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Canopy temperature depression at grain filling correlates to winter wheat yield in the U.S. Southern High Plains

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ABSTRACT

Wheat breeding has improved drought tolerance over the years. However, our knowledge on drought tolerance in relation to the diurnal pattern of canopy temperature (CT) and grain yield is limited. A three-season wheat field study ending 2012, 2015, and 2016 was conducted at Bushland, Texas to investigate the relationship between canopy temperature depression (CTD) and yield during the grain filling period. For each season, 20 elite wheat genotypes were grown under dryland conditions, and CT was measured by Smart Crop wireless IRT sensors every 15 min continuously for 12–15 days during mid-grain filling (~10–25 days after flowering). There was a genotypic variation for CTD regardless of time of the day; however, the variation was more evident during the day time (10:00–18:00 h), with the smallest CTD (i.e., warmer canopy) at 14:00–15:00 h. In a dry season of 2012, TAM 304, TAM 112, Dumas, and Hatcher had greater CTD (i.e., cooler canopy) than other genotypes. In two wet/near normal seasons (2015 and 2016) Duster, TAM 111, TAM 110, TAM 112, and TAM 105 had greater CTD. There was a significant ($P < 0.05$) positive linear relationship between grain yield and day-time CTD. Hence, a cooler plant canopy during the mid-grain filling in winter wheat appears to be an important indicator of greater drought tolerance and yield under dryland condition. This knowledge may help breeders to conduct high-throughput field phenotyping in large breeding populations.

1. Introduction

Drought is the single most important environmental factor causing substantial yield loss in winter wheat (*Triticum aestivum* L.) in the U.S. southern High Plains (SHP). The long-term annual precipitation in the SHP averages about 470 mm. The wheat growing season (Oct.–June) receives an average of about 250 mm precipitation, which is one-third of the evapotranspiration (ET) requirement for wheat (700–800 mm) grown under full irrigation (Musick et al., 1994). In dryland areas, water deficit stress can affect in wheat yield at almost any stage (Eck, 1988; Zhang and Oweis, 1999). However, drought at the critical growth stages of wheat such as tillering, jointing, anthesis, and grain filling can result in significant yield loss (Hanks and Rasmussen, 1982; Eck, 1988; Xue et al., 2006). Therefore, development and adoption of drought-tolerant cultivars, which leave more water available for these critical times, or are able to access more water from the greater soil profile depths is a key strategy for sustainable wheat production in the area (Xue et al., 2014; Thapa et al., 2017a).

Canopy temperature (CT) is one of the many physiological traits that may help identify such drought-tolerant cultivars. Under high solar radiation and drought conditions, stomatal conductance decreases when soil moisture is not adequate to keep up with evaporative demands; and this, in turn increases CT (Jones and Leinonen, 2003; Urban et al., 2007). Plant morphological trait such as canopy architecture also influences CT not only through the angle of leaves to the light source, but also through the degree of mutual-shading in the canopy (Zheng et al., 2008). For example, according to Thapa et al. (2016), compared to conventional evenly spaced planting, growing corn plants in clumps (3 plants clustered) reduced the CT because of mutual-shading. Canopy temperature can provide plant-based information on the water status of the crop (Mahan et al., 2011). Thus CT has been used in drought (Rashid et al., 1999; Lopes et al., 2012) and heat stress experiments (Reynolds et al., 1994; Amani et al., 1996; Ayeneh et al., 2002) as well as for irrigation scheduling (Gontia and Tiwari 2008; Alchanatis et al., 2010). Genotypic differences can be observed in CT, such that CT may be used to characterize genotypic variation in energy balance, stomatal

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conductance, and transpiration (Balota et al., 2008).

Canopy temperature depression (CTD) is expressed as the difference between air temperature and canopy temperature (CTD = $T_{air} - T_{canopy}$) (Jackson et al., 1981; Balota et al., 2007, 2008). When evaporative cooling from transpiration cools the canopy below air temperature, then CTD is positive, conversely, when stomata close and CT rises above air temperature, then CTD is negative. Thus, for example, this value is generally higher, or more positive in well-irrigated plants, but generally lower, or more negative under water deficit conditions (Blum et al., 1989). The CTD can be influenced by a number of biological and environmental factors such as air temperature, soil moisture, wind velocity, evapotranspiration, cloudiness, canopy architecture, leaf adjustment to water deficit, relative humidity, and solar radiation (Bilge et al., 2008). The correlation between CTD and physiological states and processes in plants such as stomatal conductance (Rebetzke et al., 2013), leaf water potential (Cohen et al., 2005), and grain yield (Reynolds et al., 1994; Amani et al., 1996; Rashidet al., 1999; Ayeneh et al., 2002; Balota et al., 2007) under the conditions of limited water supply can be used as a selection criterion for tolerance to drought. The suitability of CTD as an indicator of yield and stress tolerance prediction, however, must be evaluated for every individual environment and, in particular, for every plant species (Blum et al., 1989).

A genotype that has a cooler canopy than another genotypes during the heading and grain filling period in wheat, in the same environment, can be an important indicator of drought stress tolerance (Munjal and Rana, 2003; Bilge et al., 2008). Balota et al. (2007) found genotypic variation in CTD among three closely-related wheat lines. Our previous studies demonstrated that higher grain yield in winter wheat under dryland conditions was closely associated with the effective stem carbon reserve remobilization and the depth and amount of soil water extraction (Xue et al., 2014; Thapa et al., 2017a). We hypothesized that genotypes having a cooler canopy, relative to others, during the hottest part of day produce more grain yield because they probably are more drought tolerant. This study was conducted to compare the CTD among 20 elite wheat cultivars during mid-grain filling and to characterize the relationship between CTD and grain yield under dryland conditions.

2. Materials and methods

2.1. Experimental design

Twenty elite wheat genotypes were used in this study. All 20 genotypes were grown under dryland condition at Bushland, Texas (Lat. 35.19° N, Long. 102.06° W; elevation 1170 m) in the winter wheat seasons ending 2012, 2015, and 2016. Among 20 genotypes, 14 genotypes were grown in all three years, and they were, Billings, Dumas, Duster, Endurance, Hatcher, Jagalene, TAM 105, TAM 110, TAM 111, TAM 112, TAM 113, TAM 304, TX99A0153-1, and Winterhawk. In addition, Bill Brown, Fuller, Jagger, TAM W-101, TX86A5606, and TX86A8072 were grown in the 2012 and 2015 seasons, and AMPSY068, AMPSY588, Iba, PlainsGoldByrd, TAM 114, and TX11Vsyn0101 were grown in the 2016 season. All "TAM" cultivars and experimental lines were developed by Texas A&M AgriLife Research (TAM) at different time periods. The experimental design was a randomized complete block design (RCBD) with three replications. The soil at Bushland is Pullman clay loam, which is a fine, mixed, superactive, thermic Torrertic Paleustoll (Unger and Pringle, 1981). The wheat was seeded on Nov. 03, 2011, Oct. 31, 2014, and Oct. 13, 2015. Each plot had seven rows with row spacing of 0.18 m, and row length of 4.5 m. The seeding rate was 67 kg ha^{-1}.

In each season, fertilizers were applied before planting based on soil tests to meet the dryland wheat yield potential of about 3500 kg ha^{-1}. Pesticides were applied as needed for managing weeds and insects.

2.2. Data collection

The canopy temperature was measured by Smart Crop wireless infrared thermometers (IRTs; Smartfield Inc., Lubbock, TX, www.smartfield.com). In the past, hand-held IRTs and wired IRTs have most commonly been used to monitor CT. The hand-held IRTs, which provide point-in-time values, are more difficult to use for a large number of plots, and also are difficult to use for investigating the relationship of CT with plant growth stage or time of day. Similarly, wired IRTs require substantial time and labor to install the system, and regularly archive the data. In this study, we used continuously recording wireless IRTs that can measure temperature continuously day and night without the hassle of cable management from each sensor, or need to regularly download a data logger. A sensor was installed at the center of each plot (3 reps. in 2012 and 2015, 2 reps. in 2016) at anthesis and a base station unit was established at the edge of the field to collect and transmit data. The IRT sensors were placed in the best part of the plots, where the crops were growing more uniformly with maximum ground cover, and at about 0.15 m above the plant canopy height. The viewing angle was 60° facing downward. Each sensor collected data from a circular field of view with 0.15 m diameter, every minute, auto-averaged to every 15-min., and reported wirelessly to the base station. The CT data collected in the base station were transmitted to a computer system for archiving and subsequent analysis. The base station also recorded ambient temperature every 15 min. The data were continuously collected for 15 days in the 2012 and 2015 seasons and 12 days in the 2016 season at the mid-grain filling. Time period of about 10–25 days after flowering was considered as mid-grain filling.

At first, CTD ($T_{air} - T_{canopy}$) was calculated every 15 min and then, the hourly CTD was calculated as an average of four subsequent 15-min data. The volumetric soil water content (SWC, $m^3 m^{-3}$) was measured in 12 plots each year at anthesis (AN) and physiological maturity (MA) using a 503 DR1.5 Hydroprobe (CPN, a division of InstroTek, Inc., Raleigh, NC, USA). The probes were previously calibrated *in-situ* at the experimental site using methods described by Evett and Steiner (1995). The access tubes were installed at the center of plots and measurements were taken every 0.2 m, starting at 0.1 m and ending at 2.3 m below the soil surface.

The amount of soil water (SW, mm) in the root zone was calculated as, SW = total soil water content ($m^3 m^{-3}$) × soil depth (mm) at each layer (Xue et al., 2003; Thapa et al., 2017a). Net soil water extraction (SWE) in the 0.0–2.4 m profile between AN and MA was calculated as, SWE = SW at AN (mm) – SW at MA (mm). However, there was no SWE below 1.4 m in the 2012 and 2015 seasons. Therefore, total soil water content only from the 0.0 to 1.4 m profile was considered for each year for the calculation of evapotranspiration (ET). Evapotranspiration was calculated using the soil water balance method, that is, ET = SWC at AN + precipitation between AN and MA – SWC at MA, assuming that there was no surface runoff. Though there were small variations among the seasons, on average, AN and MA stages corresponded to the day of year (DOY) of 125 and 160, respectively. At maturity, each plot (5.67 m^2) was combine-harvested and yield was determined after air drying. The yields were only available for the 2012 and 2016 seasons because of hail damage in the 2015 season.

2.3. Statistical analysis

Statistical analysis was conducted using SAS 9.4 (SAS Institute Inc, 2013). The PROC MIXED procedure in repeated measure analysis of variance (ANOVA) was used to evaluate the difference in CTD. The ANOVA was also used to evaluate the yield difference among the genotypes. Replication was considered random effect, whereas cultivar was a fixed effect. Means were considered significantly different at least significance difference (LSD) of the 5% level. Since the study was intended to identify more drought tolerant genotypes in relation to CTD and grain yield, regardless of differences in CTD among the days and