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Irrigated Corn Production and Management in the Texas High Plains

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Abstract: Corn is the major irrigated crop in the Texas High Plains (THP) and uses 53% of the total agricultural regional water resource budget. Currently, the declining water level of the Ogallala Aquifer, coupled with irrigation pumping restrictions by regional groundwater conservation districts, is challenging sustainable, high level corn production. The objective of this article is to review production levels and evaluate corn management practices in the THP with reduced or limited levels of irrigation. Long-term field studies demonstrate that yield and water use efficiency (WUE) have increased significantly over the last forty years while seasonal corn evapotranspiration (ET) under full irrigation conditions has not increased. Among management practices, irrigation remains the single-most important factor in corn production. With recent advances in corn breeding and genetics, irrigation requirements can be reduced by up to 25% in some years and result in similar yields as compared to irrigation amounts at the 100% ET level. Also, WUE is generally maximized at irrigation levels meeting 75-80% ET demand. Newly developed drought tolerant corn hybrids have been shown to provide yield benefits of 10-15% under limited (reduced) irrigation water levels. At the higher irrigation levels (75-100% ET requirement), corn yield increased as seeding rate increased initially but did not increase further when the seeding rate exceeded 94,000 seeds ha^{-1}. Also, a multi-year planting date study indicated that high corn yields can still be achieved with a long-season hybrid when planted in the middle of May and early June. When the planting date is delayed to late June and early July, mid- and short- season hybrids showed a yield advantage over the long season hybrids.

Keywords: *drought stress, drought tolerance, irrigation, water use efficiency, limited water, evapotranspiration, water use, Zea Mays L., crop ET*

The Texas High Plains (THP) is one of the most productive agricultural regions in the U.S. From 2009 to 2012, the Texas panhandle portion of this region had 58% corn, 41% wheat, 20% grain sorghum, 13% cotton, 63% ensilage, and 10% forage crops of the crop production in the State of Texas. Together with other crops and forages, the annual economic value of crop production in the region was nearly $1.7 billion, with corn production alone accounting for 40% ($688 million) of the total crop value (Amosson et al. 2015). In 2016, 2.9 million acres of corn were planted in Texas and nearly half of the state acreage (1.4 million acres) was in the THP region (Figure 1) (NASS 2016a, b).

In the THP, high corn productivity has heavily relied on irrigation for consistency and profitable operations. Among the major crops, corn uses 53% of the entire regional water budget annually for irrigation (1.76 billion m^3). Almost all irrigation in the THP is from the Ogallala Aquifer, with development of irrigation in this region significantly increasing since the 1950s. The Ogallala Aquifer is a finite water resource with minimal recharge, and the dramatic increase in water extraction for crop irrigation has resulted in significant decline of aquifer capacity with some areas experiencing a 50% or greater reduction in saturated thickness. Irrigated land area has decreased from a peak of 2.4 million ha in 1974 to 1.9 million ha in 2000 (Colaizzi et al. 2009). Therefore, sustained corn production faces challenges as THP irrigation

water resources continue to decline. The development of profitable management strategies with limited irrigation scenarios is important for reducing production risk, maintaining profitability, and conserving water resources. The objective of this article is to review production levels and evaluate corn management practices in the THP with reduced or limited levels of irrigation based on long-term field experiments at Bushland and Etter, Texas.

Corn Yield, Evapotranspiration, and Water Use Efficiency

Figure 2 shows changes in corn yield from the mid-1970s to recent years at three levels (national, THP county average, and Research & Demonstration (R&D) plots) (Musick and Dusek 1980; Howell et al. 1995, 1996; Yazar et al. 1999; AgriPartners 2007; Colaizzi et al. 2011; Hao et al. 2015). The yield data from THP county and

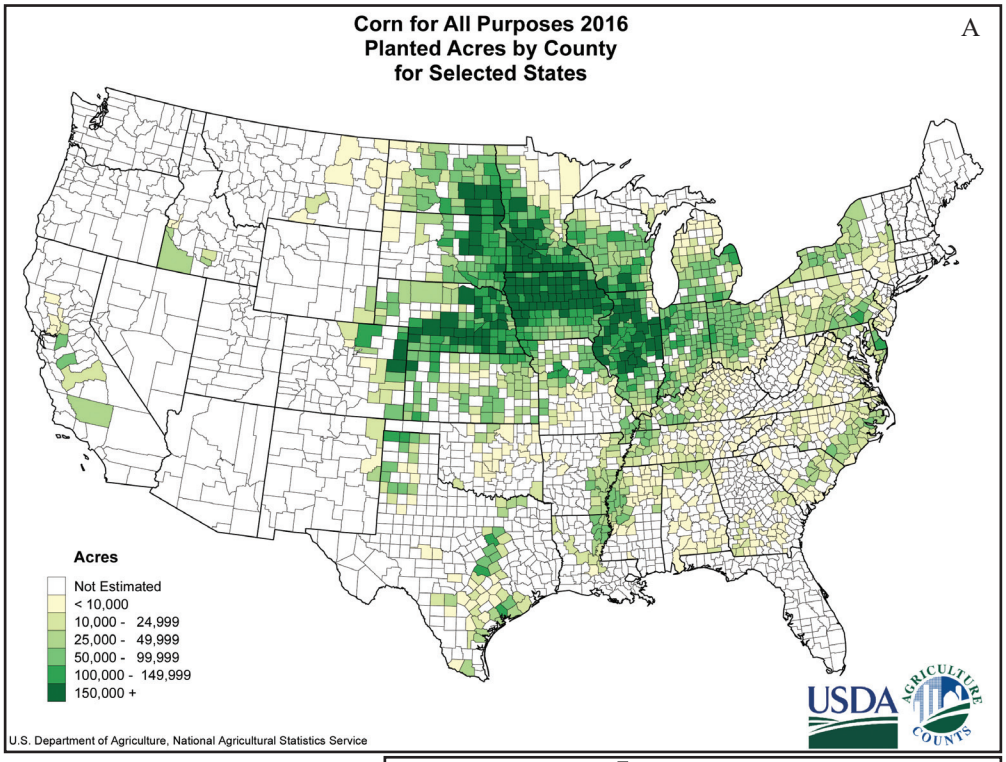

Figure 1. Corn planted acres in (A) the U.S. and (B) Texas in the 2016 growing season. (View originals at: (A) https://www.nass.usda.gov/Charts_and_Maps/graphics/CR-PL-RGBChor.pdf; (B) https://www.nass.usda.gov/Statistics_by_State/Texas/Publications/County_Estimates/ce_maps/ce_corn.php.)

R&D level were largely conducted at the 100% ET demand level. The national average corn yield was compiled from combined irrigated and rain-fed yield data. Although corn yield varied from year to year, there was a clear trend that yield has increased linearly over the last 40 years, with an annual increase of about 120 kg ha^{-1}. Interestingly, the slope of the increase is virtually the same at all three levels. Figure 2 shows that corn yield at the county level in the THP was always higher than the national average, and that the THP corn yield increased more than the national and R&D levels. At the county level, average yield increased from about 6-8 Mg ha^{-1} in the 1970s to about 13 Mg ha^{-1} in recent years (e.g., 2013). Corn yields of the R&D plots were higher than those of the county level, ranging from about 8 Mg ha^{-1} in 1970s to 16 Mg ha^{-1} in recent years (e.g., 2011-2013). The higher yield of the R&D plots is generally due to the smaller, more intensively managed production areas, as compared to field based production practice.

Corn has a high evapotranspiration (ET) demand (both daily and seasonally) in the THP (Howell et al. 1995, 1996). Daily corn ET has been measured in large, monolithic weighing lysimeters at Bushland, Texas, and often exceeds 10 mm d^{-1} for significant periods of time (Figure 3) (Howell et al. 1996). In contrast, daily ET rarely exceeds 10 mm d^{-1} in the central Great Plains of Nebraska (Grassini et al. 2011). Seasonal ET requirement for corn under varied irrigation levels has been studied at Bushland, Texas since the 1970s. Early studies under furrow irrigated conditions showed that seasonal ET ranged from 667 mm to 984 mm under full irrigation (Musick and Dusek 1980; Eck 1984). Field studies using sprinkler irrigation showed that seasonal ET ranged from 750-973 mm (mostly between 800-900 mm) in the 1990s at irrigation of 100% ET requirement (Howell et al. 1995, 1996; Schneider and Howell 1998; Yazar et al. 1999; Evett et al. 2000). Corn ET levels in producer's fields had a larger variation and ranged from 750 mm to 1200 mm. In recent studies at both

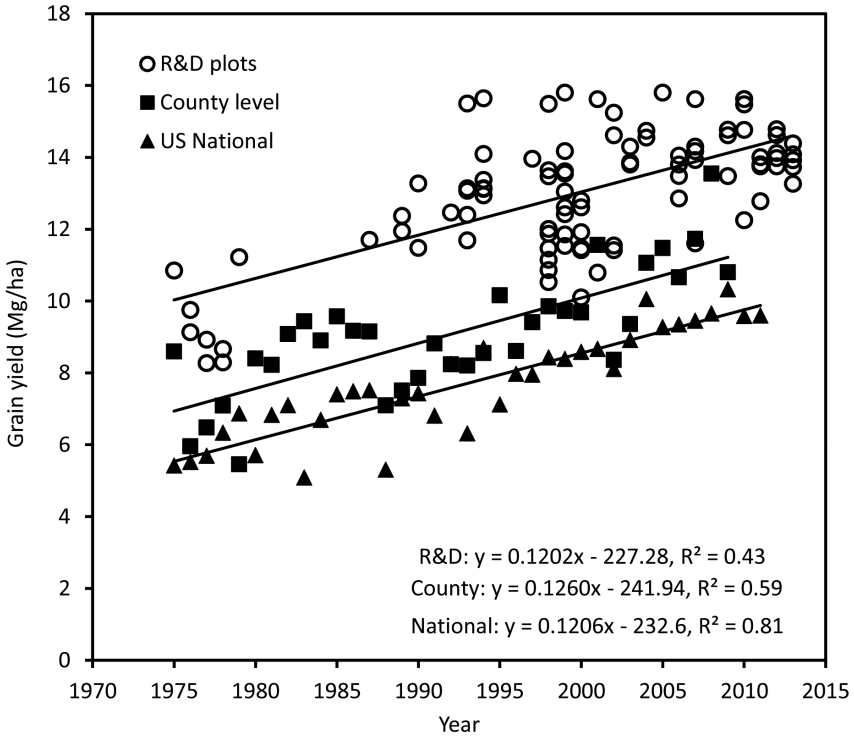

Figure 2. Corn yield from 1975 to recent time at National level, County level (average of top 26 counties in the Texas Panhandle), and Research and Demonstration (R&D) plots in the Texas High Plains. (Data sources: NASS; long-term field studies at Bushland and Etter, TX).

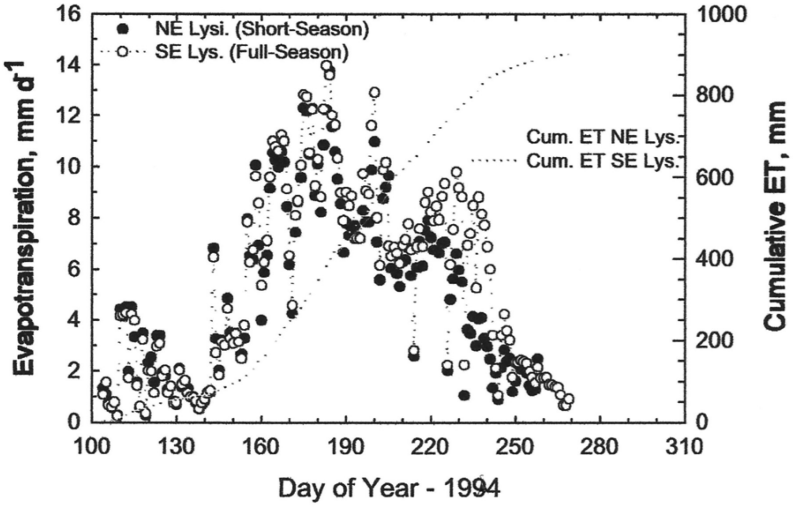

Figure 3. Daily evapotranspiration (ET) of fully irrigated corn at Bushland, TX in 1994 in lysimeters. NE lysimeter has a short-season hybrid, and SE lysimeter had a full-season hybrid (Howell et al. 1996).

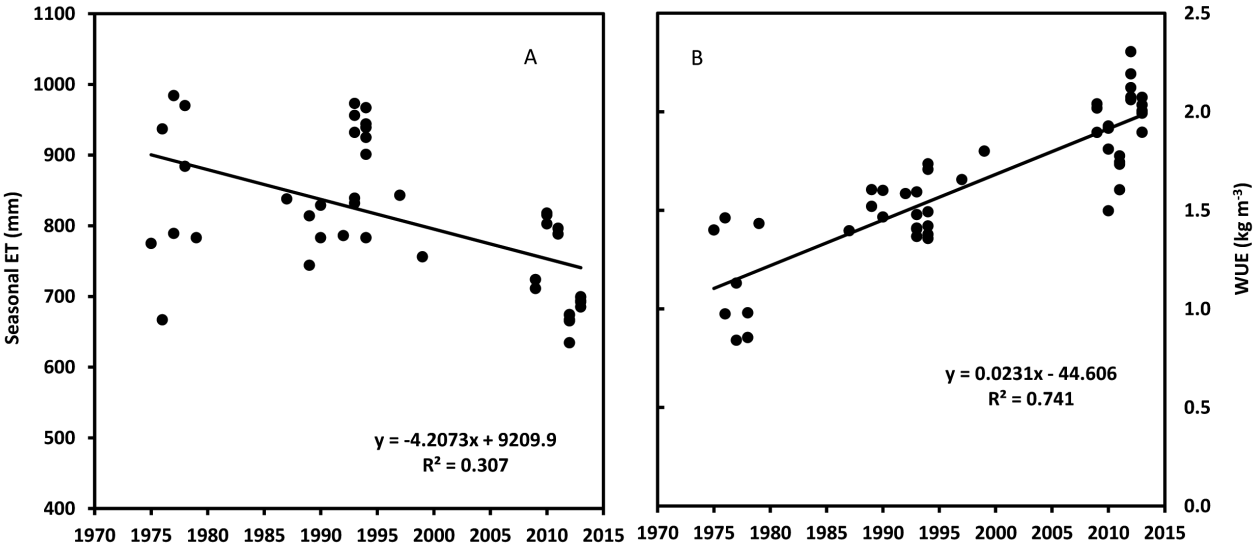

Figure 4. Changes of (A) seasonal evapotranspiration (ET) and (B) water use efficiency (WUE) under full irrigation conditions from 1975 to 2013 in the research plots (Data sources: long-term field studies at Bushland and Etter, TX).

Bushland and Etter, Texas, a lower seasonal ET was recorded under full irrigation at Etter than at Bushland. The ET is generally higher in the south than north, and in the east than west, in the THP region. Colaizzi et al. (2011) conducted a three-year experiment using a subsurface drip irrigation system and seasonal corn ET ranged from 711 mm to 818 mm at Bushland at irrigation level of 100% ET requirement. Hao et al. (2015) showed that corn under irrigation of 100% ET requirement ranged from 634 mm to 796 mm, depending on year and hybrid. Figure 4 shows that seasonal corn ET has a decreasing trend while WUE varied linearly over the years under full irrigation (100% ET requirement or greater) in the THP. In comparison, seasonal corn ET under full irrigation in other regions of the Great Plains was generally less than that in the THP, according to Rudnick et al. (2017) who summarized irrigation studies across the central and southern Great Plains from Nebraska and Colorado to Texas. In Nebraska, seasonal corn ET under full irrigation ranged from 526 mm to

655 mm in several field studies (van Donk et al. 2012; Irmak et al. 2015a, b; Rudnick et al. 2016).

The yield-ET relationship and WUE in corn have been reported in different studies at Bushland and Etter, Texas at different irrigation levels (Musick and Dusek 1980; Howell et al. 1995, 1996; Yazar et al. 1999; Colaizzi et al. 2011; Hao et al. 2015). For comparison, an analysis of the corn yield-ET relationship was used using three data sets, representing differing time periods in the THP. The first data set was from Musick and Dusek (1980). They conducted field studies at different furrow irrigation levels and frequencies from 1975 to 1977. The second data set was compiled from a field study using center pivot sprinkler irrigation in 1994 and 1995 (Schneider and Howell 1998). The third data set was from recent field studies conducted at Etter, Texas from 2011 to 2013 using different hybrids and planting densities (Hao et al. 2015). During all three time periods, corn yield increased linearly as seasonal ET increased (Figure 5). Linear regression between corn yield and ET resulted in a slope of 0.0243, 0.0277, and 0.0285 (the unit is Mg ha^{-1} mm^{-1}) in the studies of 1975-1977, 1994-1995, and 2011-2013, respectively. Based on the three linear equations in Figure 5, a threshold ET can be calculated for each study. Threshold ET is the ET level at which the first grains are initiated (Musick et al. 1994; Schneider and Howell 1998). The threshold ET value was 346 mm for the 1975-1977 study, 310 mm for the 1994-1995 study, and 214 mm for the 2011-2013 study. Schneider and Howell (1998) summarized the slopes of the linear regressions of yield and ET and threshold ET values in different studies conducted at Bushland, Texas. The slopes ranged from 0.02 to 0.34 and the threshold ET values ranged from 147 mm to 467 mm (Schneider and Howell 1998). Although the smaller threshold ET value in the 2011-2013 study (214 mm) may indicate management improvement over the decades as compared to the 1975-1977 study (346 mm), the yield-ET relationship can be affected by many factors. Nevertheless, comparing yield and ET in the three studies, corn yield increased at any ET level from 1975 to 2013, indicating overall

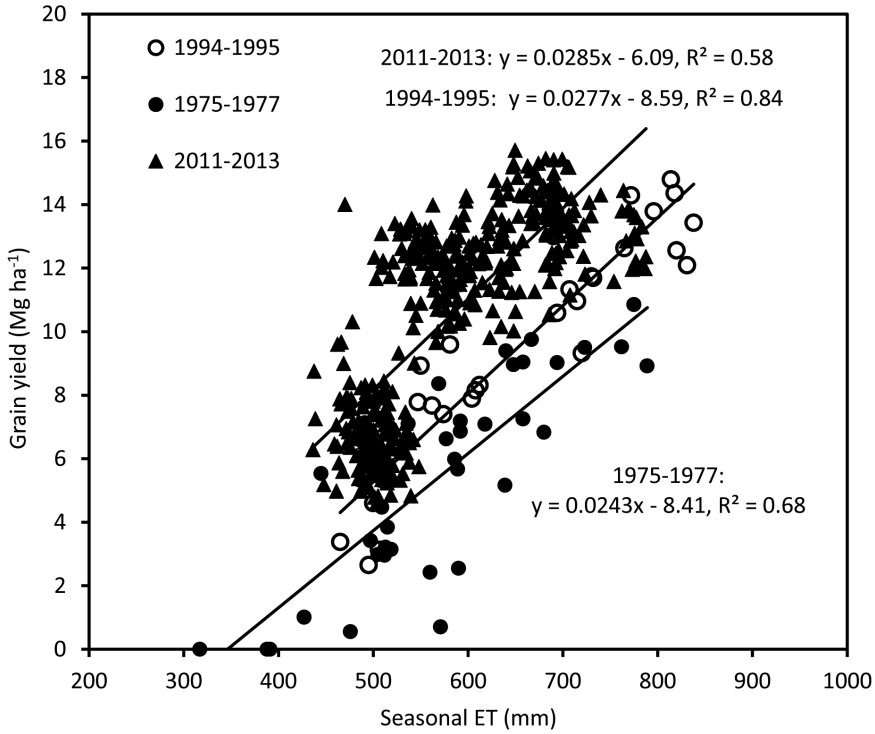

Figure 5. The relationship between corn yield and seasonal evapotranspiration (ET) in the periods of 1975-1977, 1994-1995, and 2011-2013 in the Texas High Plains (Data sources: Musick and Dusek 1980; Schneider and Howell 1998; Hao et al. 2015).

corn yield improvement in the last four decades. Greater yields in the studies of 1994-1995 and 2011-2013 at lower ET levels (<600 mm) indicate that drought tolerance technology in new corn hybrids has improved in the last four decades. The improvement of drought and other stress tolerance in corn hybrids has also been reported in the U.S. Corn-belt region and Canada (Tollenaar and Lee 2002; Hammer et al. 2009).

As WUE is the ratio of yield to seasonal ET, factors affecting both yield and ET will affect the WUE values. In the THP, WUE values were affected by irrigation amount, frequency, and management methods (Howell et al. 1995; Schneider and Howell 1998; Hao et al. 2015). Under full irrigation conditions (100% ET requirement or greater), WUE has increased from about 1.00 kg m^{-3} in the 1975-1977 study to about 2.00 kg m^{-3} in the 2011-2013 study (Figures 2, 4). The increased WUE in recent years (2011-2013) reflects the yield improvement over the last four decades. Studies have also shown that the maximum WUE is generally achieved at less than the 100% ET requirement level (Howell et al. 1995; Payero et al. 2008; Colaizzi et al. 2011; Hao et al. 2015). Corn WUE at the 100% ET level and 75% ET level ranged from 1.80 to 2.17 kg m^{-3} at Bushland (Colaizzi et al. 2011). WUE values at the same two irrigation levels ranged from 1.51 to 2.57 kg m^{-3} with a relatively low WUE (1.51-2.15 kg m^{-3}) in 2011 and a relatively large WUE (1.70-2.57 kg m^{-3}) in 2012 and 2013 in a study at Etter, Texas (Hao et al. 2015). In a two-year (1992 and 1993) field study at Bushland Texas, a lower corn WUE of 1.58-1.75 kg m^{-3} was reported by Howell et al. (1995). However, WUE decreased significantly as irrigation levels were reduced to 50% ET requirement or less (Schneider and Howell 1998; Hao et al. 2015). For example, irrigation at the 25% ET level can result in crop failure (Schneider and Howell 1998).

Irrigated Corn Management Practices in the Texas High Plains

A declining water table coupled with irrigation pumping restrictions by groundwater districts could challenge sustainable corn production in the region. Limited irrigation, the application of less irrigation water than the plants require for full crop ET (100% level), will be the primary practice in the future in the THP. As such, development of advanced management practices is important to continue improving the yield and WUE relationship under water-limited conditions. Generally, there are two approaches to improve crop performance: breeding and management practices. Improving corn yield and WUE through breeding has been a major focus in both private (Pioneer, Monsanto, and Syngenta companies) and public sectors (e.g., universities). Management practices are as important, or possibly more so, than breeding when water-limited conditions exist (Passioura and Angus 2010). Improved crop management is responsible for the larger portion of increased productivity under water-limited conditions (Anderson 2010).

Irrigation Management

Although many management factors affect corn production in the THP, irrigation management remains the most effective way to sustain high crop productivity. In the THP, irrigation systems and accommodating agricultural practices have changed significantly in the last four decades, from furrow irrigation (1950s-1970s) to center pivot sprinkler and to (a lesser degree) subsurface drip irrigation systems that are currently being used. The history and trends of irrigation research and development in the region have been reviewed in different eras from the 1990s to recent time (Musick et al. 1990; Colaizzi et al. 2009; Evett et al. 2014). The details of irrigation history, economic impact, research, and development trends can be found in the aforementioned three review papers. Based on these papers, there are three generally inferred statements regarding irrigation in the THP. First, the irrigation supply from the Ogallala Aquifer is declining. Second, irrigation efficiency through systems conversion has been dramatically increased over the last few decades in the THP. Third, the future challenge is how to efficiently use the reduced amounts of irrigation while sustaining corn yields. The last is further challenged by the fact that future increases in other regional needs (such as municipal demand, power generation, etc.) will be added to the expense of the irrigation supply (PWPG 2011). However, preserving irrigation is crucial to sustainable crop production in the region

(as well as national security item) since irrigation significantly increases WUE as compared to dryland production (Evett et al. 2014).

To increase the efficiency of the irrigation applications, events should be scheduled using measurements of ET, soil moisture depletion, and/or plant based measurements. Irrigation scheduling to enhance the WUE includes the management of both water and soils. Crop ET is typically calculated using a crop specific coefficient (Kc) and reference evapotranspiration (ET_o). ET_o is calculated evapotranspiration from a reference crop (turf grass or alfalfa) using the meteorological parameters of temperature, relative humidity, precipitation, wind speed, and solar radiation. Irrigation can also be scheduled according to changes in soil moisture. Soil moisture sensors can provide information on soil moisture fluxes in the root zone, which provide information on when to initiate and terminate irrigation events. Irrigation scheduling using ET, a soil water balance method, or a combination of the two can be successfully employed in irrigated corn production.

The seasonal average irrigation for (grain) corn is approximately 500 mm in the THP Region A (Top 26 Counties of Texas, Marek et al. 2011). However, irrigation demand can vary and be much higher during a severe drought year such as in 2011, with a seasonal ET of 900 mm and irrigation of 754 mm (Hao et al. 2015). Based on multiple-year studies at Bushland and Etter, using irrigation to meet a 75-80% of ET demand level can result in similar yields as compared to years where 100% of the ET demand was achieved with average or above average seasonal rainfall. Also, WUE is generally maximized at the 75-80% irrigation level. Unless adequate seasonal rainfall (normally > 250 mm) and excellent soil water storage exist at the time of planting, lowering irrigation levels to a 50% ET requirement or less significantly reduced corn yield (Schneider and Howell 1998; Collaizzi et al. 2011; Hao et al. 2015). Irrigation levels at the 25% ET level can result in yield failures based on studies conducted by Schneider and Howell (1998) and Colaizzi et al. (2011).

Hybrid Selection

Hybrid selection is another impacting factor for corn producers and is increasingly becoming different from choices of the past. Drought and irrigation system capacity remain the most important producer concern in the THP. Figure 5 shows that corn yield has increased sufficiently at lower ET levels from 1970s to the present, indicating corn drought tolerance has improved. Drought tolerance has been considered (and marketed) as an important component in the success of corn hybrids grown in semi-arid or arid regions such as the THP and western Corn-belt (Cooper et al. 2014). Studies conducted at Etter, Texas demonstrated that recently released drought-tolerant AQUAmax hybrids P1151HR and P1564HR consistently showed yield benefit as compared to a conventional hybrid (33D49) at lower irrigation levels (75% and 50% ET demands), especially under severe water stress conditions (e.g., 50% ET demand; Hao et al. 2015). Comparable results were found by Cooper et al. (2014), who reported that AQUAmax hybrids showed higher grain yield than regular drought-tolerant and drought-sensitive hybrids under drought conditions.

Breeding for drought tolerance in corn is a major goal to improve yield stability under drought conditions. Furthermore, corn yield performance under non-drought conditions should also be considered when breeding for drought tolerance since producers are unlikely to adopt drought-tolerant hybrids if there is a significant yield penalty in well-watered environments (Boyer et al. 2013). Hao et al. (2015) showed that AQUAmax hybrids (P1151HR and P1564HR) had greater grain yield than the check hybrid (33D49) at irrigation levels of 75% and 50% ET demands. However, no significant yield penalty was observed with either P1151HR or P1564HR at the 100% ET levels (Hao et al. 2015). Although the newly developed drought tolerant corn hybrids provide significant yield benefits (10-15%) under lower irrigation levels, a conventional new hybrid would yield the same as drought tolerant hybrids if there was sufficient water.

Seeding Rate

Due to the high corn seed prices, producers are concerned about seeding rate. Regarding corn seeding rate in the U.S. and Canada, only about 10% of corn acreage is planted at 89,000 or more seeds

per hectare. About a third of the corn area planted is at 81,000 to 89,000 seeds per hectare (Butzen 2016). Marek et al. (2016) evaluated interactions of hybrids and seeding rate at multiple irrigation levels. The seeding rate ranged from 64,000 to 138,000 seeds per hectare. At the 100% ET level, corn yield increased as population increased initially but did not increase further at populations higher than 94,000 or 109,000 seeds per hectare, depending on hybrids (Marek et al. 2016). An optimal economic seeding rate (a seeding rate where yield increase from the next increment of seed no longer exceeds the seed cost) increased as yield potential increased. For example, the economic optimum seeding rate was determined to be 77,000 seeds ha^{-1} for 9.4 Mg ha^{-1} corn yield, but it increased to 96,000 seeds ha^{-1} for 15.1 Mg ha^{-1} yield. Based on published literature and the trial results of Marek et al. (2016), a rate of 99,000 seeds ha^{-1} or less would be sufficient for corn in the THP if the yield target is about 15.6 Mg ha^{-1}.

Planting Date

Corn planting dates in the THP range from mid-April to late May. Field trials were conducted and planting date and hybrid interaction for corn yield and water use were evaluated (Xue et al. 2014). The planting dates tested were May 15, June 1, June 15, and July 1. The results from this study indicated that high yield (13 Mg ha^{-1}) can still be achieved with a longer-season hybrid (e.g., > 111-day) when planted from mid-May to early June. When the planting date was delayed to late June and early July, corn yields were significantly reduced (about 3.6-7.7 Mg ha^{-1}, depending on the hybrid) for the long-season hybrids. However, yields in a short-season hybrid (96-day) were relatively consistent (8-10 Mg ha^{-1}) as planting date was delayed to late June. Although delaying planting to late June or early July could reduce corn yield potential, late planting can save irrigation water while maintaining greater water use efficiency.

Future Perspectives

Although progress has been made to improve corn yield and WUE in the last few decades in the THP, corn production still faces formidable challenges with declining irrigation water resources and from the additional potential of abiotic stresses suggested by climate change and the increased risk of frequent droughts. The amount of irrigation water available for corn production in the THP continues to decline. Although irrigation technologies have been dramatically improved over the years, management and genetic improvement are foreseen as extremely important in corn production. Drought stress is typical during the corn growing season with limited irrigation in semi-arid and arid regions, so improving both heat and drought tolerance through breeding will be an important component of overall crop improvement. Current research efforts have focused on grain yield, but very little attention has been given to grain quality including mycotoxin contamination. High mycotoxin levels can lead to the rejection of grains and as a result cause the WUE to decline to almost zero in the economic aspect. An improved understanding of crop response to drought stress factors and the identification of plant traits as affected by each will lead to the development of improved germplasm and hybrids in this region. It is also envisioned by many that additional supporting data using unmanned aerial systems (UAV's) should aid in the assessment of these characteristics and improve limited water production and management practices, particularly with the more water sensitive crops such as corn.

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