when not irrigated at tassel. Water stress during the tasselling and ear stages (tassel/silk and blister) or both reduces total grain yield (Cakir, 2004).

With restricted seasonal rainfall, limiting irrigation to 50% of evapotranspiration (ET) throughout the growing season in the lower Central High Plains and Southern High Plains region leads to reduced grain and biomass yields, water use efficiency, harvest index, kernel weight and kernel number for conventional hybrids (Howell et al., 1995; Lyle and Bordovsky, 1995; Schneider and Howell, 1998) and drought tolerant hybrids (Hao et al., 2015).

Heat Stress

Plant growth for corn hybrids occurs in ambient air temperatures above 10 °C and below 35 °C (Singh et al., 1976). Higher ambient temperatures can lead to heat stress. Heat stress can be defined as "the rise in temperature beyond a threshold level for a period of time sufficient to cause irreversible damage to plant growth and development" (Okunlola and Adelusi, 2013). Heat stress can cause delayed germination or decreased seedling vigor, which can lead to reduced stand densities. At later growth stages heat stress may affect photosynthesis, respiration, water relations and stability of plant membranes (Wahid et al., 2007). Chronic exposure of corn plants to ambient air temperatures at or above 35 °C can lead to heat stress, which often results in delays in flowering and decreases the developmental rate of corn in the grain filling stage (Cicchino et al., 2010). Apraku et al. (1983) reported that when corn plants were exposed to ambient temperatures above 35 °C from pollination to grain fill, significant losses in grain yield occurred. Losses at the ear stage are typically due to reductions in the number of kernels per ear (Carcova and Otegui, 2001), grain weight per plant and kernel size (Duke and Doehlert, 1996). An extended period of heat stress in the grain filling stage alone can also result in a reduction of kernel dry weight as shown by (Wilhelm et al.,1999) across multiple corn hybrids. Pollen shed and viability are also adversely affected by exposing corn plants at tasseling to ambient temperatures near 38 °C (Schoper et al., 1987). Reduction in pollen shed and viability lead to declines in seed-set and the number of kernels per ear (Schoper et al., 1986). Figure 2 depicts how many days were spent in a variety of temperature ranges during the growing season. The number of days that were above 35°C were 25 and 11 for 2013 and 2014, respectively. 2013 was the only year out of the two study years that experienced temperatures above 38°C, June 26 and 27 (DOY 177, 178), which was during V6-V7 stage. Overall, 2014 was cooler than 2013 promoting better growing conditions for corn.

The Texas High Plains region can experience a relatively mild climate; however, there are occurrences of extremely high temperatures for days to weeks at a time, especially during the months of June, July and August. High air temperatures coupled with continuous high winds can become an issue with or without adequate soil moisture or within season precipitation.

Extreme Weather Events

Average rainfall for the Bushland, TX is 538.25 mm; however, rainfall can be greater or less with record lows as little as 169.93 mm (2011) and as high as 897.63 mm (1941). Rainfall for the THP area decreases from west to east (averages of 452.22 mm, 522.83 mm, 567.82 mm) based on data from weather stations within 1° latitude and longitude quadrants (collected from 1940-2013)(Fig. 3). The north to south gradient isn’t as distinct with averages of 482.94, 528.57, 489.20, 517.78 and 481.20 from north to south (Texas Water Development Board, 2014) for the 105, 205, 305, 405, and 505 quadrants (Fig. 3).

Drought or lack of rainfall for an extended period of time is usually coupled with above-normal temperatures. Beginning in October of 2010 and throughout 2011, severe drought affected the southern United States. In Texas, this drought had historic rainfall lows of up to approximately 66% below normal paired with one of the hottest summers on record (Anyamba et al., 2014). This drought also had major adverse impacts on most range and pastures in Texas, resulting in direct losses of more than $7.6 billion associated with agriculture alone (Tadesse et al., 2014). Figure 4 shows the total hectares of corn planted and harvest as well as average yield for the THP. A significant drop can be observed for 2011, especially in harvested hectares, this was due to the severe drought whereby farmers were unable to keep up with water demand for their corn crop. The increase in planted acreage that occurred after 2005 is due to the increase in corn priced due to ethanol production. Corn yields have gradually risen to the levels prior to the 2011 drought.

Drought is not 100% predictable but there are some signs that might show when a drought year is a higher possibility. El Niño and La Niña are extreme weather events caused by the strength of trade winds and temperature of seas (Tack and Ubilava, 2013). In the plains of Texas an El Nino year tends to be more favorable for crop production due to its tendency to bring more moisture into the area. La Nina bring dryer weather to the Texas High Plains and have been known to last up to 3 years, providing the area with droughty conditions for multiple growing seasons (Nielsen-Gammon, 2012).

The farther west you move away from the Corn Belt into the Great Plains the more severe the effects are without supplemental irrigation (Campos et al., 2004). Furthermore, variability in yield response increases as irrigation amounts decrease (Klocke et al., 2011). Lack of moisture is even more damaging when coarser soils are present (Campos et al., 2004). In the Southern Great Plains, a semiarid environment, the average annual precipitation varies from 405 to 560 millimeters (USDA NRCS, 2006). In recent years this amount has decreased tremendously with to 371.60, 169.93 and 265.94 millimeters measured at USDA-ARS Bushland in 2009, 2011 and 2012 respectively.

Aside from water, one could argue that extreme weather is the other main abiotic factor that contributes to stress in corn. Recent flooding and intensive precipitation events in the US Midwest, North Dakota, and along the Mississippi River have caused billions of dollars in damage and losses to crop production (Rosenzweig et al., 2002). El Niño-Southern Oscillation (ENSO) tends to cause flooding in fields, while La Niña tends to cause drought conditions (Tack and Ubilava, 2013).

Hail, another extreme event can also cause extensive crop damage. Three types of damage commonly occur in corn after a hail storm; stand reduction, defoliation, direct ear damage (later in season). However, there is limited documentation on specific hail events and the integrity of recent corn hybrids to withstand severe storms.

The National Corn Handbook, Assessing Hail Damage to Corn (Vorst, 2002) breaks down multiple methods to estimate yield loss. Since the growth point of the corn plant is under ground until the seven leaf stage, damage is minimal when a storm occurs prior to the V7 stage. From the V7 stage to tassel, the plant is most vulnerable to damage and yield reduction, once past tassel, the amount of yield reduction when damaged is reduced as the plant matures further. Step-by-step directions as well as a chart are provided in the handbook for analyzing and assessing damage for both plant population and stand reduction and defoliation. A formula is also provided for calculating direct ear damage that occurs during storms later in the year (Vorst, 2002).

Shapiro et al. (1986) compared predicted and actual damage values to see how accurate insurance companies' damage charts are. They found that complete defoliation of plants up to the 6 leaf stage did not significantly affect grain yield. In the 6 through 9 leaf stage a 100% defoliation caused a decrease in grain yield with a regression coefficient of -1.15 as the plant matures. When defoliated at a 0, 33, 66, and 100% rate at the 6-, 12-, tassel, and blister stages, grain yield decreased as the defoliation percentage increased, and showed a greater yield reduction than insurance adjustment protocol. Population density was reduced from 6.4 plants m^{-2} to 5.9, 4.9, 4.0, and 3.0 plants m^{-2} at the 6, 9, 12 and 15 leaf stages, respectively. Yield was lost with each population decrease; however, the loss was less that what was predicted in the insurance charts (Shapiro et al., 1986).

Two hail storms were observed on this experiment in 2013, May 28 and June 17, photos were taken of the crop after each. The storm occurring on May 28 (14 days after planting) was severe and contained hail up to 50 mm in diameter. Figure 5 shows the crop field after the first hailstorm. The crop was in the V2 stage. It was decided to keep the crop due to its young stage, rather than re-plant.

The second hailstorm was less severe and occurred just before the crop entered the V6 stage (33 days after planting). Through visual observation, it was apparent that the

P0876HR variety was less affected by the storm; buggy whipping and leaf damage were observed more within the 33Y75 variety. P08976HR variety was a larger plant at the time of the storm, and more mature (near V6) than the 33Y75, because it is a shorter season variety allowing it to advance through vegetative stages at a higher rate. Figure 6 shows typical hail damage suffered by each variety. Photos were taken from each of 60 treatment plots (30 from the 33Y75 and 30 from the P0876HR) at a nadir-looking view at approximately 2 meters above the canopy enclosed within the 1 m^2 aluminum foil coated frame. The analysis from these digital photos of the damaged corn plants (33Y75 and P0876HR) was accomplished with Multispec (2012, Ver. 3.3, Purdue Research Foundation). The photos were cropped as close as possible to the frame using LView Pro Image Processor and then imported to MultiSpecW32 for further processing. Once imported the photos were converted to a GIS file and analyzed using 11 different classifications. Classes were divided into vegetation or soil according to best visual fit. After the classes were characterized, the percentages of soil and vegetation were calculated and recorded into excel. An analysis of variance was run on the data from both varieties and it was determined that there were unequal variances. A t-test assuming unequal variances was run and confirmed that there was significantly less leaf area per frame in the 33Y75 variety compared with leaf area amounts in the P0876HR variety (P value of 0.01 at an alpha of 0.05)(Table 1). Existing leaf material from the 33Y75 was observed to be more torn and tattered compared with the P0876HR variety. Data from initial stand counts and from harvest data showed that there was minimal change in plant counts from the beginning of the season to the end.

Biotic Stress

The biotic stress factors include disease and pestilence issues that affect the corn plant throughout the season. Injury from disease and pestilence can be chronic or acute, and can weaken a plant, deplete the plant of needed nutrients, cause significant yield losses or reduction in yield quality, and even plant death. Microorganisms responsible for plant diseases can impact both the upper part of the plant and the root system (De-la Peña and Loyola-Vargas, 2014). Plants under water stress may be more prone to insect infestation (Brewer et al., 2014).

Corn Earworm- Potentially the most damaging crop pest in North America the corn earworm can destroy yield by feeding on the silk and even young kernels of the corn plant. In southern areas such as Texas the corn earworm can have as many as seven generations in a single growing season due to its life cycle being completed in about 30 days. Mature earworm larvae fall to the ground and bury themselves about 10 cm below the surface where they pupate and turn into moths. Earworms generally only harm the tip of the corn plant but can affect as much as half of the ears kernels. They tend to feed on a sole ear until their larvae growth stage is complete. Monitor silk for larvae presence as well as within the whorl for early stages of corn earworms since eggs are difficult to detect (Capinera, 2000).

The corn hybrids previously used a Bt (*bacillus thuringiensis*) trait that was designed and incorporated into the seed to discourage harmful insects from inflicting major damage on crops. Bt traits can significantly minimize the damaged on ears and kernels caused by European corn borer (*Ostrinia nubilalis*)(ECB) and corn earworms. Damage from ECB on non-Bt and Bt was reduced from greater than 10% to 0% respectively. No significant reduction occurred between Bt and non-Bt hybrids when affected by the corn earworm. However, the number of damaged kernels per ear was up to three times less with the high level Bt hybrids over non-Bt hybrids (Dowd, 2001). The study also showed how the addition of Bt traits to commercial corn limits the amount of ear mold (mycotoxin) by reducing the number of harmful insects. Pest resistance to Bt has become an issue. A study done in multiple countries, including the United States, found that single stack Bt traits have done well to control Lepidopteran pest. The resistance was minimal with all pests except H. Lea, Corn Earworm. Seed companies are implementing stacked Bt traits to minimize pest resistance, where multiple toxins will be present for pest consumption. The study also noted that the use of refuge is a key part of implementing a successful pest management program (Tabashnik et al., 2008).

No designated refuge was planted in 2013. In 2014, refuge was planted in the inner and outer borders of the center pivot field. Refuge is required to allow pest to eat non-Bt varieties in order to slow and possibly even avoid resistance to the Bt trait. For our cropping region, 50% of the cropped area must be planted to refuge. This means that in 2014, 5.25 ha of our 10.52 ha field was planted in a non-Bt hybrid. This didn't, however, prevent the damage on the Bt corn; damage was still observed, predominately on the ear tip, at a level not economically harmful. No difference in worm damage was visually noted between the 2013 and 2014 growing seasons.

Ears were photographed throughout the season to keep track of crop stage as well as make note of amount of worm damage. Ear tips in photos taken prior to ear thrashing were damaged due to becoming brittle during drying. The photos were analyzed to determine the percentage of worm damage on a 10 ear sample per plot. MultiSpec was used to analyze the damage amounts but due to the background in the photos an accurate result was not available. The method that was used was manually measuring the amount of grain as well as tip damage and calculating the percentage by hand. It was determined that there was less than 6% damage on the most severely damaged ears. Figure. 7 shows selected samples that were analyzed for worm damage.

Spider mites (*Tetranychus urticae*) are a common problem in crop production across the High Plains. Yield reduction occurs when photosynthesis and transpiration decrease due to tissue damage from chlorophyll removal within the leaves. The Banks Grass Mite (*Oligonychus pratensis*) and the twospotted spider mite, (*Tetranychus urticae*) Koch, are the predominant spider mite species infesting corn across the High plains of the US (Bynum et al., 1997). In corn in the THP, the rapid increase in spider-mite density was closely associated with tassel (Ehler, 1974). Uncontrolled large mite populations can cause damage at the grain fill stage and increase the incidence of lodging and stalk rot (Ehler, 1974). Spider mite were not observed in this experiment be were in a field about 1 mile north. Spider mites thrive in hot dry conditions. Control should be applied or implemented before the tassel stage. If mites are not controlled by the time the plant reaches tassel and grain development the mite populations increase exponentially. Chemical applications as well as a healthy population of predatory insects are both effective ways of controlling spider mites (Bynum, 2014). If available, irrigation should be applied in order to wet and cool the canopy temperature enough to discourage and prevent spider mite spread and damage.

Common rust (*Puccinia sorghi*) is a fungus carried by the wind that affects corn crops throughout the THP. Common rust is identified by red, oval shaped pustules on the upper and lower side of the leaf. In dent corn heavily infested areas only suffer a yield loss of less than 3%. Management can be obtained by planting resistant hybrids and applying fungicides (Texas Cooperative Extension, 2005). Common rust was noted in the field in both 2013 and 2014 but was determined to be at a level that was not harmful to overall yield. Rust was noted sporadically on plants and would be well under 5% in areas that rust was observed. Munkvold and Yang (1995) observed the effects of major flooding in Wisconsin in 1993. The flooding caused common rust to affect leaf area greater than 40% in some hybrids and reduce yields by up to 50%.

There are many species of grasshoppers (*Caelifera*), but only five cause damage to crops. Multiple years of long, hot and dry summers encourage large population of grasshoppers because it allows increased survival of young (Patrick and Davis, 2004). Grasshoppers can also become a problem when irrigation and/or adequate rainfall are present (Mongkolkiti and Hosford, 1971). An article by Brunson and Painter (1938) mentions infestation of more than five grasshoppers per stalk, after chemical control was applied, was able to completely defoliate a corn stalk. With the additional rainfall in 2014, our field observations showed grasshopper issues to be on field edges as well as along pivot road. Very few, if any, grasshoppers were seen in the individual plots and zero grasshopper damage was noted within plot and sample area.

CONCLUSIONS

Corn production on the THP Region is fraught with challenges. Farmers have to contend with abiotic and biotic stressors, which can reduce yield and affect profitability. Two corn hybrids were grown under various irrigation levels to analyze their response to multiple biotic and abiotic stressors. Extreme weather events occurred in the form of hailstorms occurred early in the 2013 growing season; in late May of 2013 a storm carrying large hail hit our field. The result of the storm was not detrimental to our yield because the growth point was still underground. Another less severe hail storm occurred in June of 2013 when the plant was nearing V6 stage. Digital analysis confirmed that the drought tolerant variety was determined to have weathered the storm significantly better than the conventional hybrid. Drought and heat stress are other factors that greatly affects crop production and this article highlights what previous research has to say about irrigation scheduling during critical growth stages. Producers will continue to face challenges with pests due to resistance build up but proper agronomic practices and implementing good integrated pest management will help alleviate some of the economic hardships.

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Table 1. Two-Sample t-Test of average leaf area per plot in a $1m^2$ area sampled on June 24, 2013. The test assumes unequal variances.

	P0876HR	*33Y75*
Mean	35.61	28.93
Variance	70.88	124.09
Observations	30	30
Hypothesized Mean Difference	0	
df	54	
t Stat	2.62	
P(T<=t) one-tail	0.005	
t Critical one-tail	1.67	
P(T<=t) two-tail	0.011	
t Critical two-tail	2.005	

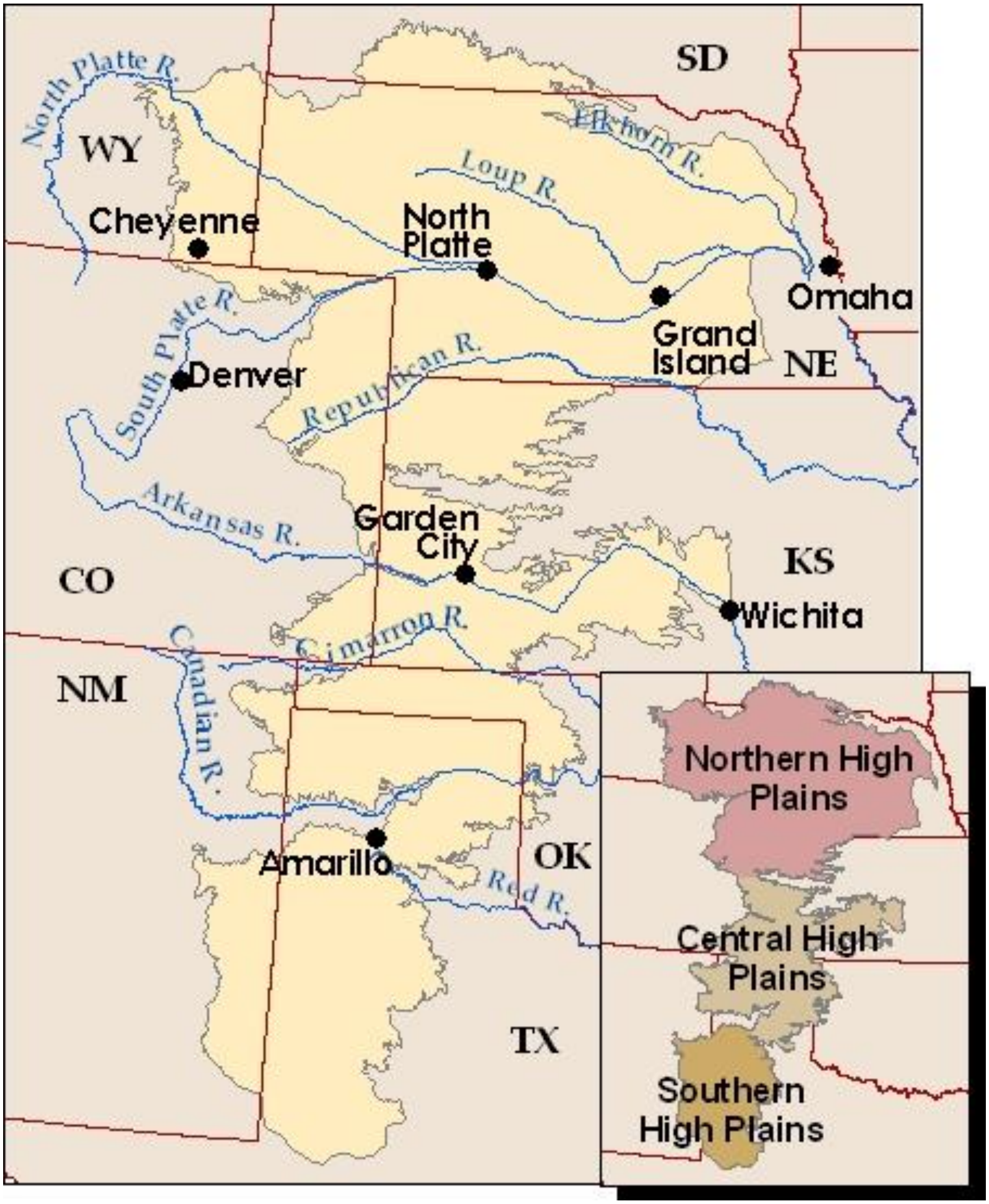
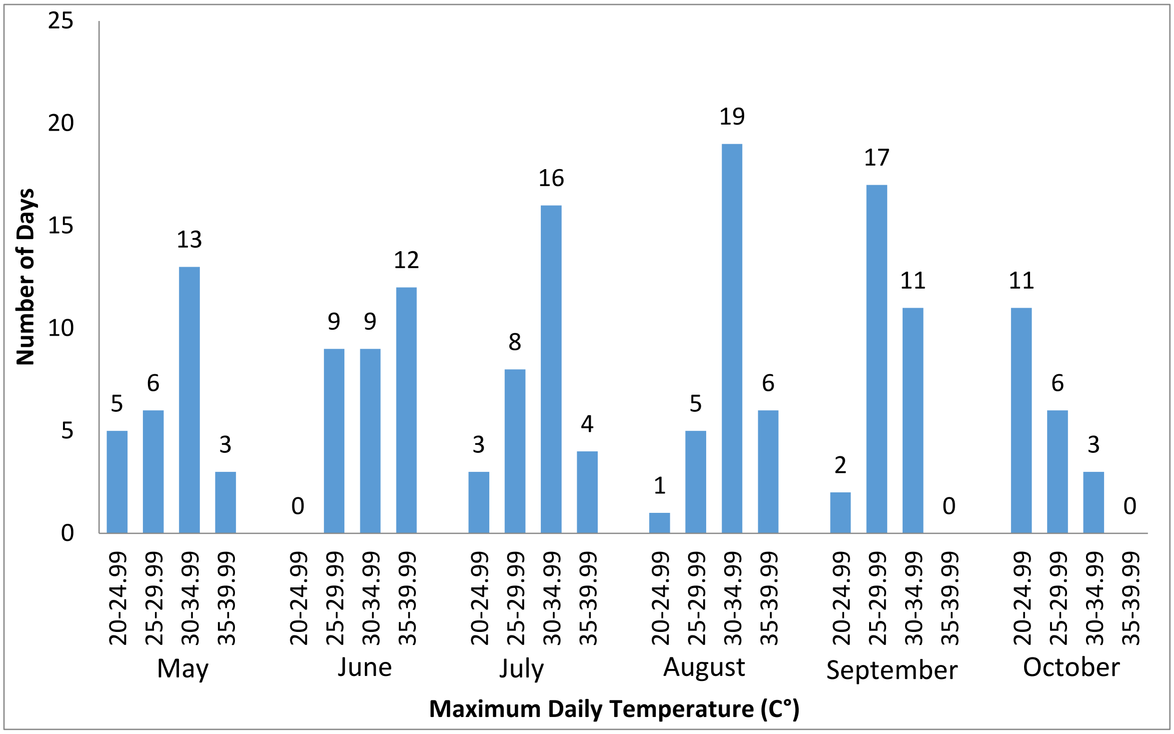
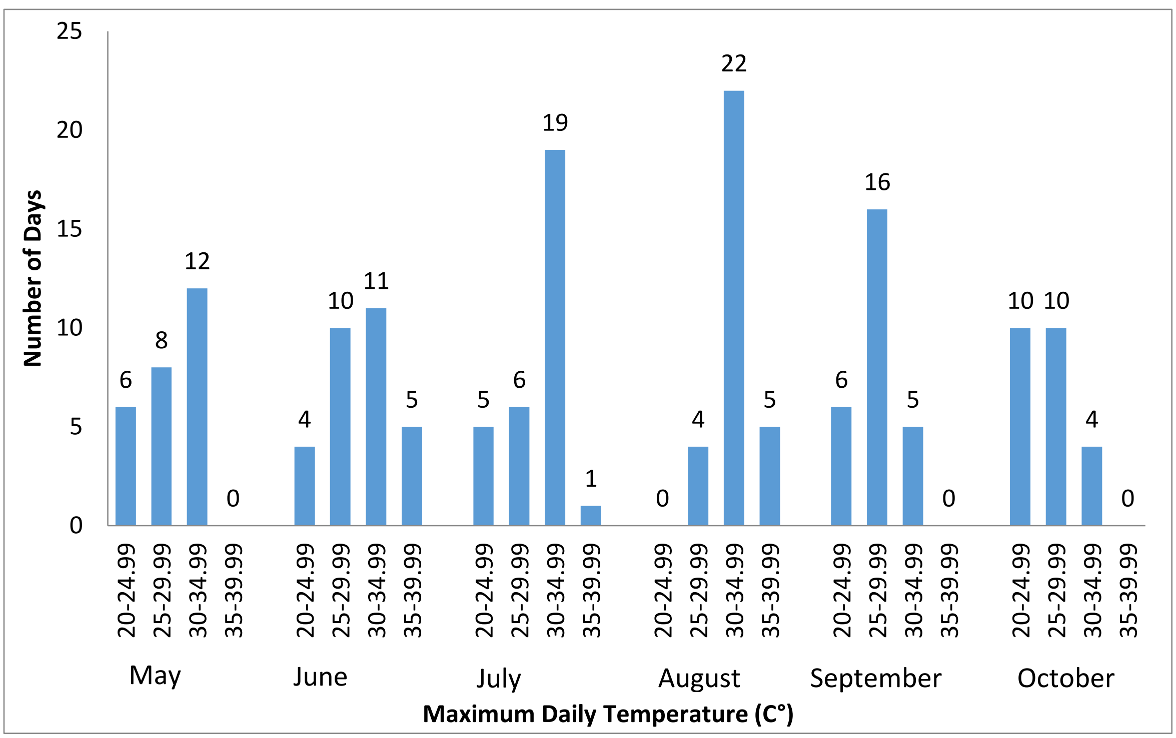


Figure 1. Map depicting regions of the High Plains as well as the underlying Ogallala aquifer (USGS, 2013).



a.



b.

Figure 2. Distribution of days and maximum air temperature range during each month of the growing season for: (a): 2013 and (b): 2014.

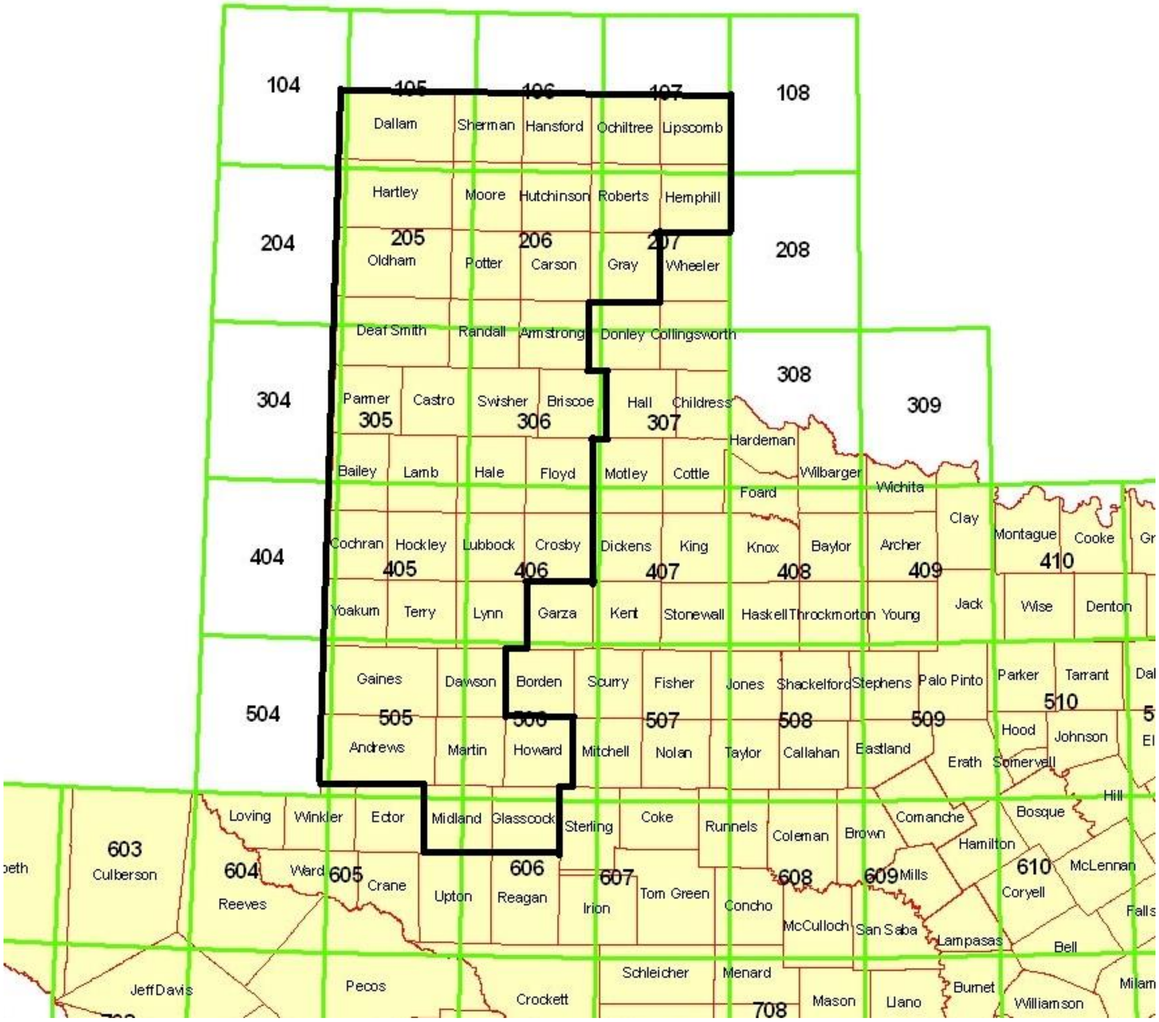


Figure 3. The Texas High Plains (THP) is shown outlined by thick border. This map of quadrants is made available by the Texas Water Development Board (2015) at http://www.twdb.texas.gov/surfacewater/conditions/evaporation/.

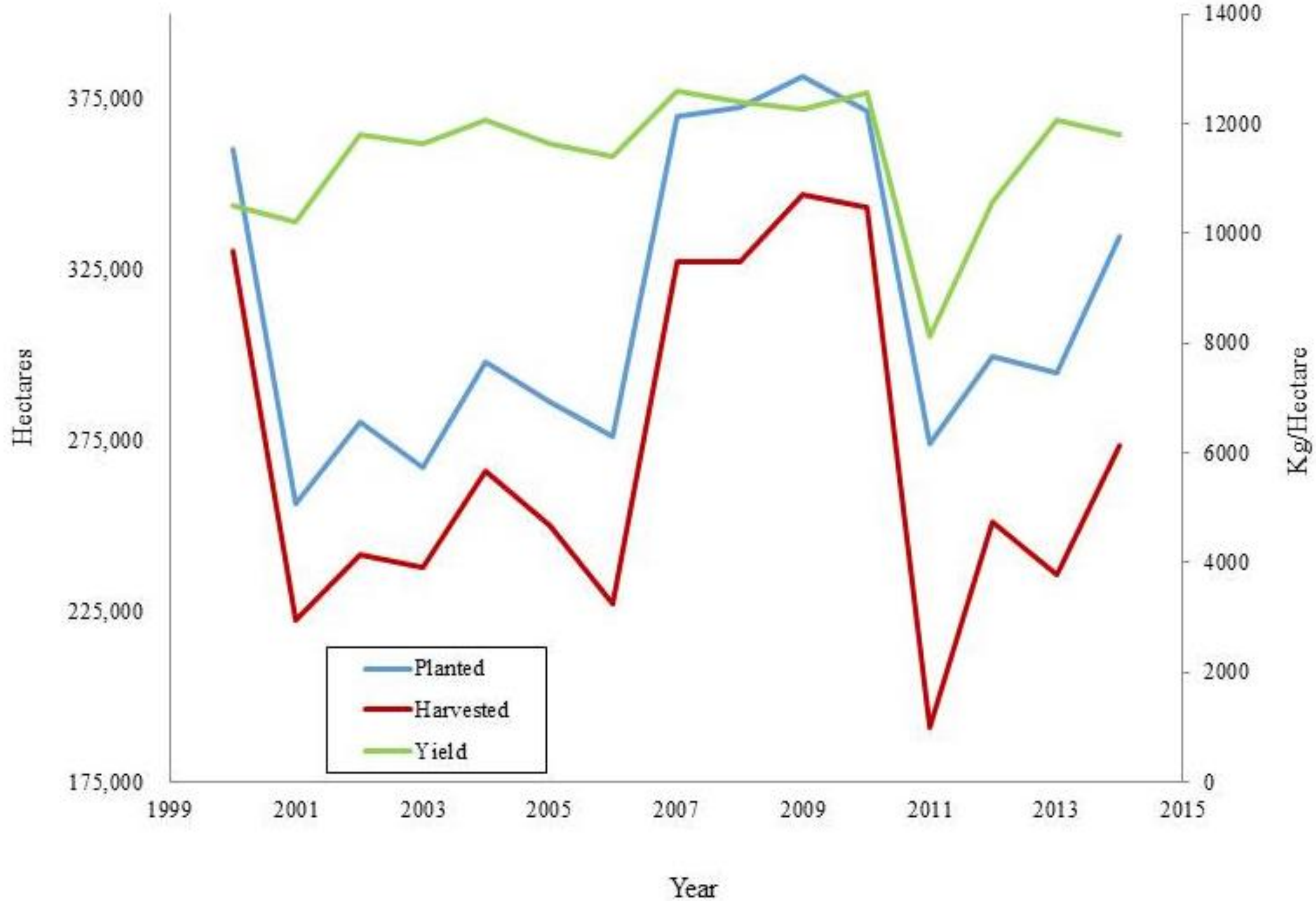


Figure 4. Yearly data on the amount corn planted in hectares in the Texas High Plains along with average yield produced in those years

a.

b.

c.

d.

Figure 5. Damage to plants and pivot field after May 28, 2013 hail storm at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas.

33Y75 Plot 1

P0876HR Plot 2

33Y75 Plot 32

P0876HR Plot 31

33Y75 Plot 55

P0876HR Plot 54

Figure 6. Comparison of damage on two varieties after second hailstorm. Storm occurred on evening of June 16th, 2013. Both varieties were planted on the same day.

a.

b.

Figure 7. Images of worm damage to ears: (a) is from plot 53, P0876HR, in the 2013 season, which was located in a C50 plot and (b) is from plot 38, a C100 treatment 33Y75 variety, in the 2014 growing season. Damage was calculated at 3.73% and 5.6% for (a) and (b) respectively.

CHAPTER III

CROP RESPONSE BETWEEN TWO CORN HYBRIDS IN A SEMI-ARID ENVIRONMENT

ABSTRACT

In the Texas High Plains Region, corn (*Zea mays* L.) is an important commodity to producers, especially since it can bring in a high price. However, under limited quality water resources, its high water use may not match the well capacity of irrigation systems, especially under drought conditions. Drought tolerant corn hybrids could allow farmers to continue to irrigate corn in a sustainable manner in this region, depending on grain and biomass yields and crop water use of these new hybrids. In this two-year study (2013 and 2014), two hybrids, Pioneer AquaMax P0876HR and Pioneer 33Y75® were planted under a center pivot in a randomized complete block pattern, and irrigated at levels of 100%, 75%, and 50% replenishment of crop water use to field capacity. The P0876HR hybrid was rated as more drought tolerant than the 33Y75 hybrid, a common short season hybrid grown in the Texas High Plains. The purpose of this study was to investigate the performance of the drought tolerant hybrid by comparing yields, crop water use (ET_c), water use efficiency (WUE), and harvest index (HI), with the common hybrid. In the

drier year (2013), grain and biomass yields were not different between hybrids compared within the same irrigation treatment level. Crop water use was greater for the 33Y75 hybrid in the 100% treatment. Grain WUE was greater for the P0876HR hybrid in the 75% and 50% irrigation treatment levels. Kernel weight for the P0876HR hybrid was greater than the 33Y75 hybrid at the 75% irrigation treatment level. In 2014, seasonal rainfall was greater than normal. Similar to 2013, grain yields were not different between hybrids within the same irrigation treatment; however, ET_c was greater for the 33Y75 hybrid in the 100% and 75% treatments. Average overall biomass for the 33Y75 hybrid was greater than the P0876HR hybrid in 2014. Kernel weight and number were not different between hybrids. Harvest index was greater for the drought tolerant P0876R hybrid within each irrigation treatment level.

INTRODUCTION

Irrigated corn yields are typically two to four times greater than rainfed corn in the Southern High Plains (SHP) region (Baumhardt et al., 2013; Colaizzi, et al., 2008). Corn yields vary with soils, surface tillage, irrigation application methods, hybrids, and seasonal climatic differences. Evapotranspiration of corn for the THP region ranges between 431 and 984 mm (Howell et al., 1998). Grain yields for fully-irrigated conventional corn hybrids in this region ranged between 0.55 and 1.55 kg m^{-2} as reported in studies performed in Bushland and Plainview, Texas. Eck (1986) irrigated Pioneer corn hybrids 3369A (1976) and 3184 in1977, 1978 and 1979 in a Pullman clay loam using furrow irrigation and realized yields between 0.83 and 1.12 kg m^{-2} with WUE ranging from 0.84 to 1.43 kg m^{-3}; Lyle and Bordovsky (1995) reported yields between 1.09 and 1.22 kg m^{-2} for the Asgrow RX905 and RX788 varieties grown in Olton loam soils using low energy precision application (LEPA) drag socks. Water use efficiency ranged from 1.49 to 1.94 kg m^{-3} for 100% of ET irrigation treatments. Howell et al. (1995) planted Pioneer 3245 in 1992 and 1993 and also irrigated with the LEPA technique achieving yields of 1.25-1.55 kg m^{-2} and WUE of 1.34-1.35 kg m^{-3}. Schneider and Howell (1998) and Howell et al. (1998) observed yields of 1.26 -1.44 kg m^{-2} and 1.13-1.43 kg m^{-2}, respectively, and WUE of 1.65-1.76 kg m^{-3} and 1.52-1.68 kg m^{-3}, respectively.

In previous studies, at lesser irrigation treatment levels, yields declined. Yields and WUE at irrigation levels of 70-75% of ET ranged from 0.77 to 1.17 kg m^{-2} and 0.01 to 1.62 kg m^{-3}; while those irrigated at 50% ranged from 0.01 to 0.89 kg m^{-2} and 1.53-2.14 kg m^{-3}. Howell et al (1995) showed dryland production to be 0.6 and 0.4 kg m^{-2} for yield and 0.97 and 0.89 kg m^{-3} for WUE in 1992 and 1993, respectively. However, the seasonal rainfall amounts (April-October) were 446 mm in 1992 and 264 mm in 1993.

Harvest index (HI) is important when analyzing the increases in yields seen throughout history because it shows the allocation of photosynthesis between the vegetative and the grain portion of a plant (Sinclair, 1998). Harvest index is the best way to show the partitioning of a plant's economic yield compared to its total above ground biomass. This means that if field corn is desired for its high grain production and nothing is going to be gained from its stover, then a high HI is the goal. Conversely, silage corn, for example, needs to have as much biomass as possible; therefore a low HI would be the target. High HI values are positively correlated to a hybrid's production efficiency and is a possible factor in evaluating criteria of corn growth and production (DeLoughery and Crookston, 1979).

Maintaining grain productivity, quality and quantity, with less irrigation water is critical for sustaining corn production in the THP. Producers now have multiple options to choose from when looking for a drought tolerant corn hybrid. Among the options are drought tolerant hybrids developed through advanced breeding techniques as well as advancements in biotechnology. Strategies for breeding stress-tolerant corn hybrids include screening and selection under deficit irrigation, multi-location testing of progenies in a representative sample of the target environments, and selection under high plant populations (Fengling et al., 2008). New and changing technologies have allowed corn hybrids to have an improved response to deficit irrigation and water stress (Dale and Daniels, 1995; Lorens et al., 1987). Heritable secondary traits such as a decrease in the anthesis-silking interval, an increase in the photosynthetic rate during dry periods, leaf-erectness, and tassel size can be factors that can aid in drought tolerant research in corn (Campos et al., 2004). Advanced technologies in genetic modification or selective breeding have also enabled the commercialization of drought tolerant hybrids of corn to be readily available for producers to purchase. Monsanto released commercially available transgenic or genetically modified products in 2013. Their technology, called Genuity® DroughtGard™, hybrids use a stress response gene that was originally found in bacteria to enable the plant to slow the rate of water absorption from the soil in drought conditions. This can allow plants extra time to receive rainfall but does not guarantee profitable yields (Eisenstein, 2013; Monsanto, 2013). Traits from native plants can be used in developing hybrids with a higher tolerance to stresses common to that area (Rommens, 2004).

The Pioneer AQUAmax corn lines are non-transgenic hybrids. Yield gains up to 8.9% greater in drought and 1.9% greater in non-drought conditions are claimed in over 11,250 on-farm comparisons with corn hybrids that were within ± 4 Comparative Relative Maturity (CRM) (DuPont Pioneer, 2013). The CRM relates to the amount of heat required for a hybrid to reach maturity. Most modified varieties perform well in one condition or another, such as under drought conditions or conditions of high air temperature. If yield productivity is significantly greater than competitive conventional hybrids, this product has the potential to change producers' hybrid choices as well as the amount of water used throughout semiarid environments with retreating water tables. It could also help lead the way in the development of other desirable traits and hybrids for future production.

As of yet, there is a limited amount of research publications available on the response of drought tolerant corn hybrids to limited irrigation regimes due to their recent release. Although not well documented in publications, websites from seed companies (DuPont Pioneer, 2013) indicated that drought-tolerant traits of the newest corn hybrids are expressed as increased stay-green characteristics or the ability to photosynthesize under drought conditions as measured by the amount of water and chlorophyll remaining in the leaves at maturity (Thomas and Smart, 1993). Traits are also expressed by enabling the plant to preserve leaf area under heat and water stress, and allowing better kernel set, and stomatal control to help limit transpiration, but maintain photosynthesis when water is limited (DuPont Pioneer, 2012; DuPont

Pioneer 2013). Along with selecting for drought tolerant traits, Pioneer incorporates "Native Trait Technology" meaning they strive to include key native traits such as enhanced fibrous root systems allowing the plant to capture as much deep soil water as possible and vigorous ear silking to increase kernel set in their breeding programs (DuPont Pioneer, 2013). A two year study using Pioneer AQUAmax hybrid (P1151HR, 111 CRM) and a conventional hybrid was conducted in Etter, Texas in 2011 and 2012 (Becker, 2013). Results showed grain yields of 1.13 kg m^{-2} and 1.20 kg m^{-2} and WUE of 1.66 kg m^{-3} and 2.02 kg m^{-3} at the 100% level for 2011 and 2012, for the drought tolerant and conventional hybrids, respectively. In 2011, grain yields at the 75% and 50% irrigation levels were 0.82 kg m^{-2} and 0.55 kg m^{-2}, respectively, for the P1151HR hybrid; for the conventional hybrid, yields were 1.10 kg m^{-2} and 0.52 kg m^{-2} for the 75% and 50% irrigation levels, respectively. In the 75% and 50% irrigation treatment levels, WUE were 2.12 kg m^{-3} and 1.25 kg m^{-3} respectively for the P1151HR hybrid, and 2.03 kg m^{-3} and 1.46 kg m^{-3} for the conventional hybrid. In 2012, grain yields at the 75% and 50% irrigation levels were 1.06 kg m^{-2} and 0.75 kg ha^{-2}, respectively, for the P1151HR hybrid; for the conventional hybrid, yields were 0.93 kg m^{-2} and 0.55 kg ha^{-2} for the 75% and 50% irrigation treatment levels, respectively. In the 75% and 50% irrigation treatment levels, WUE were 2.16 kg m^{-3} and 2.05 kg m^{-3} respectively for the P1151HR hybrid and 1.88 kg m^{-3} and 1.45 kg m^{-3} for the conventional hybrid.

Choosing the right hybrid coupled with proper agronomic practices (irrigation timing, planting rate, residue levels and crop rotation/selection) will help to aid in efficient irrigation management. Looking at how different varieties, specifically drought tolerant, react to different irrigation deficit levels will provide some insight on hybrid selection to maximize yields.

This study utilized two hybrids, a conventional and a more drought tolerant hybrid, to compare crop responses of grain, biomass, crop water use, and water use efficiency. Drought tolerance as ranked by Pioneer is based on a scale of 1-10 (1 being the worst, 10 being the best). Most hybrids that are readily available in the THP tend to be ranked at a 6 or 7 on the drought tolerance scale. The specific objectives of this study were to distinguish whether the Aquamax hybrid of drought tolerant corn was equally or more efficient than a conventional hybrid at producing grain and biomass yields at a high, slightly deficit and moderately deficit level of irrigation within the THP region. If these new drought tolerant varieties have competitive or greater yields with reduced water usage there could be a shift in the hybrid selection, agronomic practices and breeding/ technology modification of new hybrids by corn seed companies.

MATERIALS AND METHODS

Experimental site

Experiments were performed at the Conservation Production and Research Laboratory (CPRL), Bushland, TX (35°10'N, 102°05'W, 1169m above mean sea level). The field soil was a Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (Soil Survey Staff, 2004). The field capacity (0.33 $m^3 m^{-3}$) and wilting point (0.18 $m^3 m^{-3}$) water contents were assumed uniform across the center pivot field. The climate is semi-arid with an average annual rainfall of 470 mm. Half of the 20.4 ha pivot field was cropped each growing season, with the southwest side cropped in growing season 2013 and the northeast side cropped in 2014. Both hybrids were planted on the same day (DOY 134, May 14, 2013; and DOY 135, May 15, 2014) in concentric rows at a planting rate of 79,000 seeds ha^{-1}.

Corn hybrids and agronomics

Two DuPont Pioneer short-season hybrids, P0876HR and 33Y75, were used and were listed to reach relative maturity at 108 and 115 days, respectively, after planting. Short season hybrids are often used in this area since they tend to use less water in a growing season. Pioneer® Optimum® AQUAmax™ P0876HR was planted as the drought tolerant hybrid and Pioneer® 33Y75 was used as the check hybrid. The drought tolerant hybrid, P0876HR had a comparative relative maturity (CRM) of 108, a drought tolerance rating of 9, stalk strength of 3, and a plant height rating of 4, while the conventional hybrid, 33Y75, had a CRM of 115, a drought tolerance rating of 6, stalk strength of 4, and plant height of 6 (all ratings are based on a scale of 0-9, with 9 being the best performing as ranked by Pioneer). The 33Y75 hybrid was chosen due to its popularity with local producers along with is lower drought tolerance rating as compared with the P0876HR.

Both hybrids were planted on beds spaced 0.76-m apart under a six span variable rate irrigation (VRI) center pivot system. Irrigation treatments were applied using Low Elevation Spray Application (LESA), with nozzles placed approximately 61 cm above the surface, over every other furrow. Dikes were placed in furrows to reduce the amount of runoff as well as keep water within the plot area. Cultivation practices were similar to practices by local producers in the area practicing conventional till operation. Soil samples were taken and processed by Servi-Tech Laboratories (Amarillo, TX), a commercial soil testing laboratory, to determine the amount of fertilizer needed based on a yield goal of 13,809 kg/ha^{-1}. In 2013, fertilizer (32-0-0) was applied before planting at 196.6 kg N ha^{-1} using a JD6700 sprayer and then watered in with 30 mm, a second application of fertilizer was applied through a fertigation system at 75.3 kg N ha^{-1} with 9 mm of water. In 2014, fertilizer was only applied once at a rate of 252 kg ha^{-1} on DOY 94 (Apr 4). In 2013, G-Max Lite herbicide was applied at a rate of 3.5 liters ha^{-1} using a JD6700 sprayer (1 DAP, May 15). In 2014, Bicep Lite II Magnum was applied on DOY 129 (May 9) at a rate of 3.5 liters ha^{-1} (Table 2).

Treatments and plot design

For each of the two corn hybrids, three irrigation treatment amounts were applied (100%, 75%, and 50% replenishment of soil water depletion to field capacity) using two irrigation control methods (Automatic and Manual). Treatments were replicated five times in 2013 and six times in 2014. Plots were arranged in a randomized complete block design with hybrids as the main plot, and irrigation treatment level and irrigation method as the sub-plots. The hybrids were planted in a concentric pattern, 24 rows wide in 2013 and 12 rows wide in 2014. Plot widths were narrower in 2014 because additional unmixed-corn refuge for the P0876HR hybrid was unavailable and seed supply was limited. Irrigation treatment levels and method were arranged randomly in an arc-wise direction resulting in five replications in 2013 and six replications in 2014.

Manual irrigation scheduling

Manual irrigations were scheduled for every 3.5 days following soil moisture readings by neutron method which were taken weekly on at least the manual 100% treatment levels for each hybrid. Manual plots are designated as M100, M75, and M50 (Fig. 8, 9). A neutron probe (NP; model 503DR, Campbell Pacific Nuclear, Martinez, CA) was used to determine the soil water content and irrigations were scheduled for 100%, 75% and 50% of full field capacity replenishment based on readings in the top 1.5 m soil depth. Access tubes were placed near the center of all plots (24 rows in 2013 and 12 rows in 2014). The NP was calibrated to accuracy of better than 0.01 m^3 m^{-3}, resulting in separate calibrations from three distinct soil layers Ap, Bt and Btca, using methods described by Evett (2008), where Ap is the mineral horizon that has been plowed or disturbed; Bt is the subsurface horizon characterized by an illuvial accumulation of silicate clay; and Btca is subsurface horizon characterized by $CaCO_3$ accumulation. Rainfall that occurred before the irrigation was subtracted from the total irrigation required. Irrigation level was determined by the rate of discharge at nozzle, spacing between drop hoses, and the speed at which the pivot traveled. Early season irrigations for the first concentric plot in 2014 were inconsistent due to relay failure within the sprinkler zone on the variable rate irrigation system.

Automatic irrigation scheduling

Automatic irrigation scheduling was based on a plant feedback method using a thermal stress index as the threshold to control irrigations. Automatic control plots are designated as C100, C75 and C50 (Fig. 8, 9). The thermal stress index was determined using canopy temperature measurements and weather data. The analysis of the automatic plots was not part of my thesis work but are still included in plot plans.

Plant mapping

Stand counts were taken on DOY 156 (2013, number of plants in 10 m^{-2}) and DOY 149 (2014, number of plants per 1.5 m^{-2}) and were followed by weekly plant mappings (weather and time permitting). Measurements were taken from three representative plants near the center of each plot and averaged. At times, it was not possible to sample every plot, as some plots were inaccessible on plant mapping days because of a recent irrigation. However, a representative sample of plots from each hybrid and each treatment level were always included. Plant mappings that occurred during the vegetative stage consisted of height measurements, width measurements, plant counts, number of leaves, leaf angle and growth stage. Mappings during the reproductive stage consisted of growth stage, number of ears, leaf angle, and plant height and width (measured at the widest point). Height and width measurements were discontinued on DOY 233 (2013) and 240 (2014) until harvest, due to the plant ceasing to grow and beginning to put resources into ear production. Leaf angle readings were taken from the upper most collared leaf and the lowest full leaf. Plant stage was determined from the analysis of the majority of plants in each plot. Plant stage for various plots was observed and noted each time the field was visited (every other day) in order to pin point the growth stage change as close to its occurrence as possible.

Calculations

Evapotranspiration

Crop water use or evapotranspiration (ET) was calculated using the soil water balance equation:

$$\mathrm{ET} = P + I + F - \Delta S - R \qquad \text{[Eq. 1]}$$

where ET is evapotranspiration, P is precipitation (mm), I is the irrigation water applied (mm), F is flux across the lower boundary of the control volume (taken as positive when entering the control volume), ΔS is the change in soil water stored in the profile, and R is runoff, all in units of mm.

Water Use Efficiency (WUE)

Water use efficiency (WUE), is defined as

$$WUE = \frac{Yield\ (economic\ yield)}{(P_e + I + SW)} \qquad \text{[Eq. 2]}$$

where P_e is the effective rainfall, I is irrigation applied and SW is soil water used within the root zone during the growing season (Howell, 2001).

Harvest Index

Harvest index is defined as the ratio of grain yield to the total above ground biomass. (Singh and Stoskopf, 1971; AquaCrop, 2010; Sinclair, 1998):

$$HI = \frac{Grain\ Yield}{Total\ Above\ Ground\ Biomass} \qquad \text{[Eq. 3]}$$

Sampling and Harvest

Hand harvest for total above ground biomass was taken from a 1.5 m^2 area, while grain samples were taken from a 10 m^2 area from each treatment plot in 2013 (60 plots) and 2014 (72 plots) prior to mechanical harvest. Samples from each plot were placed in separate cotton bags and air-dried at room temperature then placed in oven at 60°C until moisture loss ceased. In 2014 height differences were noticed within concentric plot #8 on either side of the wheel track. To address this variability, biomass (1 m^2) and grain yield (5 m^2) samples were taken from both sides of the wheel track and averaged for analysis. All hand samples were dried until less than 10 g of moisture were lost over a 24 hour period in a drying oven set to 60°C. Dried samples were thrashed, and the grain was cleaned and weighed. Three 500 seed sub-samples were obtained for each plot, and dried again for 24 hours to achieve zero moisture. Yield results were reported as dry or 0% moisture in order to avoid confusion of preferred common moistures among readers.

Statistical Method

Harvest results were analyzed using SAS statistical analysis software (SAS 9.3 SAS Institute Inc., Cary, NC). Mixed Models were used in the PROC MIXED procedure (Littell et al., 2006). Multiple comparison of mean was performed using the Tukey-Kramer method at $p = 0.05$. Hybrids and irrigation level were treated as fixed effects. Sector was added in SAS as a random effect for the analysis in 2014. Randomized complete block design (RCBD) was used, where each concentric plot contained both methods (manual and automatic) and the three irrigation treatments (100%, 75%, and 50%)

RESULTS AND DISCUSSION

Climate and precipitation

Cooler overall maximum and minimum air temperatures were observed in 2014 as compared with 2013 making for more favorable corn production conditions in the second year of the study (Table 3). Rainfall in the 2014 growing season (May-October) (548 mm) was more than double the amount received in 2013 (273 mm). Seasonal rainfall in 2014 was similar to the long-term average rather than the droughty conditions from the previous three years. Growing degree days for 2013 were 2048 and for 2014 GDD were 1992 from May 1st through October 31st. Growing degree days were greater in all months in 2013 except in August and October. This warmer temperature could have helped dry the grain in the field, despite the greater rainfall in October. Days from planting to maturity in 2013 were 120 and 130 for the P0876HR and 33Y75 hybrids, respectively; in 2014 the P0876HR hybrid matured in 126 day and the 33Y75 hybrid matured in 137 days. As expected, minimum relative humidity was greater in 2014 compared with 2013.

Monthly maximum daily solar irradiance was similar between 2013 and 2014. May was the only month where the average daily reference ET was higher in 2014 compared with 2013.

Soil water and irrigations

Soil water measurements were taken weekly from at least the Manual 100% plots. Access tubes in all plots were read four times in 2013 and five times in 2014. Irrigations were scheduled for the manual control plots using the average soil moisture needed to replenish 100%, 75% or 50% soil water depletion to field capacity. Field capacity was established at 495 mm in the top 1.5 meters. In 2013, cumulative crop water use (ET_c) was calculated as the product of crop coefficients (K_c) and reference evapotranspiration (ET_o) (K_c X ET_o), from planting to black layer, was calculated as 722 mm and 746 mm, for the P0876HR hybrid and the 33Y75 hybrid, respectively, for the 100% irrigation treatment level (Fig. 10). In 2014, cumulative ET_c from planting to black layer was calculated as 636 mm and 668 mm, for the P0876HR hybrid and the 33Y75 hybrid, respectively (Fig. 11). Reference evapotranspiration (ET_o) was calculated as per ASCE (2005); K_c values were from historical data from the CPRL. The ET_c for 2013 was approximately 87-88% of ET_o and ET_c was around 90% of ET_o in 2014. Crop evapotranspiration calculated from ET_o and K_c were greater than ET_c calculated with the soil water balance method (Equation 1). During the season, irrigation amounts were applied at erroneous rates to two of the five replications of each hybrid and irrigation treatment amount due to a coding error. Thereby only three replications were used to compute mean crop response for each hybrid and treatment level. In 2014, the electronic relay controlling the sprinkler zones to concentric plot 1 (Fig.9) failed, reducing the scheduled irrigation amounts by 75 mm; therefore plots 1, 24, 25, 48, 49, and 72 were not included in the calculations for mean crop response.

The mean post-plant irrigation amounts in 2013 for the P0876HR hybrid were 432 mm, 330 mm, and 254 mm for the 100%, 75%, and 50% irrigation treatment levels. Amounts for the 33Y75 were 483 mm, 381 mm, and 279 mm. In 2014, post-plant irrigation amounts for the P0876HR hybrid were 356 mm, 279 mm, and 179 mm for the 100%, 75%, and 50% irrigation levels. For the 33Y75 hybrid mean irrigation amounts were 432 mm, 330 mm, and 229 mm.

In 2013, irrigation amounts for the P0876HR hybrid were consistently less compared with the 33Y75 hybrid within the same irrigation treatment level for both 2013 and 2014. Soil water in the profile at the end of the irrigation season was always greater for the P0876HR hybrid in the 100% treatment level for both years.

Crop Water Use, Grain and Biomass Yields, and Water use Efficiency

Crop water use for critical growth stages (Table 4) was calculated using the soil water balance equation (Eq. 1) from the onset through the end of each critical growth stage. Crop water use was the highest during the vegetative stage (emergence to tassel) due to the length of time spent in that stage. The P0876HR hybrid was in the vegetative stage for 68 days after planting in 2013 and 66 days in 2014. The 33Y75 hybrid was in the vegetative stage for 72 days in 2013 and 73 in 2014. The 33Y75 hybrid spent more time (difference in days) in most stages than the P0876HR hybrid [vegetative (4 days), silk (3 days), blister (3 days), dough (1 day) and dent (2 days) in 2013, and vegetative (7 days), blister (3 days), dough (2 days), dent (2 days) in 2014], which created a gap in between the growth stages and the DOY for each hybrid at the Manual 100% level. At the dough stage, the P0876HR hybrid did not require an irrigation, while the 33Y75 hybrid received required 65 mm of irrigation. At dent stage, the P0876HR hybrid required more water than the 33Y75 hybrid by over 20 mm. In 2013, both hybrids used more water in the silk-blister stage, this could be due to needing more time to develop good kernel set and early development in more droughty conditions (Claassen and Shaw, 1970; Hall et al., 1982; Lorens et al., 1987). However, in 2014 the majority of water use, outside of the vegetative stage, came in the dent stage, this could be explained by having more available water resources throughout the season and having more water leftover to produce and fill the remainder of the soft kernel. In 2014 during the final stage leading to black layer, ET_c for the 33Y75 hybrid was only 6.4 mm. This was due to the plant using very little soil moisture at this final stage, irrigations had already been terminated and there was very little rainfall (Table 4).

Dry grain yield was similar for the P09876HR 100%, 33Y75 100% and P0876HR 75%, however, grain yield at the 50% for both hybrids was significantly less than this group. Data for crop response were compared within the same year and between hybrids within the same irrigation treatment level. In 2013, there was no difference in grain yield, biomass yield, kernels per ear, or harvest index between hybrids within the same irrigation treatment level. Crop water use was greater for the 33Y75 hybrid in the 100% treatment level, but not different between hybrids at the 75% and 50% treatment levels. Grain WUE was greater for the P0876HR hybrid at the 75% and 50% treatment levels. Kernel weight was also greater for the P0876HR hybrid at the 75% treatment level. At the 75% and 50% irrigation levels the P0876HR hybrid was able to produce greater yield with less evapotranspiration than the 33Y75 hybrid at the same irrigation levels.

In 2014, mean crop responses were grouped by Sector (pie-shaped areas within the field) to determine if the elevation differences in the field influenced yields. The areas with the greatest variability in elevation were sectors 1, 2 and 3, with sector 2 ponding the most water. Dry grain yields were significantly higher in sector 2 as compared with sectors 5 and 6. Crop water use was significantly greater in sectors 1 and 2 than in sectors 4, 5 and 6. Biomass was significantly greater in sectors 1- 4 than in sectors 5 and 6. The number of kernels per ear was significantly greater in sector 2 than in sector 6 (Table 5). Differences in sector 2 were corroborated with visual observations, plant mapping (plant height) and soil water graphs for plots located in sector 2 (data not shown).

In 2014 there was also a difference in overall mean ET_c, biomass yields and harvest index between hybrids. Crop water use was greater for the 33Y75 hybrid within the 100% and 75% irrigation treatment levels. Harvest index was greater for the P0876HR hybrid within all irrigation treatment levels.

Comparison of Yields and WUE With Data from Previous Studies

The 2013 grain yields were similar to those demonstrated by Lyle and Bordovsky (1995), who reported grain yields ranging from 0.94-1.11 kg m^{-2} (dry grain) when irrigated at full. Grain yields in 2014 were similar to those reported by Schneider and Howell (1998) and Howell et al. (1998), where grain yields reached upwards of 1.44 kg m^{-2}. However, grain yields in our study (1.45-1.48 kg m^{-2} for P0876HR and 33Y75 hybrids, respectively) were greater than reported by Howell et al. (1995), which were 1.34 kg m^{-2} (dry grain for a conventional variety irrigated at full). Water use efficiency at irrigation levels of 100% and 75% as reported by Howell et al. (1995); Lyle and Bordovsky (1995); and Schneider and Howell (1998) (1.34 to 1.94 kg m^{-3}, respectively) were less as compared with WUE for all treatment levels for the P0876HR and 33Y75 hybrids for both 2013 and 2014. As reported by Howell (1995) grain yields and WUE for treatment plots with irrigations at the 40% (Yield = 0.84-0.94 kg m^{-2}, WUE = 1.21-1.55 kg m^{-3}) were similar to our 50% grain yields in 2013 (0.64-0.77 kg m^{-2}). For the 60% irrigation treatment (Howell, 1995), yield = 0.90-1.12 kg m^{-2} was similar to yields in our 50% irrigation treatment level in 2014 (1.16-1.31 kg m^{-2}). However, WUE in Howell's study (1.27-1.48 kg m^{-3}) was much less than the 50% irrigation level in our study (2.59-2.78 kg m^{-3}) (Table 6).

Comparing crop response between drought tolerant hybrids grown in this area, in 2013, the P0876HR hybrid for the 50% irrigation treatment yielded 0.77 kg m^{-2} and demonstrated a WUE of 1.70 kg m^{-3}, which was greater than results from the 2011 Texas A&M AgriLife study, where grain yields were 0.55 kg m^{-2} and WUE was 1.23 kg m^{-3} for the AQUAmax hybrid, Pioneer P1151HR (111 CRM), but less than results for the same hybrid from 2012 (yield was 0.81 kg m^{-2} and WUE was 1.995 kg m^{-3}) for both yield and WUE (Becker, 2013). At the 75% irrigation treatment level, grain yield and WUE for the P0876HR was 1.04 kg m^{-2} and 2.03 kg m^{-3}, respectively, which were less than grain yield and WUE for the P1151HR hybrid for both years in the 2011-2012 Texas A&M AgriLife study (yield was 1.07 for 2011 and 2012 and WUE was 2.06 in 2011 and 2.19 in 2012). In 2013, grain yield and WUE for the

P0876HR in the 100% irrigation treatment level was less by at least 9% as compared with the P1151HR results in both years, but the WUE (2.17 kg m^{-3}) was higher for the P0876HR hybrid. Harvest index was greater, but not significantly different, for the P0876HR hybrid across all irrigation treatments levels. In 2014, grain yields and WUE were greater for the P0876HR hybrid as compared with the P1151HR hybrid at the same irrigation treatment level for both years, 2011 and 2012 (Table 6). Likewise, when Lyle and Bordovsky (1995) increased irrigation amounts by 30% above replenishment of calculated crop ET (base irrigation amount), the WUE decreased below the base amount by 17%.

CONCLUSIONS

Corn production in the THP has its fair share of challenges; however, with new and improved hybrids it can still be a viable option in the area. When climactic conditions are favorable adequate corn yields can be obtained with most modern hybrids and drought tolerance is not necessary. When drought is a factor and adequate water is not able to be applied then a producer could benefit with a tolerant hybrid like Pioneer AQUAmax P0876HR. When less rainfall is received a farmer may benefit by irrigating at deficit levels since it was demonstrated that WUE at the 75% and 50% irrigation treatment levels for the drought tolerant hybrid were significantly greater than the conventional hybrid. During drought as well as when rainfall is plentiful the drought tolerant hybrid will have a higher HI, this shows that drought tolerant hybrids are more efficient at partitioning total biomass to grain than the conventional hybrid, as shown in our study.

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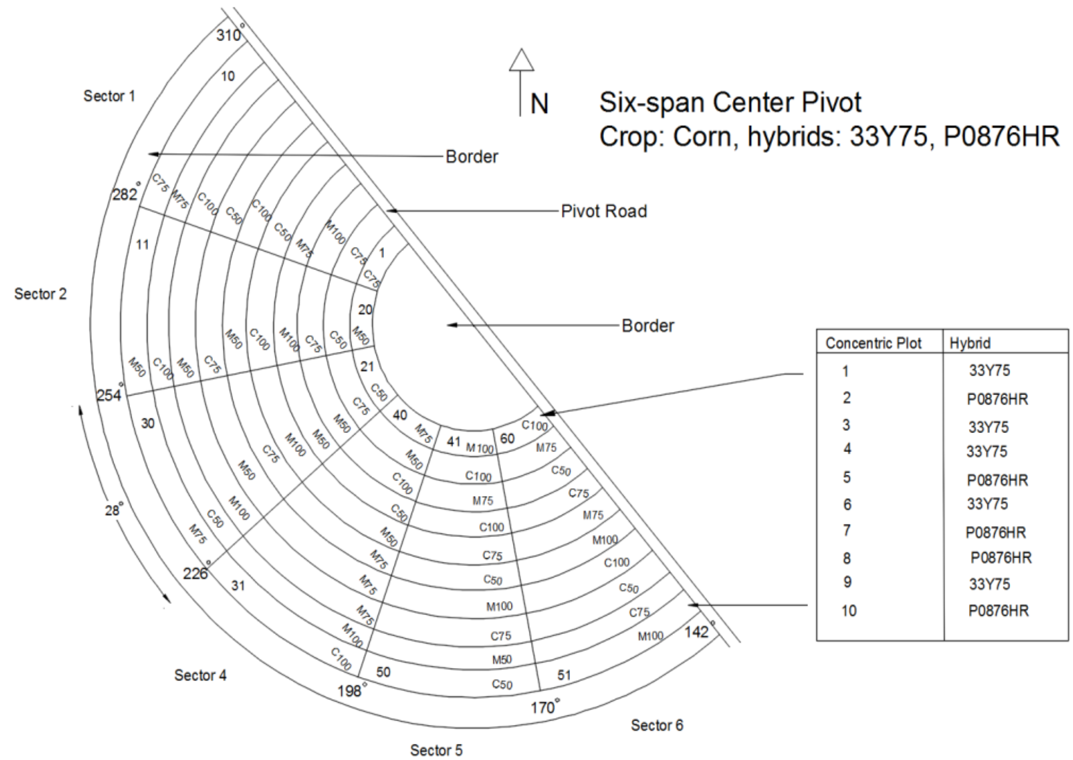
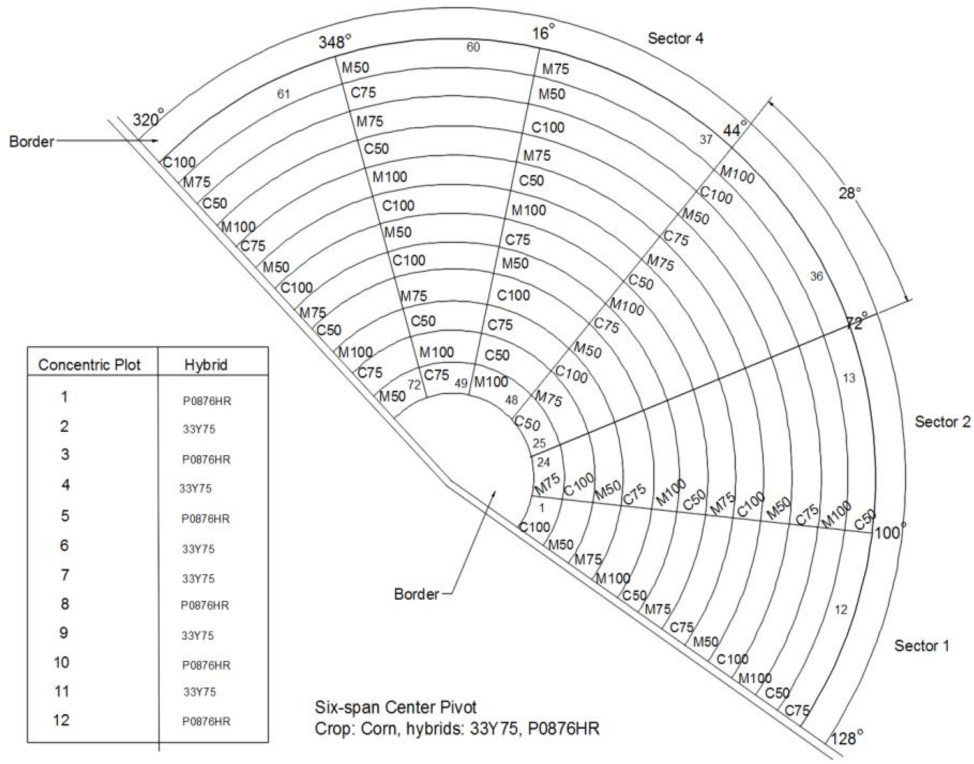


Figure 8. Plot plan, where plots designated by M100, M75, and M50 are manual plots, and plots designated as C100, C75, and C50 are automatic plots irrigated at 100%, 75% and 50% replenishment of soil water depletion to field capacity for 2013 with 10 concentric plots to corn hybrids P0876HR and 33Y75.



Concentric Plot	Hybrid
1	P0876HR
2	33Y75
3	P0876HR
4	33Y75
5	P0876HR
6	33Y75
7	33Y75
8	P0876HR
9	33Y75
10	P0876HR
11	33Y75
12	P0876HR

Figure 9. Plot plan, where plots designated by M100, M75, and M50 are manual plots, and plots designated as C100, C75, and C50 are automatic plots irrigated at 100%, 75% and 50% replenishment of soil water depletion to field capacity for 2014 with 12 concentric plots planted to corn hybrids P0876HR or 33Y75.

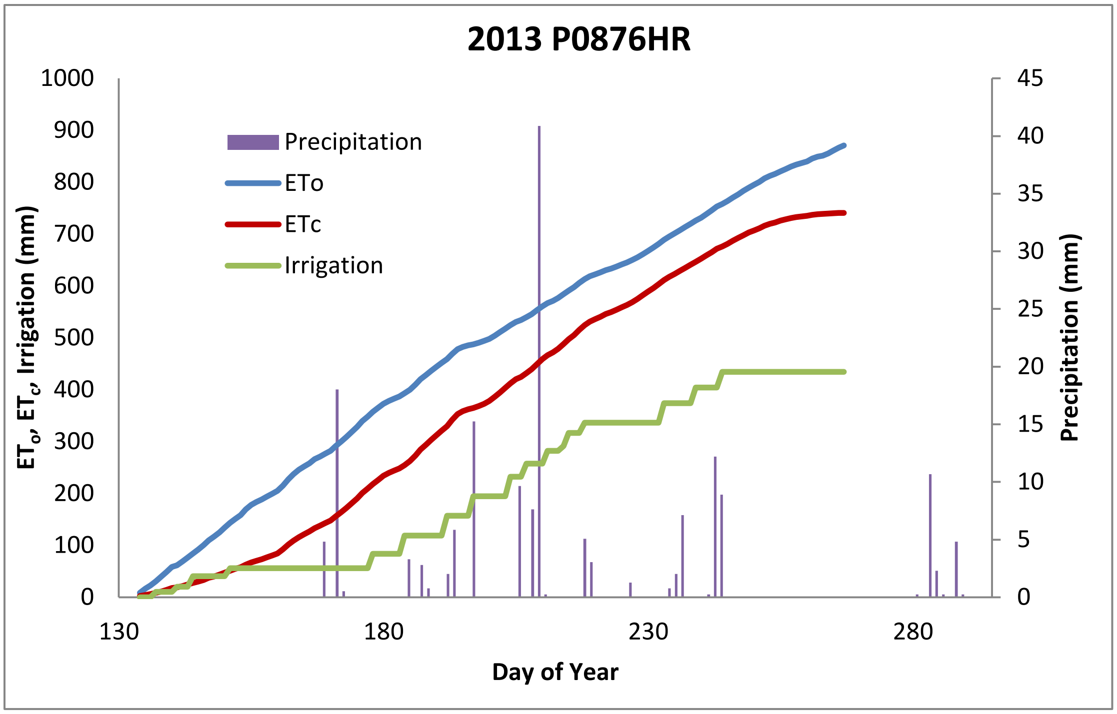
Table 2. Summary of agronomics for 2013 and 2014 growing seasons in Bushland, Texas.

Growing season	2013	2013	2014	2014
Crop varieties	Pioneer 0876HR	Pioneer 33Y75 BT/RR	Pioneer 0876HR	Pioneer 33Y75 BT/RR
Fertilizer Type/Rate DOY	32-0-0 @ 196.4 kg ha^{-1}, 128 Fertigated w/32-0-0 @ 30.3 kg ha^{-1}, 214	32-0-0 @ 196.4 kg ha^{-1}, 128 Fertigated w/32-0-0 @ 30.3 kg ha^{-1}, 214	32-0-0 @ 252 kg ha^{-1}, 94	32-0-0 @ 252 kg ha^{-1}, 94
Planting date	DOY 134	DOY 134	DOY 135	DOY 135
Planting rate	76,603 seed ha^{-1}	76,603 seed ha^{-1}	76,603 seed ha^{-1}	76,603 seed ha^{-1}
Initial neutron tube reading	DOY 156,157	DOY 156,157	163, 164	163, 164
Furrow dike	DOY 162, 177-178	DOY 162, 177-178	DOY 167	DOY 167
Irrigation Pre-water (DOY, amount)	36, 57.15 mm 77, 57.15 mm 129, 29.97 mm	36, 57.15 mm 77, 57.15 mm 129, 29.97 mm	112, 63.5 mm 122, 25.4mm 129, 19.05 mm 132, 19.05 mm	112, 63.5 mm 122, 25.4mm 129, 19.05 mm 132, 19.05 mm
Irrigation season (DOY)	137-244	137-248	136-243	136-243
Plant mapping (DOY)	Stand Counts 156 Plant map 175, 182, 191, 203, 212, 219, 233, 240	Stand Counts 156 Plant map 175, 182, 191, 203, 212, 219, 233, 240, 253	Stand Counts 149 Plant map 153, 177, 195-196, 211, 220, 232, 240	Stand Counts 149 Plant map 153, 177, 195-196, 211, 220, 232, 240
Herbicide applic-ation (Brand, Chemical, amt, DOY)	G-Max Lite (dimethenamid-P, dimethyl-thien-3, atrazine), 3.5 liters ha^{-1}, 135	G-Max Lite (dimethenamid-P, dimethyl-thien-3, atrazine), 3.5 liters ha^{-1}, 135	Bicep Lite II Magnum (Atrazine, Atrazine related compounds, S-metolachlor), 3.5 liters ha^{-1}, 129	Bicep Lite II Magnum (Atrazine, Atrazine related compounds, S-metolachlor), 3.5 liters ha^{-1}129
Hand sample harvest (DOY)	267-269	290-291*	279-281	293-294

*unable to access field due to administrative issues

Table 3. Climatic Conditions for 2013 and 2014 growing seasons.

Month	Min Temp. (°C)	Max Temp. (°C)	Total Monthly GDD	Min RH (%)	Max RH (%)	Total Monthly Precipitation (mm)	Max daily solar irradiance (MJ $m^{-2}d^{-1}$)	Avg. daily ET_0 [a] (mm d^{-1})
Growing Season 2013								
May	9.5	27.7	284	16	77	35	25	7
June	17.4	32.7	397	23	82	91	27	8
July	17.8	30.6	406	33	83	84	24	6
August	17.5	32.2	418	31	86	41	24	6
September	14.6	29.5	348	29	82	21	19	5
October	4.0	22.7	195	22	78	3	16	4
Growing Season 2014								
May	9.6	26.9	273	19	63	115	25	7
June	16.2	30.6	369	30	88	139	26	7
July	17.8	30.1	405	38	87	125	24	6
August	17.1	32.8	419	28	85	32	22	6
September	14.6	26.1	305	52	94	104	16	3
October	8.1	23.9	221	32	87	33	15	3



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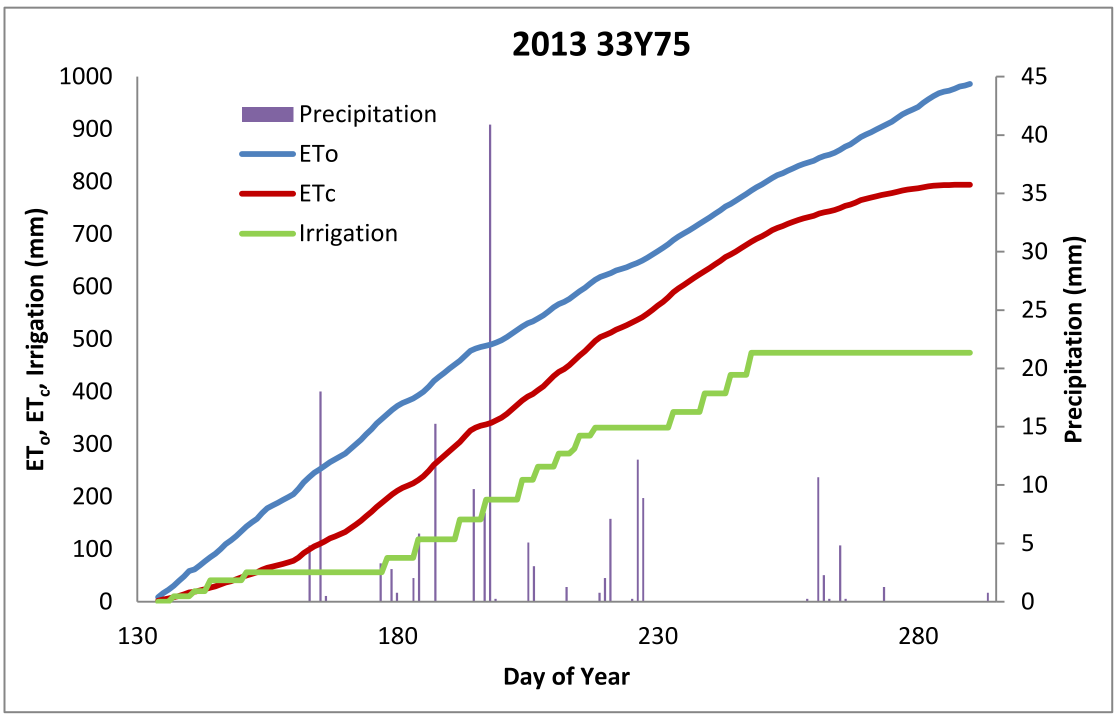
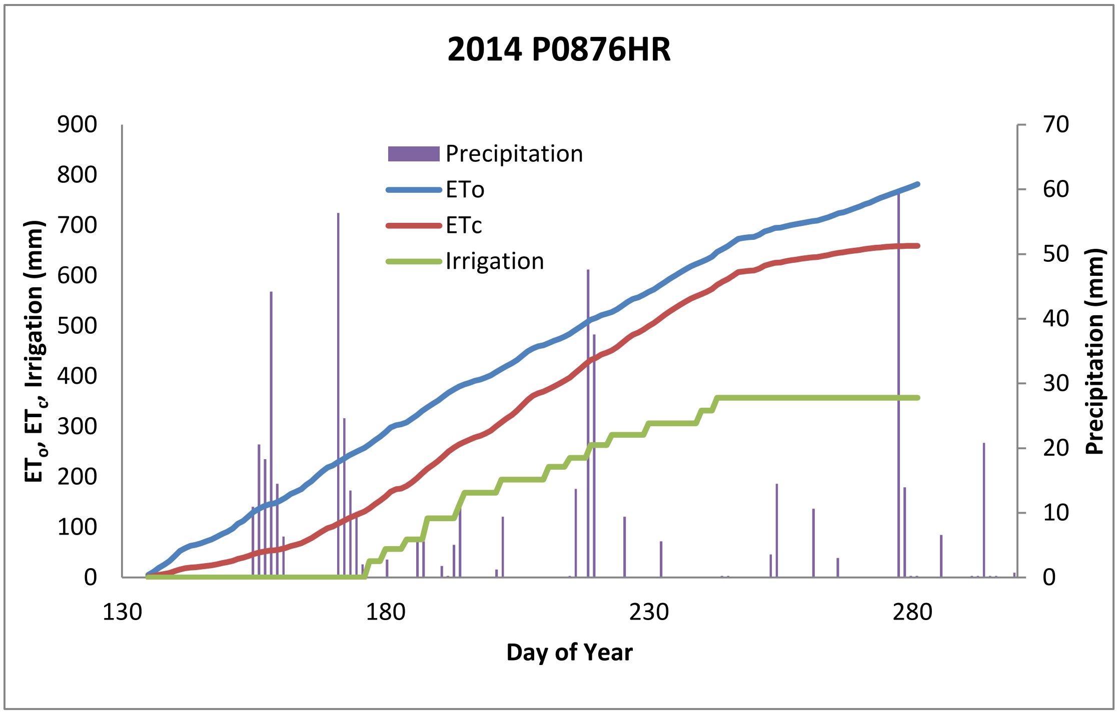


b.

Figure 10. Graphs showing precipitation, calculated reference evapotranspriation (ET_o), and mean crop water use and cumulative irrigation amount for each hybrid and year at the 100% irrigation treatment level in 2013: (a) P0876HR; and (b) 33Y75.



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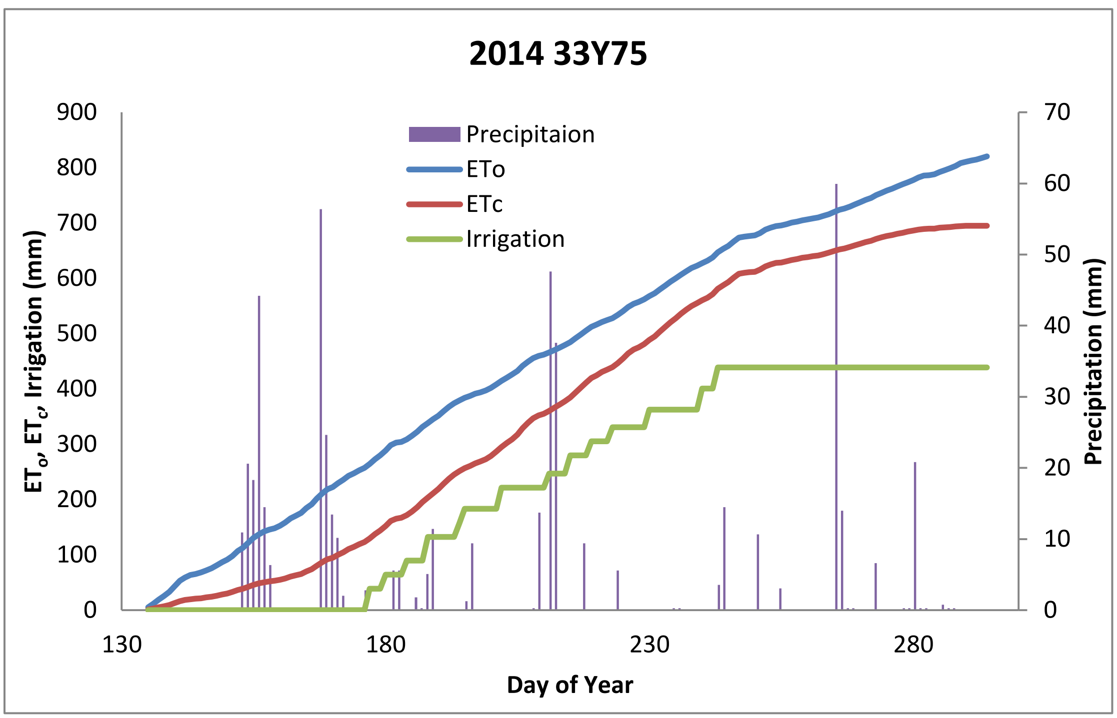

b.

Figure 11. Graphs showing precipitation, calculated reference evapotranspriation (ET_o), and mean crop water use and cumulative irrigation amount for each hybrid and year at the 100% irrigation treatment level in 2014: (a) P0876HR; and (b) 33Y75.

Table 4. Crop water use for critical growth stages at 100% irrigation treatment level

		ET_c (mm)	
	Growth Stage Range	33Y75	P0876HR
2013	Planting-Tassel	261	151
	Tassel - Silk	8	18
	Silk - Blister	113	178
	Blister - Milk	35	53
	Milk - Dough	33	36
	Dough - Dent	60	37
	Dent – ½ Maturity	93	54
	½ Maturity – Black Layer	36	66
2014	Planting-Tassel	243	165
	Tassel - Silk	75	18
	Silk - Blister	60	68
	Blister - Milk	79	96
	Milk - Dough	51	17
	Dough - Dent	30	40
	Dent – ½ Maturity	120	110
	½ Maturity – Black Layer	6	31

Table 5. Analysis of crop response by sector as a fixed effect for the 2014 growing season

Sector	Dry Grain Yield (kg m^{-2})	ET_c (mm)	Grain WUE (kg m^{-3})	Biomass (g m^{-2})	Kernel wt. (mg)	Kernels /Ear	HI
1	1.44ab	667a	2.50a	4213a	299a	555ab	0.57a
2	1.52a	649ab	2.73a	4389a	311a	565a	0.56a
3	1.41ab	606bc	2.70a	3994a	296a	552ab	0.56a
4	1.36ab	570c	2.78a	3821a	293a	521ab	0.56a
5	1.15b	592c	2.32a	3484b	274a	504ab	0.57a
6	1.14b	576c	2.25a	3329b	267a	477b	0.55a

Table 6. Mean hybrid response to irrigation for the 2013 and 2014 growing season at Bushland, TX. Means are compared within years and between hybrid, irrigation treatment and hybrid X irrigation treatment. Means followed by the same letter in each category are not significantly different.

	Mean Irrigation amount (mm)	Yield Dry (kg m^{-2})	ET_c (mm)	Grain WUE (kg m^{-3})	Biomass (g m^{-2})	Kernel wt. (mg)	Kernels /ear	HI
2013								
Hybrids								
P0876HR		1.00a	582b	1.97a	2657a	278a	533a	0.59a
33Y75		0.92b	624a	1.68b	2850a	262a	542a	0.52b
Hybrid X Irrigation Treatment								
P0876HR x 100	432	1.20a	638b	2.17a	3126a	317a	546a	0.60a
33Y75 x 100	483	1.20a	713a	1.94ab	3402a	315a	557a	0.56ab
P0876HR x 75	330	1.04ab	588bc	2.03a	2619ac	298a	542a	0.60a
33Y75 x 75	381	0.93bc	615b	1.74b	3078a	264b	543a	0.52ab
P0876HR x 50	254	0.77c	520c	1.70b	2228bc	219c	511a	0.55ab
33Y75 x 50	279	0.64c	545c	1.36c	2069b	207c	526a	0.47b
2014								
Hybrids								
P0876HR		1.32a	578b	2.63a	3692b	310a	574a	0.58a
33Y75		1.39a	649a	2.50a	4086a	319a	583a	0.55b
Hybrid X Irrigation Treatment								
P0876HR x 100	356	1.45ab	644bc	2.60a	4112a	334a	586a	0.58ab
33Y75 x 100	432	1.48a	749a	2.28a	4077a	326a	598a	0.55c
P0876HR x 75	279	1.34ab	577cd	2.70a	3725ab	309ab	583a	0.58a
33Y75 x 75	330	1.38ab	650b	2.45a	4242a	317ab	584a	0.55bc
P0876HR x 50	179	1.16b	518e	2.59a	3238b	287b	552a	0.59a
33Y75 x 50	229	1.31ab	548de	2.78a	3937ab	315ab	567a	0.54bc