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Applying plant-based irrigation scheduling to assess water use efficiency of cotton following a high-biomass rye cover crop

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Abstract

Background: This study addressed the potential of combining a high biomass rye winter cover crop with predawn leaf water potential (Ψ_{PD}) irrigation thresholds to increase agricultural water use efficiency (WUE) in cotton. To this end, a study was conducted near Tifton, Georgia under a manually-controlled, variable-rate lateral irrigation system using a Scholander pressure chamber approach to measure leaf water potential and impose varying irrigation scheduling treatments during the growing season. Ψ_{PD} thresholds were − 0.4 MPa (T1), − 0.5 MPa (T2), and − 0.7 MPa (T3). A winter rye cover crop or conventional tillage were utilized for T1-T3 as well.

Results: Reductions in irrigation of up to 10% were noted in this study for the driest threshold (− 0.7 MPa) with no reduction in lint yield relative to the − 0.4 MPa and − 0.5 MPa thresholds. Drier conditions during flowering (2014) limited plant growth and node production, hastened cutout, and decreased yield and WUE relative to 2015.

Conclusions: We conclude that Ψ_{PD} irrigation thresholds between − 0.5 MPa and − 0.7 MPa appear to be viable for use in a Ψ_{PD} scheduling system with adequate yield and WUE for cotton production in the southeastern U.S. Rye cover positively impacted water potential at certain points throughout the growing season but not yield or WUE indicating the potential for rye cover crops to improve water use efficiency should be tested under longer-term production scenarios.

Keywords: Cotton, Irrigation management, Water use efficiency, Cover crops, Cotton sustainability

Glyphosate-resistant Palmer amaranth has caused many cotton producers to abandon conservation tillage and revert to conventional tillage and cultivation along with herbicides for control (Shurley et al. 2014). Because conservation tillage has been touted to save up to 14% more water compared with conventional tillage methods (Sullivan et al. 2007), methodologies should be developed to protect cover crop-derived water savings, while also maintaining control over glyphosate resistant Palmer amaranth. Utilizing a high-biomass rye cover crop along with herbicide resistant cotton cultivars and an appropriate herbicide program has been shown to effectively control glyphosate resistant Palmer amaranth in a conservation tillage system (Shurley et al. 2014). The heavy rye cover provided savings in herbicide expense, but these savings were offset by other costs such as the seed required for the cover crop, additional nitrogen required by the cover crop, and the additional fuel for rolling of the rye (Shurley et al. 2014). Information on irrigation efficiency in this system is limited; however, multiple location studies in other states have demonstrated high residue cover crop systems as higher yielding than conventional tillage systems (Price et al. 2012). Therefore, the possibility exists for higher yields and increased water use efficiency (WUE) to offset the costs of using such a system.

To define the improvements in WUE that can be achieved using a high biomass rye cover requires an

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understanding of irrigation scheduling approaches. Due to low soil water holding capacity and periods of episodic drought, supplemental irrigation is a necessity for Georgia cotton production. Although historical rainfall data from this region indicated an average amount (61.3 cm) from May to September 2012 to 2015 (Georgia Automated Environmental Monitoring Network 2016) which was sufficient to meet the required 46 cm of rainfall for maximum yields (Bednarz et al. 2002), short-lived drought events coupled with sandy soils that have poor water retention (Chesworth 2008), often necessitating supplemental irrigation to protect from yield losses. These periods of suboptimal or insufficient soil moisture tend to coincide with crop growth stages having the highest water demand. Proper irrigation scheduling should allow a producer to decide when to irrigate a crop as well as the amount of water needed to maximize WUE while not limiting yield. A water balance approach referred to as the "checkbook" method has been utilized in Georgia as noted in Table 1 and is recommended by the University of Georgia Cooperative Extension Service (Collins et al. 2014). This approach supplements naturally occurring rainfall with irrigation to meet targeted weekly amounts of water specific to different stages of crop development. This method prevents water from being the limiting factor for cotton production systems in Georgia (Meeks 2013; Chastain et al. 2014, 2016). However, from the physiologist's perspective, irrigation triggers that use the plant to sense its environment offer advantages over the water balance approaches discussed previously, because the cotton plant integrates soil, atmospheric, and plant factors so that the need for irrigation can be accurately determined from the water status of the plant (Jones 2007; Chastain et al. 2014, 2016). Leaf water potential (Ψ_l) is a direct measure of the energy status of water expressed in units of pressure (Jones 2007). One of the most common approaches to measuring leaf water potential is the use of a Scholander pressure chamber, although variability in readings is possible due to environmental factors such as vapor-pressure deficit (VPD) and solar radiation (Jones 1990; So 1979; Chastain et al. 2014). Grimes and Yamada (1982) demonstrated relatively stable and maximum water potentials predawn within the 2-hour prior to sunrise and observed values at their minimum in the afternoon (12:00 to 15:00). Though conducted at a far less convenient measurement time, predawn leaf water potential (Ψ_{PD}) is an excellent indicator of plant water status and is not as greatly impacted by environmental fluctuations as midday measurements (Ameglio et al. 1999; Chastain et al. 2014). Ψ_{PD} has been correlated with predawn and midday physiological processes (Snider et al. 2014, 2016; Chastain et al. 2014) as well as end of season lint yield in cotton (Snider and Oosterhuis 2015). Chastain et al. (2016) recently demonstrated Ψ_{PD} irrigation thresholds ($\Psi_{PD} = -0.5$ MPa season long) could increase WUE relative to the checkbook method without penalizing yield. Using Ψ_{PD}-based irrigation scheduling should allow for a definitive assessment of the improvements in WUE attainable with high-biomass rye cover crops when compared with the conventional tillage systems. There are currently no studies that the authors are aware of that have addressed WUE of high biomass rye tillage systems using plant-based irrigation scheduling.

Table 1 Typical checkbook schedule (UGA Extension Recommendation) for cotton irrigation in Georgia (Collins et al. 2014)

Growth stage	Irrigation per week/cm
Pre-bloom	1.91 to 2.54
1st bloom (week 1)	2.54
2nd week after 1st bloom	3.81
3rd week after 1st bloom	5.08
4th week after 1st bloom	5.08
5th week after 1st bloom	3.81
6th week after 1st bloom	3.81
≥ 7th week after 1st bloom	2.54

If a rye cover crop increases Ψ_{PD} during episodic drought events relative to conventionally tilled treatments, rapid in-season physiological assessments should identify periods during the growing season where rye cover measurably improved plant performance. Previous reports have demonstrated the sensitivity of photosynthesis to plant water status in cotton (Snider et al. 2014, 2016; Chastain et al. 2016). Chlorophyll fluorescence has been used to detect abiotic stress by monitoring the efficiency of the thylakoid reactions of photosynthesis and has been proposed as an useful tool for high throughput drought or heat tolerance screening (Burke 1990, 2007). Some of the common parameters derived from chlorophyll a fluorescence measurements include maximum quantum yield of photosystem II in dark-adapted leaves (F_v/F_m), actual quantum yield of photosystem II in illuminated leaves (Φ_{PSII}), and photosynthetic electron transport rate (ETR) (Chastain et al. 2014; Flexas et al. 1999; Maxwell and Johnson 2000; Snider et al. 2009, 2010; Valentini et al. 1995; Woo et al. 2008; Zhang et al. 2011). However, recent work by Snider et al. (2014) has indicated that primary photochemistry is relatively insensitive to water deficit even under stress levels severe enough to drastically limit net photosynthesis in the field. A more recently developed chlorophyll fluorescence method termed "OJIP" fluorescence analysis (O, J, I, and P are used to indicate steps in the chlorophyll fluorescence trace and are not abbreviations for other terms; Strasser et al. 2000), has been touted as more sensitive to drought and high temperature stress than traditional fluorescence methods (Boureima et al. 2012; Oukarroum et al. 2007, 2009; Tan et al. 2011), especially when the photosynthetic performance index (PI_{ABS}) is used as a bio-indicator. However, the utility of these novel methods for detecting drought stress has not been evaluated for field-grown cotton.

The current study was novel in that previous research has not been done in cotton examining Ψ_{PD} as an irrigation trigger while also addressing the effect of tillage system on water use efficiency or in-season physiological status of the cotton crop. Therefore, it was hypothesized that a high biomass rye cover crop could maintain Ψ_{PD} at higher levels during the growing season, potentially increasing WUE over conventionally tilled plots, mitigating in-season stress and improving cotton yield and water use efficiency. Consequently, the objective of this study was to measure the physiological and agronomic responses of the cotton crop to multiple Ψ_{PD} irrigation thresholds in order to better define the improvements in water use efficiency that can be achieved by the cotton crop through the use of a high biomass rye cover crop in the previous winter.

Methods/experimental design

A field study was established to assess the growth, yield, and physiological response of cotton to a wide range of leaf water potential-based irrigation thresholds at a site near Tifton, GA (USA) (31°164 8 N, 84°172 9 W) at 354 ft. above mean sea level. The experimental design was a randomized complete block design with one cultivar, two tillage strategies (conventional or high biomass rye cover crop), and three irrigation treatments ($n = 6$). Tillage was blocked by irrigation treatment due to constraint of irrigation system. Plots were 7.3 m wide and 13.3 m long with 6.3 m bare-soil alleys. The soil type at the Tifton study site is a Tifton loamy sand (Fine-loamy, kaolinitic, thermic, Plinthic Kandiudults). Conventionally tilled plots were left fallow over the winter. In rye plots, cereal rye (*Secale cereal* L.) was sown at a rate of 125.53 kgper hectare on November 8, 2013 and November 12, 2014, respectively. Supplemental fertilization of 28 kg·hm^{-2} of ammonium nitrate (NH_4NO_3) for the rye cover crop was applied within 3 days of planting according to the recommendations of Georgia Cooperative Extension Service. The rye cover crop was simultaneously terminated, and roller crimped on April 9, 2014 and April 11, 2015, respectively, according to the recommendations of Georgia Cooperative Extension Service. Rye biomass was characterized by cutting 1 m^2 sections from each plot and drying each sample for 24 h at 80℃to determine dry matter per square meter. No significant differences were noted in dry mass between 2014 and 2015 with the average biomass observed values of 3 932 kg·hm^{-2} in 2014 and 3 495 kg·hm^{-2} in 2015. Seeds of *Gossipium hirsutum* cv. FM 1944 GLB2 (Bayer CropScience) were sown at a 2.5 cm depth on May 7, 2014 and May 11, 2015. A 0.91 m inter-row spacing and a target seeding rate of 13 seeds·m^{-1} row were used. Seeds were either planted using a no-till approach directly into the cover crop residue (Rye treatment) or were planted into raised beds following conventional tillage (Conventional). All other seedbed preparation, fertilization, and pest management were conducted according to the recommendations of University of Georgia Cooperative Extension Service (Collins et al. 2014). Uniform stand establishment and preemergent herbicide activation were obtained for all treatments by supplementing rainfall with sprinkler irrigation (2.54 cm applied within 7 days of planting both years). Plant stands averaged 12.6 plants·m^{-1} row across all treatments, which is above the plant density recommended to maximize yields (Collins et al. 2014).

Three different irrigation treatments were initiated on June 30, 2014 and July 3, 2015; each treatment is defined in Table 2. A brief description of treatments follows. **T1**: a leaf water potential of − 0.4 MPa was used to trigger irrigation. **T2**: plants were irrigated at a leaf water potential threshold of − 0.5 MPa [previously shown to maximize WUE in cotton (Chastain et al. 2016)]. **T3:** plants were irrigated at a leaf water potential of − 0.7 MPa. Treatments 1–3 were irrigated using leaf water potential thresholds after the first bloom growth stage. Irrigation management from emergence up to first bloom utilized UGA checkbook recommendations (Table 1). Plants were irrigated using a lateral irrigation system to allow for irrigation only in the plot area via manual shut off valves. Irrigation decisions were made twice weekly (Tuesday and Thursday) based on treatment average predawn leaf water potential (Ψ_{PD}) using an uppermost, fully expanded mainstem leaf (the fourth unfurled leaf node below the apical meristem). When a given treatment threshold was reached, the maximum application amount that could be applied was 1.78 cm due to irrigation system limitations.

Table 2 Rainfall, irrigation, and total water received (/cm) by the cotton crop in irrigation treatments 1 (T1) through 3 (T3) during the 2014 and 2015 growing seasons near Tifton, GA

Year	Treatment	Irrigation threshold /MPa	Irrigation /cm	Rainfall /cm	Total /cm
2014	T1	−0.4 MPa	25.1	40.1	65.2
	T2	−0.5 MPa	23.9	40.1	64.0
	T3	−0.7 MPa	22.6	40.1	62.7
2015	T1	−0.4 MPa	29.5	51.2	80.7
	T2	−0.5 MPa	29.5	51.2	80.7
	T3	−0.7 MPa	27.9	51.2	79.1

The leaf was severed from three plants in each plot between 04:00 and 06:00 and used for predawn water potential measurements. The petiole was sealed in a compression gasket, and the leaf blade was sealed in a Scholander pressure chamber (PMS Instrument Company, Albany, OR) with a chamber pressurization rate of 0.1 MPa per second. Required pressure to bring the water column to the cut surface of the stem was recorded in MPa with less than 30 s elapsing from when the leaf was severed from the plant to the initial pressurization of the chamber. To further assess plant performance during the growing season, the same leaf was utilized in predawn measurements of Photosynthetic Performance Index (PI_{ABS}) and Maximum Quantum Yield of PSII (F_v/F_m) utilizing a FluorPen FP 100 (Photon Systems Instruments, spol. s r.o. Drasov 470 664 24 Drasov, Czech Republic) prior to measuring water potential. Specifically, the instrument measures ground-state fluorescence intensity under a low-intensity modulation light and then assesses the increase in fluorescence intensity during exposure of the leaf sample to a saturating pulse of light until the maximum value of fluorescence is reached. By using fluorescence intensity at key points in the resulting curve, maximum quantum yield of photosystem II and photosynthetic performance index were estimated according to Strasser et al. (2000). Water potential measurements and irrigation were terminated at first open boll for the latest maturing plot.

Crop growth and development were assessed by measuring plant height, total number of mainstem nodes per plant, and the number of mainstem nodes above the first-position white flower (NAWF) every 2 weeks after irrigation treatments were initiated. Collection of this data was done by sampling five plants from the center two rows of each plot and obtaining average values for each plot prior to statistical analysis. In-season data collection was terminated at NAWF < 2 in the earliest maturing treatment. At 65% open boll in the latest maturing treatment, plot harvest aides were applied to promote defoliation and boll opening in order to facilitate timely harvest. Lint yield was determined at crop maturity by mechanically harvesting the 2 center rows with a John Deere 9930 cotton spindle picker. Harvested samples were weighted on site using a hanging scale (Intercomp CS750, Intercomp, 3839 County Road 116 Medina, MN 55340–9342) positioned immediately adjacent to the field and then samples were taken to the University of Georgia Micro Gin (Tifton, GA) to obtain a realistic lint percent and fiber quality for each sample. Lint yield was expressed as $kg{\cdot}hm^{-2}$, and a 454 g fiber sample was retained from each plot and taken to the local USDA classing office in Macon, GA to obtain HVI fiber quality measurements. All statistical analyses were conducted using JMP Pro 12 (SAS Institute Inc., Cary, NC) and graphs were constructed using SigmaPlot 11.0 (Systat Software Inc., San Jose, CA). In all instances where comparative analyses were performed, $\alpha = 0.05$. Effect of irrigation treatment on end-of-season fiber yield, total plant nodes, plant heights, NAWF, WUE, chlorophyll fluorescence parameters, and fiber quality parameters were assessed using a mixed effects ANOVA according to a randomized complete block design. Blocks represented random effects, whereas irrigation treatment and tillage were fixed effects. When significant main effects were observed, mean separation was performed using LSD post hoc analysis.

Results

Environmental data recorded in 2014 and 2015 at the field site near Tifton, GA indicated similar trends for T_{min} and T_{max} in both years; however, differences in rainfall were noted between the two growing seasons (Fig. 1). For example, average T_{min} and T_{max} were 20.4 and 31.3 °C and 20.5 and 31.6 °C in 2014 and 2015, respectively. The highest recorded daily temperatures occurred on August 23, 2014 (36.4 °C) and July 17, 2015 (36.4 °C). In contrast to the ambient temperature conditions, the two growing seasons differed substantially in rainfall patterns and applied irrigation (Table 2 and Fig. 1). For example, total rainfall was 40.1 cm in 2014 compared with 51.2 cm in 2015 (Table 2). The 2014 growing season had more extended episodic drought periods with the last 12 days of May 2014 having no measureable rainfall and severe water deficit conditions occurring between July 1 and 16, and August 1 and 12. In 2015, there were fewer episodic drought periods than those in the 2014 season, with only one 7-day period without rainfall occurring the week of May 31 (Fig. 1). Differences in water availability are illustrated further by extended periods of lower than − 0.7 MPa leaf water potential (Ψ_{PD}) occurring in 2014 in T3 (Fig. 2), whereas 2015 had only one period of leaf water potential lower than − 0.7 MPa in T3 (Fig. 2). The rye cover crop in T3 led to higher Ψ_{PD} readings late in the 2014 season (Fig. 2); however, in the wetter 2015 growing season the T3 treatments responded similarly regardless of cover crop (Fig. 2). T1 and T2 responded similarly regardless of cover crop in 2014 until late in the season with T1 and T2, with rye cover having slightly higher leaf water potential than the T1 and T2 treatments without cover crops. T1 and T2 responded similarly in 2015 regardless of cover crop. The longest period of decline in Ψ_{PD}, occurred from July 30, 2014 to cutout on August 11, 2014 with measurements in T3 Conventional below − 0.8 MPa and nearly reaching − 1.2 MPa; other treatments did not exhibit this severe drop in Ψ_{PD} (Fig. 2). This severity of drought stress was not present in 2015, with both T3 treatments briefly dropping to − 1.1 MPa on August 3, 2015 but recovering to greater than − 0.8 MPa

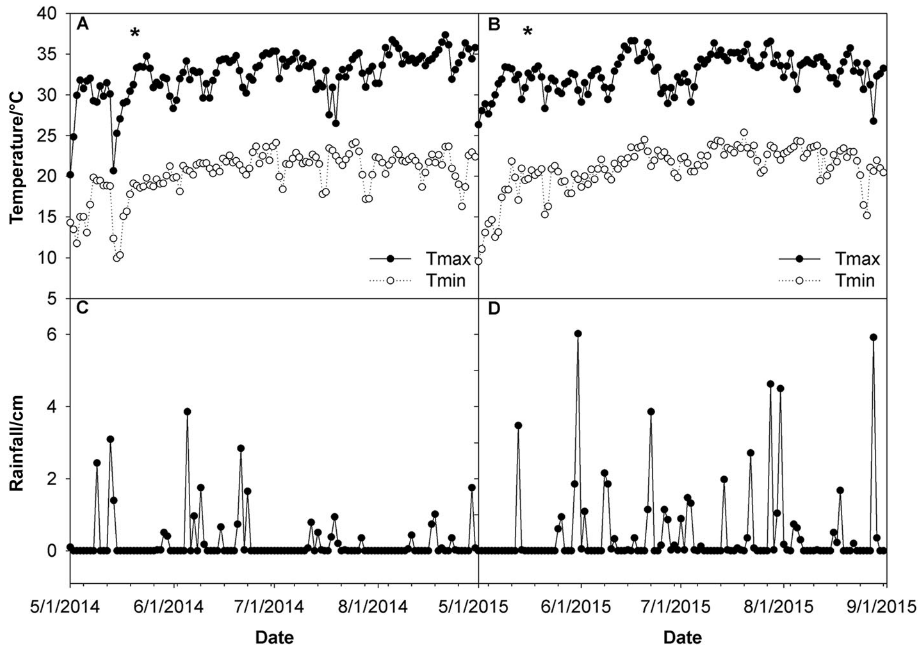

Fig. 1 Environmental data for the 2014 and 2015 growing seasons near Tifton, GA in 2014 and 2015. Data collected include maximum (T_{max}) and minimum (T_{min}) daily temperatures in 2014 (**a**) and 2015 (**b**) and rainfall events in 2014 (**c**) and 2015 (**d**). Asterisks in A and B indicate dates of planting

by August 10, 2015 (Fig. 2). Rye treatments T1 and T2 were observed to have slightly higher Ψ_{PD} near the end of the 2014 growing season (July 30, 2014 to August 11, 2014) than T1 and T2 under conventional tillage (Fig. 2). In 2015, Ψ_{PD} was similar for all treatments until August 3, 2015 with T3 treatments significantly lower than the other treatments for 1 week (Fig. 2). Ψ_{PD} was maintained at a level above the thresholds more often in 2015 with values above − 0.4 MPa in both T1 and T2 treatments regardless of cover crop occurring twice as often as the 2014 observations. In contrast, the lowest leaf water potentials in T1 and T2 were above − 0.4 MPa only twice in 2014.

During the 2015 growing season, T1 and T2 irrigation treatments had the same amount of irrigation water applied (29.5 cm), with a 1.6 cm reduction in applied irrigation compared to T3 which was irrigated at a − 0.7 MPa Ψ_{PD} threshold (Table 2). The 2014 growing season had reduced rainfall (40.1 cm vs. 51.2 cm). Irrigation events were reduced by 1 with the T2 treatment and by 2 in the T3 treatment compared with the T1 treatment,

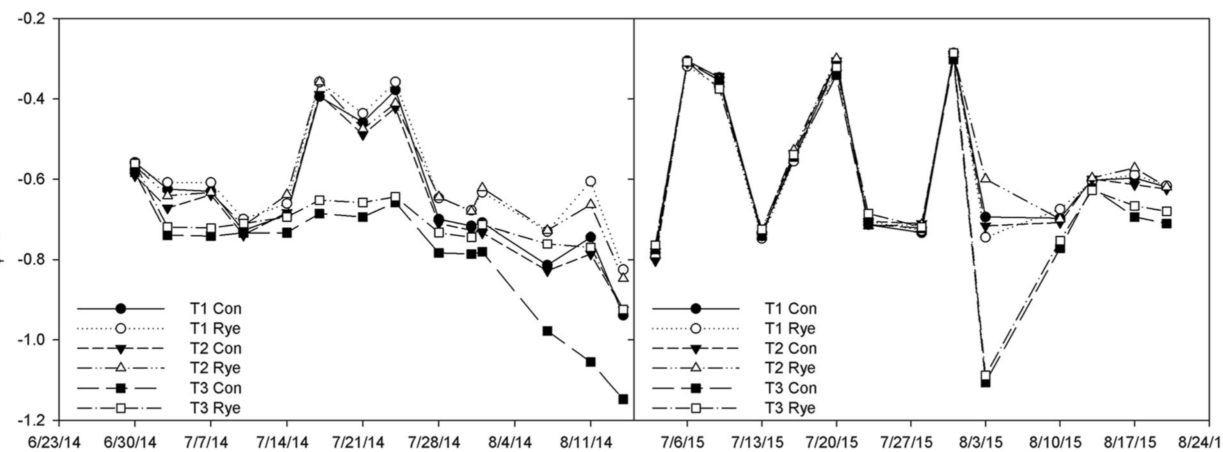

Fig. 2 Predawn leaf water potential readings (Ψ_{PD}) for cotton grown under irrigation regimes T1-T3 and planted into either conventionally tilled beds (Con) or a heavy rye cover crop residue (Rye) during the 2014 and 2015 growing season near Tifton, GA. There were six replicate plots per treatment, and 3 Ψ_{PD} readings were averaged for each plot prior to analysis

with irrigation amounts ranging from 25.1 cm for T1, 23.9 cm for T2, to 22.6 cm for T3 (Table 2).

Plant heights were not affected significantly by irrigation treatment or tillage in 2014, with T1-T3 having similar heights on all sample dates in 2014 (Fig. 3). Tillage system did not significantly affect plant height in either year. However, irrigation threshold significantly impacted final plant heights which were considerably higher in 2015 ranging from 140 cm for T3 to 160 cm for T2 compared with the 2014 range of 75 cm for T3 to 100 cm for T1 (Fig. 3). Total mainstem nodes were similar between T1-T3 in 2014, regardless of tillage system (Fig. 3). Total nodes in 2015 were similar for all irrigation treatments, as well averaging 19.5 mainstem nodes per plant during end of season measurements on August 16, 2015 (Fig. 3). The 2015 node counts were considerably higher than 2014 counts with end of season measurements averaging only 14 mainstem nodes per plant on August 8, 2014. No treatment differences were observed for NAWF in either year of the study. In contrast, cutout was hastened in 2014 as evidenced by NAWF being highest on July 21, 2014 at first flower but then rapidly declining to average NAWF = 2 on August 6, 2014 (Fig. 4). In 2015 cutout was reached considerably later with NAWF = 7 on July 12, and not reaching cutout until August 15 (NAWF =3) (Fig. 4).

No significant irrigation treatment effects were observed in 2014 for lint yield or WUE (Fig. 5). There was also no significant tillage main effect in 2014. While there was not a significant tillage main effect in 2015 either, there was a significant irrigation treatment main effect for lint yield and WUE ($P < 0.05$; Fig. 5). For example, lint yields ranged from 1 286 $kg{\cdot}hm^{-2}$ for T1 averaged across both tillage treatments to 1 187 $kg{\cdot}hm^{-2}$ for T3 in 2014, with no significant differences observed between any treatments. In 2015, yields ranged from 2 073 $kg{\cdot}hm^{-2}$ (T1) to 2 236 $kg{\cdot}hm^{-2}$ (T3) (Fig. 5). Similar to yield trends, WUE was substantially different between years, averaging 18 $kg{\cdot}hm^{-2}{\cdot}cm^{-1}$ and 27 $kg{\cdot}hm^{-2}{\cdot}cm^{-1}$ for all irrigated treatments in 2014 and 2015, respectively (Fig. 6). The average WUE response to irrigation,

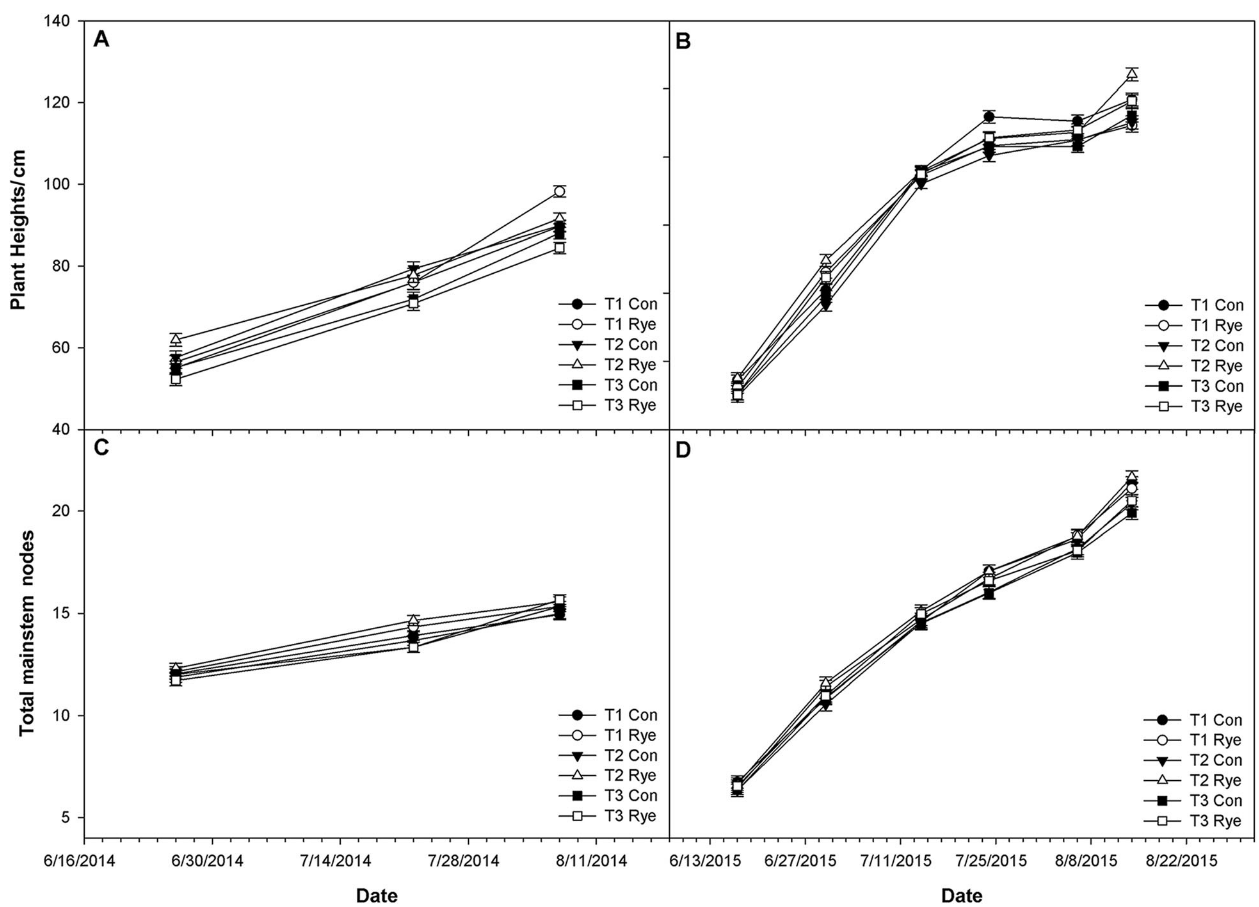

Fig. 3 Plant height and total mainstem nodes for cotton grown under irrigation regimes T1-T3 and planted into either conventionally tilled beds (Con) or a heavy rye cover crop residue (Rye) during the 2014 (**a**, **c**) and 2015 (**b**, **d**) growing seasons at a field site near Tifton, GA. Values are means ± standard error ($n = 6$)

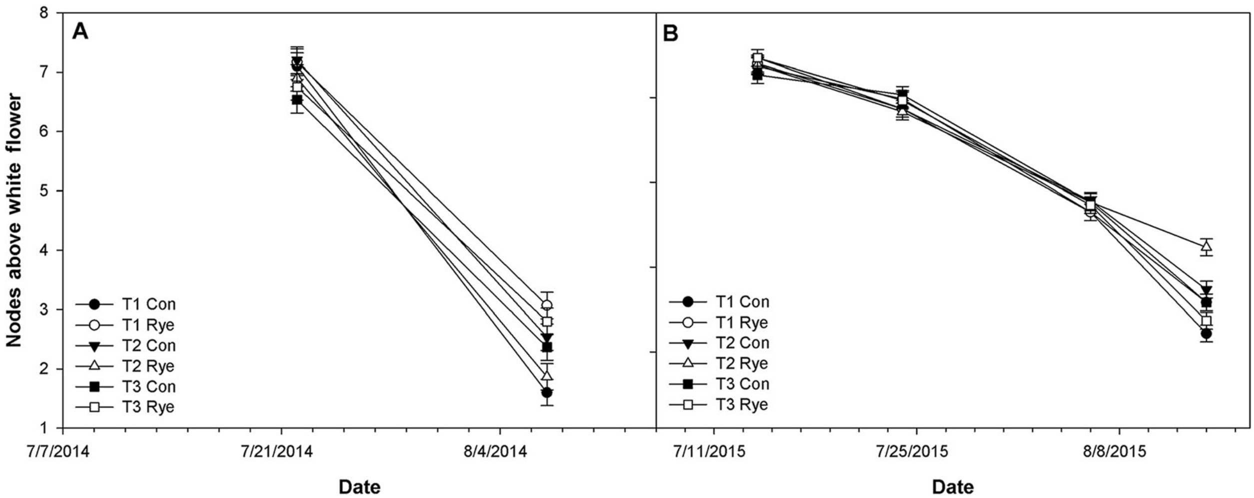

Fig. 4 Mainstem nodes above the first position white flower for cotton grown under irrigation regimes T1-T3 and planted into either conventionally tilled beds (Con) or a heavy rye cover crop residue (Rye) during the 2014 (**a**) and 2015 (**b**) growing seasons at a field site near Tifton, GA. Values are means ± standard error ($n = 6$)

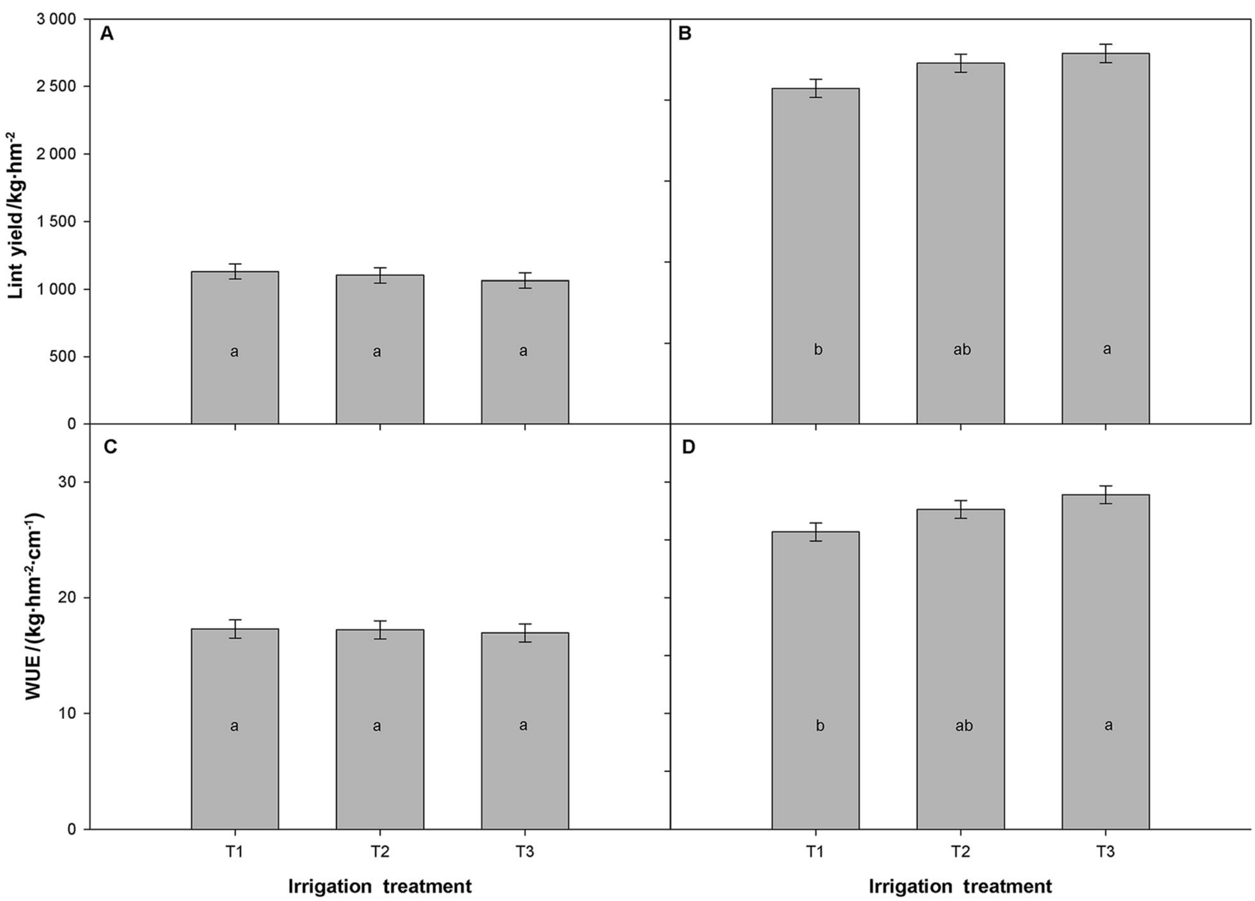

Fig. 5 Lint yield and water use efficiency (WUE) in the 2014 (**a**, **c**) and 2015 (**b**, **d**) growing seasons (kg·hm^{-2}·cm^{-1}) under irrigation regimes T1-T3 at a field site near Tifton, GA. Values are means ± standard error ($n = 6$), and bars not sharing a common letter within a given year are significantly different ($P < 0.05$)

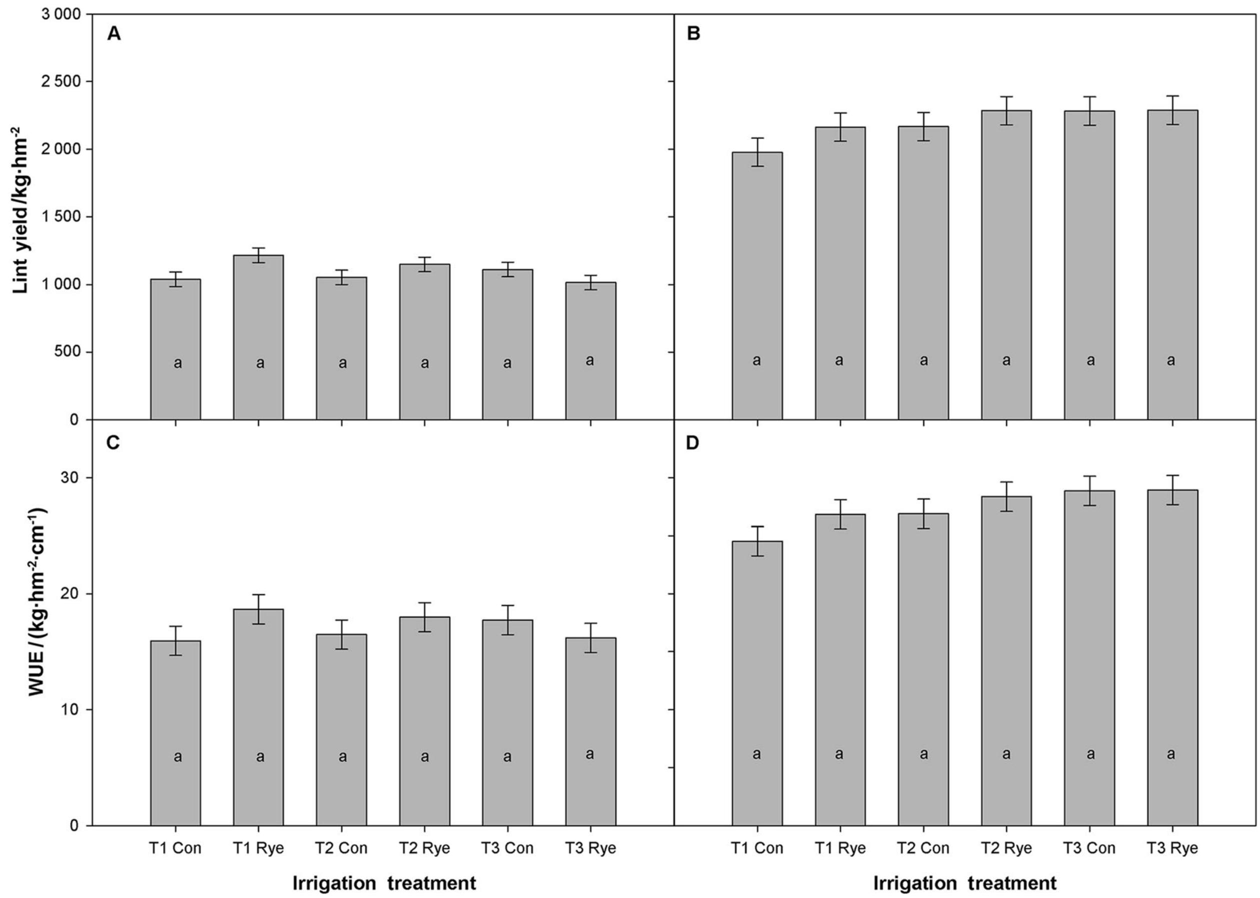

Fig. 6 Lint yield and water use efficiency (WUE) in the 2014 (**a**, **c**) and 2015 (**b**, **d**) growing seasons (kg·hm^{-2}·cm^{-1}) under irrigation regimes T1-T3 and planted into either conventionally tilled beds (Con) or a heavy rye cover crop residue (Rye) at a field site near Tifton, GA. Values are means ± standard error ($n = 6$), and bars not sharing a common letter within a given year are significantly different ($P < 0.05$)

combined across tillage system, showed a similar trend to yield with no significant differences in 2014 (18 kg·hm $^{-2}$ average). Significant differences in 2015 were observed in WUE between irrigation treatments with 32 kg·hm^{-2}·cm^{-1} for T3 compared with 28 kg·hm^{-2}cm^{-1} for T1 (Fig. 5). While there was no significant interaction between irrigation treatment and tillage in any year of the study, the mean yields and WUE for each irrigation treatment × tillage combination are shown in Fig. 6 to provide readers with additional information.

Throughout both growing seasons, PI_{ABS} ranged from 1.08 to 5.91 in 2014 and 1.36 to 6.68 in 2015 and varied greatly depending on sample date with no consistent association with irrigation treatments or rye cover (Fig. 7). Similar observations were noted for maximum quantum yield of PSII (F_v/F_m) in 2014 and 2015 (Fig. 7). For example, the ranking of each treatment varied greatly, depending upon sample date. Importantly, no clear association with plant water status was observed for chlorophyll α florescence measurements (data not shown). In fact, where large differences in Ψ_{PD} were observed (August 14, 2014), the lowest Ψ_{PD} treatment produced the highest F_v/F_m value (Fig. 7). Season average PI_{ABS} was similar in both 2014 and 2015, where T2 produced with conventional tillage had the highest PI_{ABS} in both 2014 and 2015 (Fig. 8). Season average F_v/F_m was similar for all treatments regardless of irrigation or tillage in both 2014 and 2015 (Fig. 8).

Discussion

The observations from 2 years of field trials in Tifton, Georgia demonstrated that the high biomass rye cover crop system impacted plant water status, but there was no improvement in WUE or yield, indicating no short-term agronomic benefits. This study hypothesized that rye treatments would maintain Ψ_{PD} thresholds better than conventional tillage treatments which could lead to increased WUE; however, WUE did not differ statistically among tillage treatments and there was not interaction between tillage and irrigation treatment, which does not support this hypothesis. Importantly, even though WUE was not positively affected by tillage, no

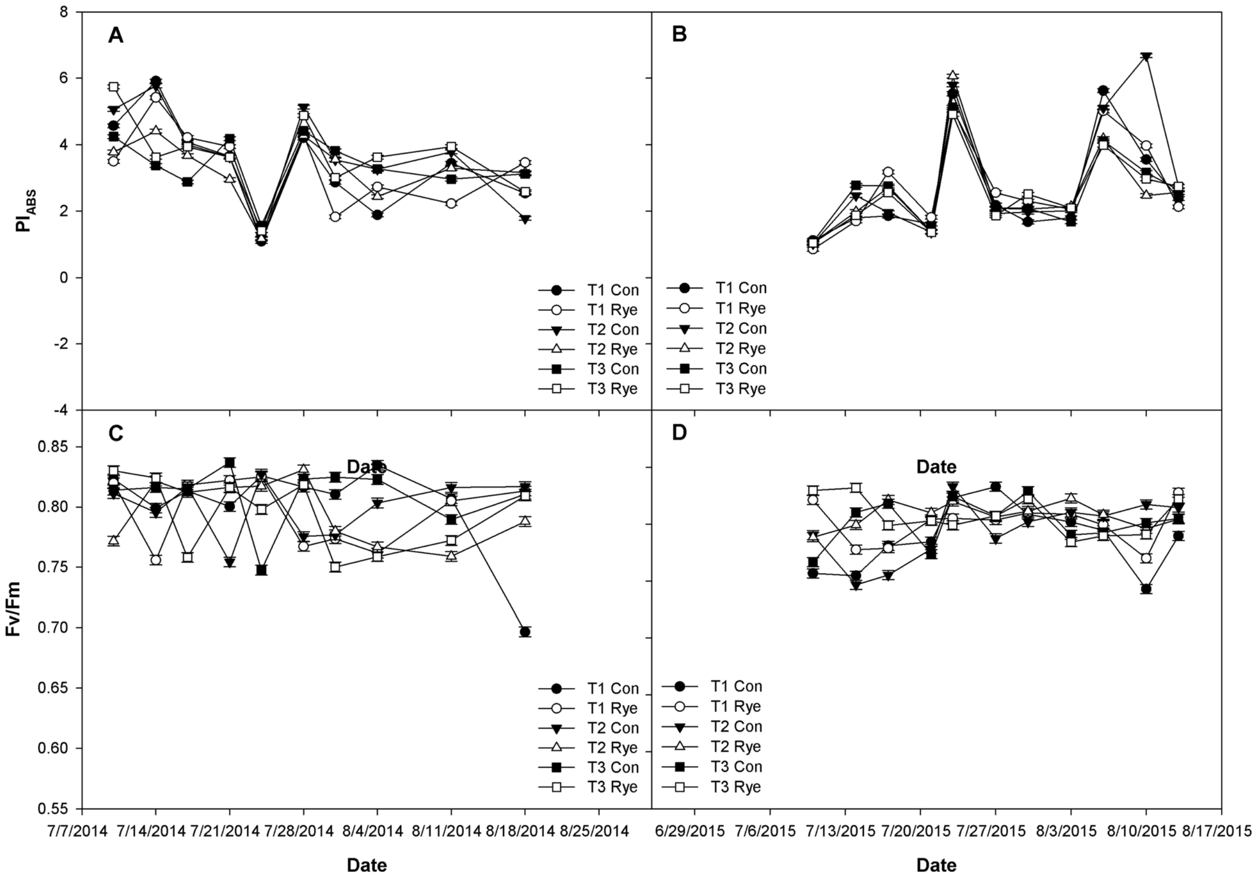

Fig. 7 Photosynthetic performance index (PI_{ABS}) and maximum quantum yield of photosystem II (F_v/F_m) for the 2014 (**a**, **c**) and 2015 (**b**, **d**) cotton crop grown under irrigation regimes T1-T3 and planted into either conventionally tilled beds (Con) or a heavy rye cover crop residue (Rye) at a field site near Tifton, GA. Values are means ± standard error ($n = 6$)

significant yield loss (Fig. 5) was detected from utilizing any of the Ψ_{PD} thresholds in 2014 and no yield loss was observed in 2015 by using lower Ψ_{PD} thresholds, with the increase in yields. Furthermore, season-long irrigation water savings of 1.5 to 2.5 cm less applied irrigation were observed for the − 0.7 MPa triggers. Therefore, these results verify that lower Ψ_{PD} threshold of − 0.7 MPa could be used to conserve irrigation application while still providing a suitable environment for optimum yields (Fig. 5). For example, Fig. 5 illustrates similar yields for all 3 irrigation treatments in 2014, even with 11.1 cm less rainfall in 2014 than 2015. In contrast, substantial yield differences and declines in WUE are seen for T1 relative to T3 in 2015, illustrating the importance of applying irrigation appropriately in cotton production in the southeastern U.S., and highlighting the possibility of negative impacts of excessive irrigation during periods of adequate rainfall (Figs. 5-6). Cetin and Bilgel (2002) noted that providing excess irrigation tends to lead to reduced yield due to increases in fruit shed. These observations also suggest that − 0.4 MPa Ψ_{PD} threshold is not realistic for cotton production in the southeastern U.S. High yields in 2015 led to increased WUE, especially with increased rainfall during the bloom period as compared with 2014. Based on the data presented herein, it appears that predawn leaf potential irrigation thresholds between − 0.5 MPa and − 0.7 MPa may be feasible in the southeastern U.S. to help maximize water use efficiency and limit yield losses resulting from excess irrigation. However, it should be noted that Chastain et al. (2016) reported maximum yields at $\Psi_{PD} = -0.5$ MPa and yield losses when utilizing season-long Ψ_{PD} irrigation thresholds ≤ − 0.7 MPa. This is likely because that study was conducted under much drier conditions than the 2015 growing season, and drip irrigation allowed for more frequent irrigation events relative to the overhead irrigation system used in the current study, thereby allowing for greater yield separation between treatments. Similar to the current study, WUE was maximal whether using $\Psi_{PD} = -0.5$ or − 0.7 MPa. Chastain et al. (2016) also noted that − 0.5 MPa Ψ_{PD} irrigation threshold produced similar yields to the well-watered "checkbook" method recommended by the University of Georgia Cooperative Extension Service (Collins et al.

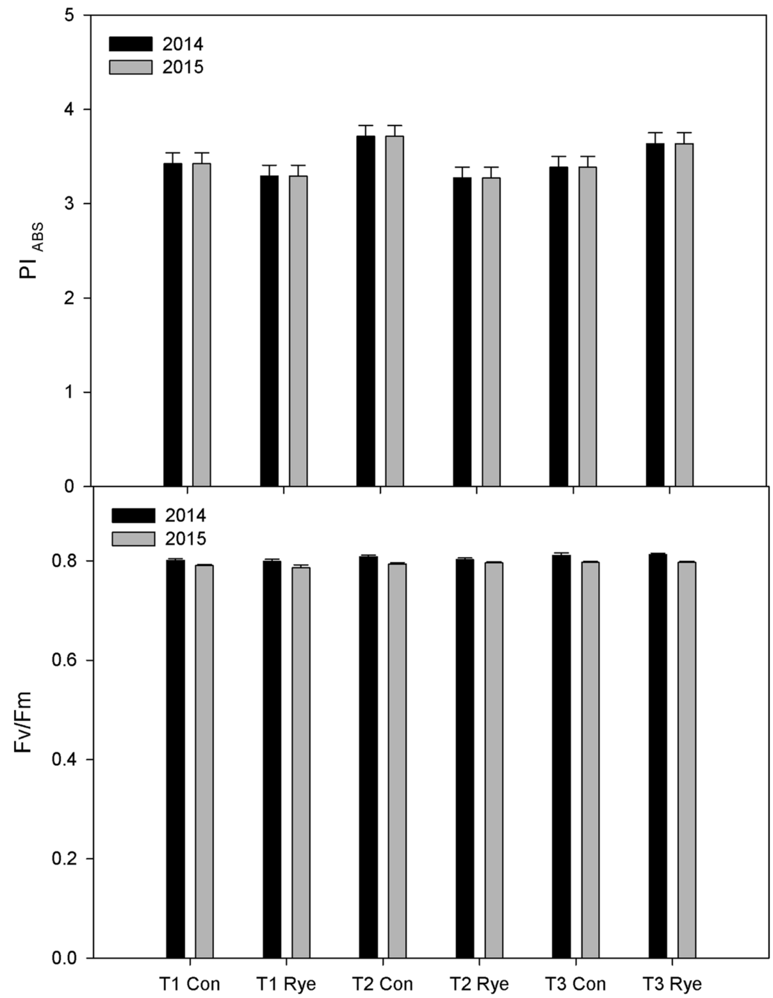

Fig. 8 Photosynthetic performance index (PI_{ABS}) and maximum quantum yield of photosystem II (F_v/F_m) for the 2014 and 2015 cotton crop grown under irrigation regimes T1-T3 and planted into either conventionally tilled beds (Con) or a heavy rye cover crop residue (Rye) during the 2014 and 2015 growing seasons at a field site near Tifton, GA. Values are means ± standard error (n = 6)

2014) while increasing WUE, demonstrating the potential to increase WUE with this type of irrigation strategy without reducing yields below optimum levels.

It is important to note that using a particular tillage system in the short term does not necessarily mean that cover crops do not increase WUE for a cotton crop. For example, season ending Ψ_{PD} suggests that given enough time, tillage system can impact plant water status (Fig. 2). Previous work done by Sullivan et al. (2007) has indicated that long term use of a rye cover crop (10 years) can lead to substantial water savings up to 14% due to increased infiltration and reduced runoff. The lack of significant yield differences between tillage treatments can also be seen as a positive observation as well because declines in the productivity of other summer crops have been observed when planted after a rye cover crop (Raimbult et al. 1991).

Using the fluorescence-based bio-indicators, PI_{ABS} and F_v/F_m, measurements season-long indicated no consistent differences among irrigation or tillage treatments, reinforcing recent work (Chastain et al. 2014; Snider et al. 2014) which indicated that primary photochemistry was relatively insensitive to water deficit even in situations that drastically limited net photosynthesis in the field. Relatively new chlorophyll fluorescence methods termed OJIP fluorescence have been touted as more sensitive to drought and high temperature stress than traditional fluorescence methods (Boureima et al. 2012; Oukarroum et al. 2007, 2009; Tan et al. 2011) especially utilizing PI_{ABS} as a bio-indicator. However, this method was no more sensitive than F_v/F_m for detecting drought stress in field-grown cotton in a plant-based irrigation scheduling system, where PI_{ABS} was not correlated with Ψ_{PD} in either year or across years (data not shown).

It has been demonstrated that drought stress occurring prebloom could result in shorter plants with fewer nodes than well-watered plants, but despite the decrease in plant height, the cotton crop could achieve comparable end of season lint yields (Bauer et al. 2012; Snowden et al. 2014). However, in this study, comparable yields were not observed when comparing the yields of the 2 years (Figs. 5-6). In this study, reduced total water in 2014 led to reduced plant heights (Fig. 3), indicating physiological limitations to cellular expansion processes. Growth has long been regarded as the most sensitive physiological process to the onset of water deficit (Hsiao 1973). Crop maturity, as measured by mainstem nodes above white flower (NAWF), was hastened in 2014 (T1-T3 all had comparable NAWF throughout the season), indicating a cessation of new vegetative growth and fruiting site development. In 2015, crop maturity was not hastened, with longer periods of NAWF > 5. This effect was noted by Pettigrew (2004) as well, with irrigated plants maintaining vegetative growth longer after reproductive growth undertaken by the plants. Additional nodes on the plants allowed for flowering to be sustained and for the production of more fruiting sites relative to stressed plants, leading to substantially higher yields in 2015 (Figs. 3 and 5).

Fig. 1 illustrates the season long environmental conditions encountered in 2014 and 2015 with similar minimum and maximum temperature trends noted in both 2014 and 2015. However, precipitations patterns were substantially different, with extended drought periods in 2014 during the second half of the growing season. Rainfall events occurring in 2015 were more frequent and intense than 2014, with rainfall amounts at times reaching 6 cm per event. Rainfall amounts during the 2015 growing season were in excess of that needed to maximize yield according to previous work conducted by Bednarz et al. (2002). Field conditions in 2014 were not optimal in terms of irrigation due to the limitations of the lateral irrigation system and its inability to supply higher amounts of irrigation. Despite attempts to irrigate according to predefined thresholds, it should be noted that Ψ_{PD} for most treatments was below target thresholds for much of the 2014 growing season. This indicates that irrigated cotton may often experience yield-limiting water deficit stress despite using the best available practices due to irrigation system time requirements between successive irrigation events.

Conclusions

There are three major conclusions that can be derived from this study. First, when using the leaf water potential monitoring system and methods defined herein, these results suggest that irrigation thresholds between − 0.5 MPa and − 0.7 MPa can be used to provide adequate irrigation for optimum yields and WUE. Yield data in 2015 especially reinforces this conclusion with yields above 2 000 kg·hm^{-2}. Second, excessive irrigation as noted in 2015 at − 0.4 MPa threshold limited yield through processes that may include excess vegetative plant growth and increased boll rot. Lastly, despite the fact that the high biomass rye cover crop approaches did not increase WUE in a drier year (2014) or wet year (2015), other studies such as Raper et al. (2016) have noted increased WUE; therefore, further studies are needed to better define the utility of high biomass rye cover crops in cotton production. However, this study did document higher Ψ_{PD} in rye plots versus conventional tillage plots at some points during the growing indicating that rye cover can increase plant water potential.

Abbreviations

Ψ_{PD}: Predawn leaf water potential; F_v/F_m: Maximum quantum yield of photosystem II; PI_{ABS}: Photosynthetic performance index; WUE: Water use efficiency

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Authors' contributions

Meeks CD collected the majority of the data and performed crop management practices. Snider JL was the major professor of Meeks CD and provided guidance for this research project and collected some physiological data. Culpepper S performed cover crop management as well as provided the equipment to perform the cover crop management as well as the cotton planting operations. Hawkins G provided soil health management expertise as well as soil and water conservation expertise. The author(s) read and approved the final manuscript.

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Ethics approval and consent to participate

N/A

Consent for publication

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Competing interests

None of the authors have any competing interests within the scope of this experiment and its publication.

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