Arguably the most limiting factor in agricultural production is drought, which has caused the collapse of past agricultural civilizations (Kennett et al., 2012). In the humid southeastern United States, evaporative demand is low relative to other production regions, and typical season total precipitation amounts are above the 46-cm total of water required to maximize cotton yields (Bednarz et al., 2002; Ritchie et al., 2009). However, in Georgia specifically, episodic drought stress is common due to sporadic periods of low rainfall coupled with the limited water-holding capacity of the coarse-textured soils of the Coastal Plain (Ritchie et al., 2009). Drought limits productivity in cotton by negatively impacting a number of underlying physiological processes that determine final yield. Decreases in overall plant growth are among the first negative responses associated with drought (Hsiao, 1973). Leaf area development, mainstem elongation, and a limited number of available fruiting sites are all consequences of drought-induced growth limitations (Jordan, 1970; Grimes and Yamada, 1982; Krieg and Sung, 1986; Turner et al., 1986; Pace et al., 1999;
Loka and Oosterhuis, 2012; Lokhande and Reddy, 2014). In addition, total source strength (the product of total leaf area and average photosynthetic efficiency of those leaves) is limited under drought, due to inhibited cellular expansion and resultant declines in leaf area noted above (Krieg and Sung, 1986; Pace et al., 1999), and average photosynthetic efficiency can be limited through stomatal or nonstomatal limitations to photosynthesis proper or through increases in respiratory carbon losses, depending on drought severity (Hsiao, 1973; Turner et al., 1986; Tezara et al., 1999; Cornic and Fresneau, 2002; Pettigrew, 2004; Ennahli and Earl, 2005; Zhang et al., 2011; Chastain et al., 2014). This decline in source strength limits the photosynthetic available to support a developing boll load. As a result, poor fruit retention appears to be the weakest link in the response of cotton to drought and likely explains most drought-induced yield declines (McMichael et al., 1973; Krieg and Sung, 1986; Loka and Oosterhuis, 2012; Lokhande and Reddy, 2014; Snider and Oosterhuis, 2015).

However, if drought stress is severe enough, individual boll mass can be negatively impacted as well (Gerik et al., 1996; Lokhande and Reddy 2014). Given the negative impacts of drought stress, supplemental irrigation is commonly utilized by producers in the southeastern United States to mitigate the yield-limiting effects associated with drought. Equally concerning are the impacts of excessive irrigation. Specifically, overirrigating can limit economic sustainability by unnecessarily increasing input costs; it has been implicated as a threat to environmental sustainability, and has been the subject of debate in high-profile lawsuits between states arguing over water rights (Tilman, 1999; Golladay et al., 2004; Beman et al., 2005; Perry and Barnes, 2012). Thus, efficient irrigation scheduling will be essential if producers are to minimize risks associated with water deficit while also minimizing the negative consequences of overirrigating. However, deciding when and where water should be applied has proved problematic. Producers have adopted a wide scope of irrigation scheduling methods. These range from calendar-type methods to rainfall-budget approaches and the use of environmental sensors. Irrigation triggers based on environmental parameters, such as remote sensing of soil moisture status, offer (i) the promise of timely irrigation scheduling based on soil water status and (ii) the possibility of complete automation (Snider et al., 2015). These methods are also problematic, however, due to factors such as heterogeneity in soil composition, the accuracy of the method used for their calculation, and the need for site-specific calibration (Leib et al., 2003; Jones, 2007). These methods, while useful and easily applied, are limited due to their lack of information on the stress level of the crop in question. For cotton grown in Georgia, many producers use a “checkbook” approach, where each phenological growth stage is allotted a weekly amount of water (i.e., Collins et al., 2014); rainfall amounts are supplemented with irrigation to reach the weekly target. While the abovementioned approaches consistently result in high yields, recent interest in adopting more sustainable irrigation practices for large-scale agriculture spawned research into maximizing water productivity (WP; agricultural product yield per unit of water, supplied through rainfall or irrigation; reviewed in Ali and Talukder, 2008). Models that estimate crop evapotranspiration have the potential to improve WP more than the methods described above because they take into account environmental factors that influence reference evapotranspiration (Vellidis et al., 2014). All of the aforementioned approaches are limited, however, in that they do not provide an indication of the water status of the crop itself, nor do they account for actual plant growth characteristics (actual rooting depth, leaf area development, etc.) that influence the soil reservoir of readily available water and the rate of crop water use.

The environmental factors limiting the use of indirect measures of plant water status can potentially be accounted for by region-specific calibration using a direct measure of plant water status (Jones, 2004). Direct measures of plant water status include the relative water content and water potential ($\Psi_W$). Predawn water leaf potential ($\Psi_{pd}$), a well-established direct measure of crop water status (McMichael et al., 1973; Ameglio et al., 1999; Chastain et al., 2014; Snider et al., 2014; Snider et al., 2015; Chastain et al., 2016), may be the most useful direct water status measure for irrigation scheduling in the southeastern United States. Water potentials (as measured with a pressure chamber) are generally at a maximum immediately before sunrise (Jordan 1970; Turner et al., 1986), after which they fall to a minimum around midday, before steadily rising through the afternoon and leveling off overnight at values similar to presunrise values (Jones, 1990).

While midday water potential ($\Psi_{md}$) is highly indicative of the physiological state of the plant (Turner et al., 1986; Pettigrew, 2004; Ennahli and Earl, 2005; Chastain et al., 2016) and a strong indicator of water-induced variation in productivity (Grimes and Yamada, 1982), $\Psi_{pd}$ measurements have the advantage of being less sensitive than $\Psi_{md}$ measurements to environmental fluctuations (i.e., vapor pressure deficit or cloud cover; Grimes et al., 1987), as well as leaf position on the plant (Jordan, 1970). Sensitivity to midday cloud cover is a particularly notable constraint to using $\Psi_{md}$ in Georgia for irrigation scheduling purposes because extensive midday cloud cover is often observed during a typical cotton production season the southeastern United States. Furthermore, $\Psi_{pd}$ has been shown to correlate with evapotranspiration, has been used to schedule irrigation in tree species (Ameglio et al., 1999), and is highly predictive of midday metabolic trends, such as decreases in net photosynthesis and a proportional increase in respiration as well as photorespiration (Chastain et al., 2014). Although the direct measures of plant water status offer the greatest potential to maximize WP, major constraints to their potential adoption is the need for manual measurements, which limits the number of fields that...
could be measured on a given day, and with $\Psi_{PD}$ inconvenient measurement times.

Many crop researchers have sought to enhance irrigation efficiency by using indirect measures of plant water status such as crop canopy temperature (Ehler et al., 1978; Idso et al., 1981; Mahan et al., 2010; Conaty et al., 2012). Briefly, as water becomes limiting, transpiration decreases as a result of stomatal closure (Hsiao, 1973), ultimately resulting in elevated canopy temperatures. One of the more successfully demonstrated canopy temperature-based methods for detecting water deficit, the crop water stress index (CWSI; Idso et al., 1981), compares the canopy temperature response of a given crop to vapor pressure deficit (VPD) with that of a well-watered crop to indicate the severity of drought stress. While this approach is very effective in arid regions (high VPD), application in more humid regions, like the southeastern United States, has been limited because low VPD could potentially lead to high canopy temperatures even in the absence of water deficit stress, and because humid environments are said to alter the relationship (slope) between canopy temperature and VPD (Jones, 2004). One caveat of using direct or indirect plant-based water stress indication is that a stress level does not indicate how much water needs to be applied to relieve the stress (Jones, 2004).

In the current study, we sought to couple the use of $\Psi_{PD}$ as an irrigation threshold with modified use of the Georgia Checkbook irrigation recommendations. By using this combined approach, our plant-based thresholds gave information on when to apply water, whereas the Georgia Checkbook provided information on irrigation quantity. We hypothesized that the use of $\Psi_{PD}$ as an irrigation trigger, combined with recommended application amounts based a phenology-specific checkbook approach, could lower water use and increase crop WP without reducing lint yield relative to the recommended checkbook approach alone. In addition, through continuous monitoring of crop canopy temperature and season-long measurement of $\Psi_{PD}$ during our study, we hypothesized that a CWSI derived from a well-watered baseline would be closely associated with $\Psi_{PD}$ and predictive of water-induced variability in lint yield.

MATERIALS AND METHODS

Plant Material

To evaluate the usage of predawn leaf water potential as an irrigation trigger, research plots (six rows with two row borders) were established at C.M. Stripling Irrigation Research Park near Camilla, Georgia (31°16′55.5″ N, 84°17′39.9″ W) in 2013 and 2014. A rye (Secale cereale L.) cover crop was established in the off season and subjected to a glyphosate burndown and mowing before planting. Fields were then strip tilled to a 0.45-m depth. On 6 May 2013 and 2 June 2014, seeds of two commercially available Gossypium hirsutum cultivars (PHY 499 WRF [Dow AgroSciences] and FM 1944 GLB2 [Bayer CropScience]) were sown at an interrow spacing of 0.91 m and a rate of 11.5 seeds m$^{-1}$. Plots were 12.2 m long with 2.4-m alleys. To promote uniform stand establishment and comparable early season plant growth for all treatments, supplemental irrigation (14.9 in 2013 and 18.5 cm in 2014) was blanket applied to all plots via overhead sprinklers until squaring, at which time irrigation treatments were initiated. Upon initiation of irrigation treatments, plots were irrigated via subsurface drip tape placed 0.3 m deep, in alternating rows. Phosphorus and potassium were maintained according to Cooperative Extension Service recommendations (upper-medium range, as per soil-testing recommendations) with application before planting. Nitrogen was applied at 134.5 kg ha$^{-1}$ with one-third applied before planting, followed by two-thirds applied by sidedress between squaring and first flowering. Pest management practices were conducted according to University of Georgia Cooperative Extension Service recommendations (Collins et al., 2014). Rainfall and environmental data were provided by the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net) weather station, located on site and immediately adjacent to the experimental field.

Irrigation Treatments

In this study, irrigation treatments consisted of the Georgia Cooperative Extension Checkbook recommendations (Collins et al., 2014; treatment one [T1]), three modifications of the checkbook using $\Psi_{PD}$ thresholds as irrigation triggers (T2, $\Psi_{PD} = -0.5$ MPa; T3, $\Psi_{PD} = -0.7$ MPa; T4, $\Psi_{PD} = -0.9$ MPa) and dryland (T5). The Georgia Checkbook method consists of weekly irrigation and rainfall-budget target amounts based on crop phenological stage. Briefly, a crop would require 1.9 cm of water from planting to first bloom. Weeks one through seven (and beyond) of bloom would require 2.54, 3.81, 5.08, 5.08, 3.81, 3.81, and 2.54 cm of water, respectively (typically a total of ~45.72 cm). In some instances, the total amount of water received by the crop would exceed target checkbook amounts because the checkbook approach treats each week independently, thus high rainfall events substantially exceeding checkbook requirements in preceding weeks are not counted toward irrigation requirements the following week. This is mainly due to the limited water-holding capacity of the coarse-textured soil of the experimental site. Plant-based irrigation triggers were based on thresholds previously shown to differentially affect midday photosynthetic trends (Snider et al., 2014). The $\Psi_{PD}$ was measured between 0400 and 0600 h in each plot (one leaf per plot), three times per week (Monday, Wednesday, and Friday) beginning at the onset of squaring. When $\Psi_{PD}$ for a given irrigation treatment average declined to the thresholds noted above, one-third of the weekly checkbook requirement was applied. Irrigation treatments were continued until open bolls were present in every plot.

Regardless of irrigation treatment, $\Psi_{PD}$ was measured in every plot using a Scholander pressure chamber (Model 615; PMS Instruments, Albany, OR). Measurements were conducted on the uppermost, fully expanded leaf. Cut leaves were sealed in the chamber within 5 s of excision and pressure was applied at 0.1 MPa s$^{-1}$ until xylem sap reached the cut surface of the petiole.

Canopy Temperature and Crop Water Stress Index

Beginning at the initiation of irrigation treatments (squaring), 15-min average canopy temperatures ($T_{c}$) were monitored throughout the growing season using an infrared thermometer...
in each plot (SmartField, Lubbock, TX) until irrigation was terminated. Sensors were maintained 20 cm above the canopy at 60° relative to the horizontal plane. The field of view (~20-cm diameter) was oriented towards the east, down a given row. Before analysis, data were filtered to include only TCavg, averaged from 1200 to 1400 h, when irradiance (measured at a weather station adjacent to the study) was above 600 W m−2. Dates when sensors were down due to fertilizer, growth regulator, or pesticide application were also excluded.

To calculate a CWSI (Idso et al., 1981), canopy-to-air temperature differentials (TCanopy − TAir) were plotted against ambient VPD for 100% checkbook plots in 2013 only, since the crop often received rainfall during this season well in excess of checkbook recommendations on days preceding those in which the aforementioned solar radiation requirements were met; therefore, the crop should have been under truly nonwater-stressed conditions. The aforementioned data were subjected to linear regression to quantify the relationship between TCanopy − TAir and VPD for a well-watered cotton crop to provide a nonwater-stressed (TNWS − TAir) baseline. Canopy temperature − TAir for a nontranspiring crop (TDry − TAir) was estimated by regression, according to the method described in Idso et al. (1981). Briefly, a negative VPD, equal in magnitude to the TCanopy − TAir VPD at saturation, was used to estimate TDry − TAir using the linear equation previously defined for the well-watered crop. The CWSI for each plot was then estimated using the equation CWSI = [(TCanopy − TAir) − (TNWS − TAir)] / [(TDry − TAir) − (TNWS − TAir)], where CWSI = 0 would represent a crop without any water limitations and CWSI = 1 would be a completely nontranspiring, drought-stressed crop.

**RESULTS**

**Weather Conditions**

Daily minimum and maximum air temperatures are illustrated in Fig. 1. In 2013, total rainfall (Table 1) from planting to defoliation was 67 cm, ~21 cm greater than what is recommended by the Checkbook approach (Collins et al., 2014). In contrast, the 2014 growing season total rainfall was less than Checkbook total recommendations (11 cm less; Table 1). In 2014, 3 cm (9.5%) of the season total rainfall occurred between 24 June and 8 August, a time encompassing prebloom to peak bloom.

**Predawn Water Potential and Growth**

In 2013, Ψpd trends were similar amongst all treatments (Fig. 2A), and not all Ψpd irrigation thresholds were reached. In contrast, all Ψpd irrigation thresholds were reached in 2014 (Fig. 2B). In 2013, Ψpd ranged from −0.8 to −0.1 MPa, across all treatments and sample dates. In 2014, the maximum observed Ψpd during the growing season for T1 through T5 were −0.15, −0.25, −0.2, −0.1, and −0.2 MPa, respectively. The minimum observed Ψpd for T1 through T5 during the entire growing season were −0.8, −0.9, −1.1, −1.7, and −2.1 MPa, respectively. When expressed as season-long treatment averages (Fig. 3), all treatments were similar in 2013; in 2014, however, only T1 and T2 were similar and had the highest water potentials of any other treatment. Treatments T3 through T5 had Ψpd values 17, 22, and 30% lower than average Ψpd for T1 and T2 (Fig. 3B).

Similar to Ψpd trends, total mainstem height and total mainstem node number did not respond to irrigation treatments throughout the 2013 growing season (Fig. 4A and 4C). In contrast, growth parameters were significantly affected by irrigation treatment at multiple times during the 2014 growing season (Fig. 4B and 4D). This is particularly evident on the 8 August sample date (P < 0.001 for height and mainstem node number). On this date, mainstem heights were similar for T1 and T2 (121 cm) and T3 through T5 (94 cm). Furthermore, the number of mainstem nodes per plant was numerically highest in T2 on this same sample date (18, no significant difference between T1 and T2) and lowest in T5 (14, Fig. 4D).

**Yield and Water Productivity**

For both years included in this study, lint yield did not vary due to cultivar. As a result, cultivar effects will not be assessed for any parameter discussed below. In 2013, irrigation treatments did not affect total lint yield (Fig. 5A), with yield averaging 1601 kg ha−1 for all irrigation treatments in...
Crop Water Stress Index

To develop a well-watered baseline for calculation of CWSI, \( T_{\text{Canopy}} - T_{\text{Air}} \) data were regressed with VPD (Fig. 7). A strong, negative relationship was found between VPD and \( T_{\text{Canopy}} - T_{\text{Air}} \) (\( r^2 = 0.79 \)), representing our well-watered baseline (\( T_{\text{Canopy}} - T_{\text{Air}} = 0.44 + -1.79 \text{VPD} \)). Season average CWSI was then calculated for all irrigation treatments for both 2013 and 2014 (Fig. 8). In 2013, no significant

Table 1. Irrigation total, rainfall total, and overall total water applied to cotton grown near Camilla, GA during the 2013 and 2014 growing seasons.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Irrigation (cm)</th>
<th>Rainfall (cm)</th>
<th>Total water (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>T1</td>
<td>17.4</td>
<td>66.9</td>
<td>84.3</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>11.5</td>
<td>66.9</td>
<td>78.4</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>2.5</td>
<td>66.9</td>
<td>69.4</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>0</td>
<td>66.9</td>
<td>66.9</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>0</td>
<td>66.9</td>
<td>66.9</td>
</tr>
<tr>
<td>2014</td>
<td>T1</td>
<td>29.9</td>
<td>34.9</td>
<td>64.8</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>23.7</td>
<td>34.9</td>
<td>58.6</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>14.2</td>
<td>34.9</td>
<td>49.1</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>10.0</td>
<td>34.9</td>
<td>44.9</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>0</td>
<td>34.9</td>
<td>34.9</td>
</tr>
</tbody>
</table>

2013. In 2014, irrigation treatments had a strong effect on lint yield (\( P < 0.001 \)). Yields ranged from 1995 kg ha\(^{-1}\) for T2 to 817 kg ha\(^{-1}\) for T5. Specifically, our highest-yielding treatments (T1 and T2) had 23, 43, and 58% higher lint yields than T3 through T5, respectively (Fig. 5B). The use of \( \Psi_{\text{p}} \), irrigation triggers decreased applied water (irrigation) by 7 to 9% (T2, −0.5-MPa threshold) and 21 to 31% (T4, −0.9-MPa threshold) relative to the Checkbook for the 2013 and 2014 growing seasons, respectively. In 2013, WP was lowest in T1 (Georgia Checkbook). Although statistically comparable to T1, T2 also had a mean WP that was statistically the same as treatments with the highest WP (T3 and T4). Treatments T3 and T4 had 20% higher WP, relative to T1. Treatment T5, while not significantly different from T2, had 19.4% higher WP than T1 (\( P < 0.001 \), Fig. 6A). In 2014 (Fig. 6B), WP was highest for T2 and T3 (\( P < 0.001 \), average of 40 kg ha\(^{-1}\) cm\(^{-1}\) for the two treatments). Treatment T1 had 12% lower WP, relative to T2. Treatment T4 WP was similar to T1, with T5 having the lowest WP (30.23 kg ha\(^{-1}\) cm\(^{-1}\), Fig. 6B).
differences were found across T1 through T5 (Fig. 8A). In 2014, T1 and T2 were similar and near zero. In contrast, T3 through T5 CWSI values averaged for the entire season were 0.35, 0.66, and 0.84, respectively (Fig. 8B), and differed significantly from each other ($P < 0.001$).

**Relationships among $\Psi_{PD}$, Lint Yield, and Crop Water Stress Index**

To assess the relationship between $\Psi_{PD}$ and lint yield, season average $\Psi_{PD}$ was plotted against end-of-season lint yield and subjected to second-order polynomial regression. A strong relationship was observed between the two variables ($P = 0.001, r^2 = 0.81$, Fig. 9). Season average $\Psi_{PD}$ was then plotted against season average CWSI for each irrigation treatment before conducting second-order polynomial regression. A strong relationship was found between the two variables ($P < 0.001, r^2 = 0.93$, Fig. 10). Finally, average CWSI was plotted against average lint yield and subjected to second-order polynomial regression, and a strong relationship was observed ($P = 0.003, r^2 = 0.81$, Fig. 11), where higher CWSI values were indicative of yield-limiting stress.

![Fig. 2. Seasonal trends in predawn leaf water potential ($\Psi_{PD}$) for cotton grown in Camilla, GA, during the 2013 (A) and 2014 (B) growing seasons for irrigation treatments T1 through T5. Dashed horizontal lines represent leaf water potential thresholds for treatments T2 through T4 ($-0.5$, $-0.7$, and $0.9$ MPa, respectively). Data represent means $\pm$ SE ($n = 8$).](image_url)

![Fig. 3. Season-long average predawn leaf water potential ($\Psi_{PD}$) for cotton grown near Camilla, GA, during the 2013 (A) and 2014 (B) growing seasons irrigation treatments T1 through T5. Within a given year, bars sharing the same letter were not significantly different ($P > 0.05$). Dashed horizontal lines represent $\Psi_{PD}$ thresholds for treatments T2 through T4 ($-0.5$, $-0.7$, and $0.9$ MPa, respectively). Data are means $\pm$ SE ($n = 8$).](image_url)
Fig. 4. Average mainstem height (A, B) and number of mainstem nodes per plant (C, D) for cotton grown near Camilla, GA, during the 2013 (left panel) and 2014 (right panel) growing seasons under irrigation treatments T1 through T5. Data are means ± SE (n = 8), and five plants were measured per replicate plot to provide a representative value for each parameter within a given plot.

Fig. 5. Lint yield for cotton grown near Camilla, GA, during the 2013 (A) and 2014 (B) growing seasons under irrigation treatments T1 through T5. Within a given year, bars sharing the same letter were not significantly different (P > 0.05). Data are means ± SE (n = 8).
DISCUSSION

Our current study supports the hypothesis that $\Psi_{PD}$ can be used as an effective irrigation trigger to maximize WP in drip-irrigated cotton in years with substantial differences in water availability. For example, 2013 can be considered a wet year, as rainfall amounts during the growing season were 21 cm greater than the 46-cm total requirement for maximal cotton yields previously reported for Georgia (Bednarz et al., 2002; Ritchie et al., 2009); by comparison, 2014 rainfall amounts were 11 cm lower than the previously noted requirement, and the lowest rainfall amounts were observed during the first few weeks of flowering, the period with the greatest sensitivity to water deficit (Snowden et al., 2014). The use of $\Psi_{PD}$ decreased irrigation 7 to 9% (T2, −0.5-MPa threshold) to 21 to 31% (T4, −0.9-MPa threshold) relative to the Checkbook for the 2013 and 2014 growing season, respectively. Additionally, WP was consistently maximized, while simultaneously producing maximal yields in a high (2013, Fig. 6A) and low (2014,
Fig. 6B) rainfall year. Water productivity increased by as much as 20% (T4) in 2013, with no detectable difference in fiber yield among any treatment (Fig. 5A). During this year, season average $Y_{PD}$ (Fig. 3A) remained above our lowest irrigation threshold for all treatments ($-0.5 \text{ MPa}$). In addition, for the majority of the growing season, all irrigation treatments were near or above this threshold (Fig. 2A). This confirms the observations of McMichael et al. (1973), where fruit abscission (a major driver of yield loss; Loka and Oosterhuis, 2012) should be limited at $Y_{PD}$ values above $-0.5$ to $-0.4 \text{ MPa}$. In addition to lint yield, our growth data agrees with the observations of Jordan (1970), where $Y_{PD}$ values less than $-0.8 \text{ MPa}$ can inhibit mainstem growth. Specifically, growth was not affected by irrigation treatment in 2013 (a year with little to no drought stress, Fig. 4A and 4C); in 2014, however, the average $Y_{PD}$ values of water-limited treatments (T3–T5) were below $-0.8 \text{ MPa}$ on several sample dates (Fig. 2B), and mainstem height and total mainstem node number were significantly lower than nonstressed treatments (Fig. 4B and 4D).

The use of $Y_{PD}$ as an accurate indicator of drought stress is a heavily debated topic. Some researchers against the use of $Y_{PD}$ because this metric fails to accurately reflect soil water status, and is often lower than $Y$ values from wetter soil portions in the rooting zone (Jordan and Ritchie, 1971; Klepper et al., 1973). As stated previously, if one assumes that no transpiration occurs overnight, $Y_{PD}$ would be in equilibrium with soil in contact with the entire root system (Ameglio et al., 1999; Jones, 2004). However, recent research indicates that nighttime transpiration can occur, creating disequilibrium between the soil and plant (Donovan et al., 2001; Snyder et al., 2003; Caird et al., 2007). Irrespective of this disequilibrium, $Y_{PD}$ represents the maximum water potential within a 24-h period (Jordan, 1970; Turner et al., 1986). In addition, $Y_{PD}$ has been linked to changes in growth and boll retention in cotton (Jordan, 1970; McMichael et al., 1973) as well as in midday carbon metabolism (Chastain et al., 2014; Snider et al., 2014). Without rewatering, $Y_{PD}$ represents the sum of all water-loss mechanisms by the crop from the time a stress is initiated to the time of measurement (Jordan, 1970), thereby giving an accurate indication of cumulative water stress. The use of a $-0.5 \text{ MPa}$ $Y_{PD}$ threshold as an irrigation trigger resulted in decreased irrigation amounts in both a wet and a dry year (Table 1), without negatively impacting fiber yield (Fig. 5) relative to the checkbook approach. Furthermore, when considered across both years, the $-0.5\text{-MPa}$ threshold was the only treatment to have WP and yield statistically equivalent to...
the highest-yielding treatment, thus indicating that this threshold was the most consistent, irrespective environment. Furthermore, $\Psi_{pd}$ showed a very strong, nonlinear relationship with cotton fiber yield for both 2013 and 2014 (Fig. 9, $r^2 = 0.81$), strengthening the argument for the utility of $\Psi_{pd}$ as an indicator of drought stress and the need for irrigation. The quadratic response of lint yield to $\Psi_{pd}$, noted in Fig. 9, is likely an artifact of including the 2013 data in the analysis. This year had generally lower yields for all treatments, relative to well-watered plots in 2014. Thus, Fig. 9 appears to attribute yield loss to high water potential, which may not be the case. While regression models (or crop models in general) do not fully account for all factors that could potentially impact yield, it is noteworthy that a quadratic response of lint yield to $\Psi_{pd}$ alone was able to predict 81% of all yield variability in both years (Fig. 9).

Based on canopy temperature data, our calculated CWSI values for 2013 and 2014 were highly reflective of season-long crop water status. Specifically, $\Psi_{pd}$ and CWSI exhibited a very strong, nonlinear relationship for $\Psi_{pd}$ values between approximately −0.4 and −0.7 MPa ($r^2 = 0.81$, Fig. 10). In addition, elevated CWSI in T3 through T5 during the 2014 growing season (Fig. 8B) agreed closely with yield losses observed in those same treatments relative to T1 and T2 (Fig. 5B). Furthermore, a strong, nonlinear relationship was seen between CWSI and lint yield ($r^2 = 0.81$, Fig. 11), suggesting the possibility of using $T_{Canopy}$-derived CWSI during the flowering period in cotton as a potentially viable irrigation scheduling parameter for humid regions. It is interesting to note that the well-watered baseline for $T_{Canopy} - T_{Air}$ response to VPD that was developed for Georgia in the current study is very similar to the earliest published well-watered baseline for cotton in the desert southwestern United States. (Idso, 1982), indicating that the well-watered baseline response may be fairly universally applied across a range of environments. This is an important finding because the use of $T_{Canopy}$ as an indicator of water deficit stress or the need for irrigation allows for simultaneous, automated monitoring of multiple locations (potentially reducing producer costs); however, short-term fluctuations in cloud cover may potentially limit its utility as a scheduling method (Jones, 2004). Further studies using the equations presented herein to schedule irrigation with predefined CWSI values should further establish the validity of such irrigation scheduling practices in the southeastern United States.

The overall conclusions that can be drawn from the current study are as follows: firstly, $\Psi_{pd}$ appears to be an effective means of determining the need for irrigation in cotton, and in the current study, yield and WP were maximized at a season-long average $\Psi_{pd}$ threshold of −0.5 MPa. Secondly, utilizing $\Psi_{pd}$ thresholds for irrigation scheduling purposes allowed us to accurately define the improvements in WP that could be obtained relative to the conventional irrigation scheduling method in 2 yr differing substantially in season-long precipitation. Thirdly, canopy temperature-based CWSI, when calibrated by means of a direct indicator of plant water status ($\Psi_{pd}$) offers the potential for usage as an indirect, plant-based irrigation scheduling method for low VPD environments, assuming adequate afternoon solar radiation.

References


