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Water-induced variation in yield and quality can be explained by altered yield component contributions in field-grown cotton

Wei Hu[a,b,*], John L. Snider[b], Haimiao Wang[a,b], Zhiguo Zhou[a], Daryl R. Chastain[b], Jared Whitaker[b], Calvin D. Perry[c], Freddie M. Bourland[d]

[a] *College of Agriculture, Nanjing Agricultural University, Nanjing, Jiangsu Province, 210095, PR China*
[b] *Department of Crop and Soil Sciences, University of Georgia, 115 Coastal Way, Tifton, GA, 31794, United States*
[c] *C.M Stripling Irrigation Research Park, University of Georgia, Camilla, GA, 31730, United States*
[d] *Northeast Research & Extension Center, University of Arkansas, Keiser, AR, 72351, United States*

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ABSTRACT

Novel yield component traits and fiber quality indices have been recently developed by breeders to screen for desirable cotton (*Gossypium hirsutum* L.) lines, but assessing these components in response to water-induced yield variability has received little attention. We investigated the hypothesis that differential sensitivities of whole-crop and intra-boll yield components to drought will largely explain water-induced yield and fiber quality variation in cotton. To test this hypothesis, two cotton cultivars were grown in the field under five contrasting irrigation regimes during the 2013 and 2014 growing seasons near Camilla, GA. Measurements included pre-dawn leaf water potential (Ψ_{PD}) throughout the growing season and extensive yield component and fiber quality assessments at the end of the season. Water-induced yield variability was primarily associated with Ψ_{PD} at the flowering and boll development phase of crop growth. Boll density (bolls ha^{-1}) was the dominant driver of drought-induced yield loss, but reduced boll mass and seed number per boll also contributed somewhat to yield loss. By comparison, increased drought severity decreased fiber density but increased individual fiber mass, producing a peak in total fiber weight per seed at a -0.7 MPa Ψ_{PD} irrigation threshold and increasing lint percentage in stressed treatments. Thus, the negative impacts of drought on overall boll mass and seed number per boll are partially offset by increased dry matter partitioning toward fiber growth. Fiber length declined with increased drought severity, whereas fiber micronaire increased in the most severely stressed treatments. This indicates that increasing drought severity during flowering and boll development decreases the number of individual fibers per seed and their final length, but their thickness is increased. The end result is a decline in the overall fiber quality index (Q-score) under drought stress.

1. Introduction

Water deficit substantially limits lint yield and fiber quality in cotton (*Gossypium hirsutum* L.), even in production regions characterized by high annual rainfall (Chastain et al., 2014, 2016b; Pettigrew, 2004). This is especially true for cotton production regions in the Coastal Plain of the southeastern United States, where the coarse textured soils are characterized by limited water holding capacity, resulting in episodic drought events during the growing season (Ritchie et al., 2009). Drought limits yield by disrupting a number of underlying physiological processes. For example, soil water declines result in decreased cell turgor, which limits total source strength by inhibiting leaf area development and photosynthetic efficiency of the canopy (Chastain et al., 2014; Krieg and Sung, 1986; Pace et al., 1999; Pettigrew, 2004). This decline in source strength decreases the capacity to support a developing boll load, resulting in low fruit retention under drought stress (Krieg and Sung, 1986; Lokhande and Reddy, 2014; Snider and Oosterhuis, 2015). In agreement with these findings, some studies have shown that water-deficit significantly inhibited plant biomass production (Wang et al., 2016a; Zhang et al., 2017) and biomass accumulation of reproductive organs (Da Costa and Cothren, 2011). As a result, significant declines in both seedcotton yield and lint yield are observed under water-deficit conditions (Dağdelen et al., 2009; Wang et al., 2016b).

Other scientists analyzed yield components to explain the underlying declines in cotton yield under drought stress and attributed them to lower individual boll weight, decreased boll numbers per plant, or lower lint percentage (Pettigrew, 2004; Sharma et al., 2015; Wang

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[*] Corresponding author at: College of Agriculture, Nanjing Agricultural University, No. 1 Weigang, Nanjing, Jiangsu, 210095, PR China.
E-mail address: wh65027@uga.edu (W. Hu).

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et al., 2016b; Zhang et al., 2016; Zahoor et al., 2017). The product of the aforementioned components is lint yield. However, some breeders have utilized novel yield component traits that reflect fiber quantity, density, and weight to screen for high yielding cotton lines (Ali and Awan, 2009; Groves and Bourland, 2010). Because cotton fibers are unicellular trichromes protruding from the seed coat surface, Smith and Coyle (1997) reported that breeding for large seed surface area and number of seeds per boll could provide more surface area to increase lint yield (Culp and Harrell, 1973). Moreover, increased fiber density is a potentially useful selection criterion for improving fiber quantity per seed to increase lint yield (Groves et al., 2016). Cook (1908) suggested that lint index (lint mass per 100 seeds), could be used as a preferred selection tool for increased lint yield by increasing the total lint mass per seed (Groves et al., 2016), which is a function of average fiber number per seed and average individual fiber weight (Ali and Awan, 2009). Although improving these traits has been shown to increase lint yield through breeding efforts (Groves et al., 2016) and these yield component characteristics could be assessed to provide a detailed explanation of the underlying limitations to yield under water deficit, this information is extremely limited for field-grown cotton.

Drought, depending upon severity, also negatively affects cotton fiber quality, including fiber length (Zheng et al., 2014), uniformity ratio (Niu et al., 2016), fiber strength (Dabbert et al., 2017) and micronaire (Wang et al., 2016b). However, different cotton fiber processing methods have different fiber quality requirements, and no single high volume instrument (HVI) parameter can be applied to all situations. Bourland et al. (2010) developed a fiber quality index called quality score (Q-score). Q-score is based on up to six HVI fiber parameters, and the user can apply specific weightings to each (Bourland et al., 2010). Since different drought levels can have different effects on fiber traits (Wang et al., 2016a), Q-score should be able to evaluate the effect of drought on overall fiber quality.

The impact of drought on yield components and fiber quality in cotton differs from study to study (Snider and Oosterhuis, 2015), likely because irrigation treatments imposed under field conditions can vary greatly in drought severity due to environmental influence. Most studies define stress levels or irrigation treatments under field conditions using water balance approaches (Basal et al., 2009; Dağdelen et al., 2009). However, plant water status in the field can be affected by soil physical characteristics (Rab et al., 2009), atmospheric demand (Schulze et al., 1987; Jackson et al., 1981), and plant factors such as effective rooting depth and leaf area development (Snider and Chastain, 2016). Direct measures of leaf water potential integrate all of these factors and provide an accurate indicator of the need for irrigation (Grimes and Yamada, 1982). Predawn leaf potential (Ψ_{PD}) is a direct index of plant water status that has been strongly correlated with growth and physiological parameters such as leaf area, plant height, stomatal conductance, and photosynthetic rate (Jordan, 1970; McMichael et al., 1973; Turner et al., 1986; Jones, 2007; Snider et al., 2015; Chastain et al. 2016a).

Previous work conducted in our laboratory quantified lint yield and water use efficiency (WUE) responses for cotton grown under five different irrigation treatments employing a combination of conventional and Ψ_{PD}-based irrigation scheduling thresholds during two growing seasons (Chastain et al., 2016b). Regardless of treatment, Ψ_{PD} was routinely measured for all irrigation treatments throughout the growing season, and Ψ_{PD} thresholds for optimal yield and WUE were identified. Because Ψ_{PD} was monitored near-continuously, the level of drought stress experienced by plants at key growth stages could be determined and combined with detailed yield component and fiber quality assessments to identify how underlying processes respond to increases in drought severity. We hypothesized that 1) apart from boll density, boll weight and lint percentage, the novel yield component traits mentioned above (seed index, seeds boll^{-1}, seed surface area, lint weight seed^{-1}, fibers seed^{-1}, fiber density, weight fiber^{-1} etc.) also will be decreased by drought stress and contribute to yield loss under drought stress; 2) overall fiber quality based on fiber length, strength and uniformity, and micronaire will be decreased by drought stress as a result of intra-boll yield component alterations. The objectives of the present study were to: 1) determine the effects of different degrees of drought stress on boll density, boll weight and lint percentage, and these novel yield component traits and to quantify the contributions of different yield components to yield loss; 2) estimate the effects of drought stress on fiber quality parameters, with a focus on the Q-score (obtained by normalizing HVI fiber length, strength, micronaire, and uniformity into an overall quality index).

2. Materials and methods

2.1. Plant material and study site

To address the impact of crop water status on yield components and fiber quality in cotton, a field study was conducted at C.M. Stripling Irrigation Research Park (31°16′48″N, 84°17′29″W) near Camilla Georgia during the 2013 and 2014 growing seasons. The soil type at this site is a Lucy loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults). Seeds of two commercial cotton varieties (PHY 499 WRF [Dow AgroSciences]) and FM 1944 GLB2 [Bayer CropScience]) were planted on May 6, 2013 and June 2, 2014. Practices such as tillage, row spacing, seeding rate, and planting depth were conducted according to University of Georgia Extension Service recommendations (Collins et al., 2014), and were described in detail by our previous paper (Chastain et al., 2016b). Individual plots were 6 rows wide × 40 m long with two buffer rows between adjacent plots. Immediately after planting, pre-emergence herbicides were applied to the soil surface, and irrigation was uniformly applied to the entire field using overhead sprinkler irrigation delivered via center-pivot to ensure herbicide activation and to prevent yield limitations due to poor stand establishment. Stand counts were conducted approximately two weeks after planting, and in-row plant densities were above levels needed to maximize yield (Collins et al., 2014). Supplemental irrigation was uniformly applied over the entire study until the first floral buds were visible to the naked eye (squaring; SQ). At this time, irrigation treatments (described below) were initiated. Crop management, including fertility and pest control, were conducted according to recommended practices (Collins et al., 2014).

2.2. Irrigation treatments

The study was arranged as a split plot, randomized complete block design with four replications, where irrigation treatment was the whole plot factor and cultivar was the subplot factor. At squaring, five unique irrigation treatments were imposed. **T1:** Irrigation scheduled according to a well-established water balance approach referred to as the “checkbook” method (Collins et al., 2014), where supplemental irrigation is provided to meet crop growth stage-specific water requirements after accounting for weekly rainfall. **T2-T4:** Irrigation scheduled using predawn leaf water potential (Ψ_{PD}) values to trigger an irrigation event. Using this approach, Ψ_{PD} (measurements described in Section 2.3) was measured every two days during the irrigation treatment period, and when Ψ_{PD} was equal to or below predefined thresholds (T2 $= -0.5$ MPa; T3 $= -0.7$ MPa, and T4 $= -0.9$ MPa), water was delivered at 1/3 of total weekly checkbook recommended amounts since irrigation decisions were made three days per week. **T5:** No supplemental irrigation was provided during the irrigation treatment period. The Ψ_{PD} thresholds for T2–T4 were selected because these values correspond to plant water status levels shown previously to differentially impact net photosynthesis (Snider et al., 2015). Irrigation water was delivered using subsurface drip tape positioned at a 30 cm depth in alternating row middles. Weather data were obtained from an on-site weather station as part of the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net). The minimum and