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Soil water extraction, water use, and grain yield by drought-tolerant maize on the Texas High Plains

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ABSTRACT

Anticipated water shortages pose a challenge to the sustainability of maize (*Zea mays* L.) production on the Texas High Plains. Adoption of drought-tolerant (DT) hybrids is a critical management strategy for maize production under water-limited conditions. However, limited information is available concerning water use by recently released DT hybrids. The objective of this study was to investigate the soil profile water extraction, evapotranspiration (ET), water use efficiency (WUE), and grain yield of one conventional and one DT hybrid. Field experiments were conducted in 2012 and 2013. The DT hybrid (AQUAmax™ P1151HR) and the conventional hybrid (33D49) were grown under three water regimes (I_{100}, I_{75} and I_{50}, referring to 100%, 75% and 50% of the ET requirement, respectively). The depth of soil water extraction was not affected by hybrid or water regime with the maximum extraction depth being 1.2–1.4 m. Water extraction was higher at I_{50} than at I_{75} and I_{100}. The maximum soil water extraction at I_{50}, I_{75} and I_{100} occurred in 0.6–0.8 m, 0.6–1.0 m and 0.8–1.0 m soil layers, respectively. Hybrid differences in soil water extraction were found in 2012, mainly at the grain-filling stage. At I_{100}, P1151HR had less soil water extraction than 33D49. Under water stress conditions at I_{50}, P1151HR had less soil water extraction in the upper soil layers but more water extraction in the deeper layers than 33D49. P1151HR had the same or less seasonal ET as compared to 33D49, indicating that the AQUAmax hybrid did not use more water than the conventional hybrid. P1151HR had higher yield and WUE than 33D49, particularly under the lower water regimes. On the average, yield and WUE of P1151HR were 6% and 9%, 14% and 17%, 24% and 30% higher than those of 33D49 at I_{100}, I_{75} and I_{50}, respectively. Higher yield of DT hybrid was associated with a higher biomass, a greater harvest index, and heavier kernel weight as compared to the conventional hybrid.

1. Introduction

Maize (*Zea mays* L.) is a major grain crop in the United States and a vital determinant of the world maize grain supply (Campos et al., 2004). For example, during 2008–2010, 39% of global maize was produced in the United States and this contributed to 49% of total global exports of maize (Boyer et al., 2013). Drought is a major factor constraining maize production in the world (Araus et al., 2002; Campos et al., 2006; Sammons et al., 2014). Average annual maize yield loss caused by drought is approximately 17% in tropical regions and15% in temperate zones (Barker et al., 2005). The 2012 drought in the United States that affected 80% of agricultural land (Claeys and Inzé, 2013) reduced maize yields by 21% and increased grain prices by 53% relative to the five previous non-drought years (Boyer et al., 2013). Furthermore, the United States Climate Change Science Program concluded that drought frequency and intensity is likely to be greater in the future, particularly in the western and southwestern portions of the country (Hatfield et al., 2008).

On the Texas High Plains, rainfall during the growing season for grain production in maize averages about 233 mm. This is only 31% of the estimated seasonal water requirement (evapotranspiration, ET, 745 mm) for maximum production of maize grain (Kapanigowda et al., 2010). Therefore, irrigation is required during the maize growing season to obtain high yields. The primary source of irrigation on the Texas High Plains is from the Ogallala Aquifer, an essentially closed aquifer with minimal recharge capacity (Howell, 2001; Xue et al., 2014). Increases in water withdrawal over the last 40 years for irrigation have been correlated with a severe decline

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of the groundwater level (Colaizzi et al., 2009). Therefore, anticipated water shortages pose a challenge to sustainability of maize production on the Texas High Plains.

During the past century, genetic improvements have significantly enhanced grain yield of maize in the United States (Duvick, 2001; Bruce et al., 2002; Duvick et al., 2004; Ciampitti and Vyn, 2012; Ciampitti et al., 2012). Much of the genetic gain in maize yield has been attributed to increased stress tolerance (Cassman, 1999; Tollenaar and Wu, 1999; Tollenaar and Lee, 2002; Campos et al., 2004; Duvick et al., 2004). As water resources for agronomic use become more limiting, adoption of drought-tolerant hybrids may be a viable solution for maintaining sustainable maize production under drought conditions. Drought tolerance is considered as an important component for the success of maize hybrids grown in drought regions. Improving drought tolerance in maize has been listed as a target of breeding programs (Cooper et al., 2014a,b). Previous studies have shown that drought-tolerant maize hybrids have a grain yield advantage over conventional hybrids during drought (Tollefson, 2011; Varshney et al., 2011; Ziyomo et al., 2013; Cooper et al., 2014a; Sammons et al., 2014). Higher grain yield by drought-tolerant hybrids is a result of maintaining a more favorable soil–plant water balance throughout plant growth and development, particularly during the critical flowering and grain-filling periods (Campos et al., 2004; Cooper et al., 2014a).

Compared to older maize hybrids, modern hybrids generally show higher yield under drought conditions (Cooper et al., 2006, 2014a), due possibly to increased drought tolerance of the newer hybrids (Duvick, 1997; Tollenaar and Wu, 1999; Campos et al., 2006). In addition, certain physiological traits have been associated with the yield gains under drought conditions. For instance, Hammer et al. (2009) reported that the longer term improvements in yields of maize in the United States Corn Belt may be attributed to a larger root system architecture and function supporting greater water capture. Corresponding to this, Barker et al. (2005) showed a significant trend in lower canopy temperature in more recent hybrids grown under stress, and attributed it to increased capacity to access soil water.

Physiological traits also contribute to increased drought tolerance in maize (Bänziger et al., 2006; Bruce et al., 2002; Blum, 2009; Lopes et al., 2011). To date, nearly all commercially available conventional maize hybrids exhibit some degree of drought tolerance (Sammons et al., 2014). Recently, DuPont Pioneer released several drought-tolerant AQUAmax hybrids that showed higher grain yield than regular drought-tolerant hybrids under both favorable water and drought conditions (Cooper et al., 2014a). In northwest Indiana, Roth et al. (2013) investigated the physiological responses of conventional and drought-tolerant AQUAmax hybrids to various plant densities and nitrogen levels. However, little information is known about differences in water use between conventional and drought-tolerant AQUAmax hybrids.

In addition to hybrid selection, appropriate irrigation water management, such as deficit irrigation (application of water at less than 100% of ET requirements) is another approach to reduce groundwater use for irrigation, while maintaining maize production on the Texas High Plains. Previous reports indicated that deficit irrigation could increase crop production per unit of water and reduce irrigation water input with only a limited impact on grain yield (Fereres and Soriano, 2007; Geerts and Raes, 2009; Aydinsakir et al., 2013). In the Western U.S. Corn Belt, Grassini et al. (2011) reported that, as compared with actual applied irrigation amounts used by farmers, limited irrigation can generate water savings of up to 22%, with a yield penalty of only 4%. Previous studies have indicated that maize plants showed the highest soil water extraction under low irrigation levels (Lenka et al., 2009; Aydinsakir et al., 2013). Pandey et al. (2000) reported that, under water stress conditions, maize plants could enhance water extraction from the deeper soil profile by increasing their root depth. However, little research has been done to compare the difference in soil water extraction patterns between conventional and drought-tolerant hybrids under deficit irrigation conditions. Thus, we investigate the differences in soil profile water extraction patterns, water use, and yield for one conventional and one drought-tolerant hybrid maize varieties.

2. Materials and methods

2.1. Experimental site description

This field experiment was conducted in 2012 and 2013 at the Texas A&M AgriLife Research Station near Etter, TX (35°52′ N, 101°58′ W; elevation 1114 m above mean sea level) on a Sherm silty clay loam soil (fine, mixed, mesic Torrertic Paleustolls). The chemical properties of the 0–0.3 m soil layer were as follows: pH 7.6, 60 kg KCl-extracted NO_3–N ha^{-1}, 13 mg kg^{-1} of Mehlich-3-extractable P, 404 mg kg^{-1} ammonium acetate-extractable-K and 11 g organic matter kg^{-1}. Winter wheat (*Triticum aestivum* L.) was the previous crop in both years. Meteorological data for the maize growing season in 2012 and 2013 were obtained from an agro meteorological station located at the experimental site.

2.2. Experimental design and treatments

The experimental design was a split-plot design with three replications. Irrigation treatment was the main plot factor with hybrid as the subplot factor. Irrigation treatments consisted of 100% (I_{100}), 75% (I_{75}) and 50% (I_{50}) of expected ET requirement. Irrigation was carried out with a center pivot irrigation system using low elevation spray application (LESA) method. Irrigation scheduling was determined by reference evapotranspiration (ETo), crop coefficient, and available soil water at the root zone on a daily basis for I_{100} (Marek et al., 2011). For I_{75} and I_{50} treatments, irrigation frequency was the same as that of I_{100} but the irrigation amount was proportional to that of I_{100}, by changing the nozzles. The same irrigation timing for all three irrigation levels used in this study was to accommodate different well capacities. Because of the declining trend of water resources in the Ogallala Aquifer, well capacity will decrease over time in the future (Colaizzi et al., 2009). For the low capacity wells, the amount of irrigation water pumped may satisfy only a portion of full ET requirement. The total irrigation amounts for I_{100}, I_{75} and I_{50} treatments were 612, 473, and 334 mm in 2012, and 608, 474 and 340 mm in 2013 (Fig. 1).

Two hybrids that differed in their drought-tolerance characteristics were planted in both years: DuPont Pioneer AQUAmax™ brand P1151HR and DuPont Pioneer 33D49; P1151HR was designated as the drought-tolerant hybrid. The drought tolerance scores for P1151HR and 33D49 as determined by DuPont Pioneer on a 9 point scale (1 = Poor, 9 = Excellent) were 9 and 7, respectively. The relative maturities of P1151HR and 33D49 were 111 days and 115 days (DuPont Pioneer Hi-Bred Intl., Inc., IA), respectively. The two hybrids were planted on 10 May in 2012 and 16 May in 2013, using a John Deere Max-Emerge planter. Planting density was 74,000 plants ha^{-1} in both years. Each experimental plot was comprised of four rows, 3.0 m wide (0.76 m row-spacing) and 9.1 m long. Based on soil tests, all treatments received supplemental nutrients at 280 kg ha^{-1} of N, 112 kg ha^{-1} of P_2O_5 and 33 kg ha^{-1} of S in 2012. In 2013, 100 kg ha^{-1} of N and 67 kg ha^{-1} of P_2O_5 were applied before planting, and 100 kg ha^{-1} of N was applied by fertigation during the growing season. Weeds were controlled by Status (diflufenzopyr + dicamba), Sharpen (saflufenacil) and Roundup (glyphosate) as pre-emergence and ResolveQ (rimsulfuron + thifensulfuron-methyl) plus Status