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AGRONOMY AND SOILS

Three Soil Water Potential Strategies to Schedule Irrigation Events using S3DI in Cotton

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ABSTRACT

Scheduling irrigation events in the humid Southeast can be challenging due to unreliable rainfall patterns. The objective of this study was to evaluate three water potential strategies for scheduling irrigation events in cotton (*Gossypium hirsutum* L.) using shallow subsurface drip irrigation (S3DI) with respect to lint yield and quality, irrigation water-use efficiency (IWUE), and value water-use efficiency (VWUE). Research was conducted in 2012 through 2016 in southwest Georgia, U.S. using an S3DI system. Water potential sensors were installed at 25- and 50-cm soil depth. Irrigation treatments and events occurred when the average water potential values were: -40 kPa (treatment I1), -70 kPa (treatment I2), -70/-40/-60 kPa (treatment I3) (emergence to 1st square/1st square to 1st cracked boll/1st cracked boll to defoliation) and a dryland control. All irrigated treatments had higher yield (1975 kg ha^{-1}) than dryland (987 kg ha^{-1}) except during 2013 (wet year). When 2013 data was deleted, there was no lint yield difference across years (p = 0.07) or across irrigation treatments (p = 0.06). Irrigation treatments I2 and I3 applied 170 mm less irrigation water compared to I1. There were differences in lint quality by irrigation treatment and year, but quality values were within acceptable ranges little or no price deductions. Dry year IWUE for treatments I2 and I3 averaged 3.1 kg lint mm^{-1} compared with I1 at 2.2 kg lint mm^{-1}. For VWUE, both I2 and I3 had 44% greater value per unit of irrigation applied compared with I1. Either I2 or I3 can be used for scheduling irrigation events efficiently and economically.

Cotton production in the southeastern U.S. is limited by erratic distribution of rainfall during the growing season. Although Georgia averages in excess of 1,270 mm of rainfall annually, unreliable rainfall patterns have prompted producers to increase dependence on irrigation to supplement the soil during drought periods. Irrigated cotton land area in Georgia increased to 31% by 2012 compared with 2007 data (USDA-NASS, 2007, 2012). In large field areas, overhead sprinkler irrigation systems predominate. Drip irrigation may only be considered for small or irregular shaped fields where sprinkler systems are not practical.

Scheduling irrigation events for cotton has been of great interest for many years to reach a goal of increased water water-use efficiency, lint production, lint quality, economics, and water conservation. Cotton growers want to be efficient with irrigation water and need an inexpensive technique that can guide them when and how much to irrigate. Nuti et al. (2009) used soil water potential sensors and the expert system IrrigatorPro for peanut (*Arachis hypogaea* L.) modified for cotton to schedule irrigation events (Brown et al., 2008; Davidson et al., 1998). The IrrigatorPro model was designed to avoid crop stress while triggering irrigation at the most efficient timing and volume to avoid over-irrigation. Data required for IrrigatorPro for cotton include soil type, planting date, daily rainfall, irrigation amounts, and cotton growth stages including first-square, first open bloom, and first cracked boll. A weighted system is used to average soil water potential over three soil depths (20, 40, and 60 cm) from shallowest to deepest sensor using factors of 43, 32, and 25%, respectively. An average soil water potential of three sensors of -50 kPa will trigger an irrigation event (Nuti et al., 2009).

Other ways to determine when to schedule an irrigation event include measuring soil water status (water content or potential), plant water status (leaf temperature, gas exchange, etc.), meteorological data with associated empirical equations, or combinations of these techniques (Baker et al, 2013; Conaty et al, 2014; Lascano and Van Bavel, 2007; Nuti et al.,

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2009; Padhi et al., 2012). Although each of these techniques has proven effective, each technique requires a specific set of information from various sensors that can or cannot be installed easily, maintained, or analyzed by the local grower. The use of soil water potential sensors can be an inexpensive system and can be used wirelessly (Sui and Baggard, 2015).

Both sprinkler and subsurface drip irrigation (SSDI) work well as an irrigation system with cotton. However, burying the drip tubing 1.5- to 2-in below the soil surface (shallow subsurface drip irrigation [S3DI]) can significantly reduce rodent damage (Sorensen et al., 2007) and has the potential of lasting up to 8 yr before reinstalling drip laterals. Yield potential of irrigated crops using S3DI was more than two, three, and seven times greater than nonirrigated crops of peanut, cotton, and corn, respectively, depending on yearly precipitation timing and amount (Sorensen et al., 2010). Sorensen and Lamb (2015) reported that thinner wall tubing (8 mil) had 3.5 times more holes compared with thicker wall tubing (15 mil). Tube longevity for S3DI used in conventionally tilled areas had less tube repairs compared with strip- or no-tilled practices. The cost-to-repair versus cost-to-replace tubing indicates average replacement time at approximately 5.4 yr (Sorensen and Lamb, 2015). The increased yield and eventual gross revenue were great enough in the installation year to cover the cost of the in-field portion of the S3DI system expenses compared with the nonirrigated revenue (Sorensen et al., 2010). The use of S3DI is cost effective on small field areas, but there are no recommendations on scheduling irrigation events using this irrigation system.

A study by Whitaker et al. (2008) conducted in the Southeast, evaluated cotton yield, quality, and maturity using overhead sprinkler irrigation, SSDI, and nonirrigated production. No yield differences resulted between overhead sprinkler and SSDI, and both irrigation methods resulted in average yield increases of 54% compared to nonirrigated production. They also concluded that water-use efficiency with SSDI was higher than overhead sprinkler irrigation. Lamb et al. (2015) showed that an overhead irrigation system in the Southeast applying 100, 66, and 33% of water replacement determined by IrrigatorPro along with a nonirrigated control had the highest irrigated water-use efficiency (IWUE) at the 66% level compared with the other treatments. A 3-yr study in West Texas focused on varying irrigation rates based on evapotranspiration (ET) replacement with SSDI compared to a nonirrigated control. The highest yield and net return were observed with 100% ET replacement, and the highest water-use efficiency was measured in the 33% ET replacement with a threefold increase in lint yield for 100% ET replacement (DeLaune et al., 2012).

The use of drip irrigation on cotton has resulted in yields similar to or greater than overhead sprinkler irrigation (Sorensen and Lamb, 2008; Sorensen et al., 2010, 2011; Whitaker et al., 2008). However, there are no recommendations of when to schedule irrigation events for drip irrigation in cotton specifically for S3DI. The objective of this research was to evaluate three water potential value strategies for irrigation scheduling when using S3DI and the effects on lint yield, lint quality, IWUE, and economic water-use efficiency (VWUE).

MATERIALS AND METHODS

This research was conducted at the USDA-ARS Multi-crop Irrigation Research Farm in Shellman, GA (31° 47' 44" N, 84° 36' 30" W) during the 2012 through 2016 growing seasons (cotton was not planted in 2014) on a Faceville fine sandy loam (Fine, kaolinitic, thermic Typic Kandiudults) with up to 3% slope. The topography was undulating with a general slope towards the east with a north aspect.

Two irrigated areas were used with this project. Both areas were irrigated with S3DI (described below) and were rotated with corn or cotton. Cotton either followed corn or cotton, depending on crop rotation schedule for other research projects. Irrigation treatments were -40 kPa, -70 kPa, -70/-40/-60 kPa and a dryland control (irrigation treatments described below). Individual plots were 5.5-m wide by 30-m long consisting of six crop rows. Crop rows were 0.91-m wide planted in a single row orientation. At harvest, the middle two rows were selected for yield. Harvesting procedures and data collection are described below.

Irrigation events for cotton were determined using soil water potential sensors installed at 25- and 50-cm soil depths (MPS1 and MPS2 sensors, Decagon Devices, Inc., Pullman, WA). Water potential sensors were connected to a radio-equipped datalogger (EM50R, Decagon Inc., Pullman, WA) with a 1-hr interrogation time. All data were downloaded daily and evaluated manually to determine irrigation events. Sensors were installed after cotton emergence approximately 5-cm off the crop row adjacent drip tube laterals. In 2012 and 2013, both sensors were placed in the same hole. A 5-cm hole was augured to a depth of 55 cm. A small amount of soil was backfilled into the hole and approximately 250 ml of water was poured in the hole. The sensor was then placed at 50 cm. The hole was then backfilled with soil to approximately 10 cm. Another 250 ml of water was poured in the hole and the next sensor was installed at 20-cm soil depth. The hole was then filled with soil and 250 ml of water was slowly poured on the soil surface to settle the soil. In 2015 and 2016, sensors were installed in separate holes using the procedure described above.

Irrigation events were determined using the following treatments. Irrigation treatment 1 (I1) had an irrigation event when the average value of both the 25- and 50-cm sensors was -40 kPa. When this occurred, 20 to 25 mm of water was applied. Irrigation treatment 2 (I2) was irrigated when the value of the two sensors averaged -70 kPa and a total of 25 to 30 mm of water was applied. Irrigation treatment 3 (I3) scheduled an event when the average value of the two sensors was -70 kPa (germination to 1st square/flower), -40 kPa (1st square/flower to 1st cracked boll/flowering at the top of the plant), and -60 kPa thereafter till cutout or leaf defoliation. The total water applied for each irrigation event per irrigation treatment was related to a general water-release curve for this soil type. This irrigation strategy was similar to Nuti et al. (2009) except for the use of two soil sensors using a simple average value compared with a weighted average of three sensors to trigger an irrigation event.

Irrigation water was supplied through a series of 5-cm diameter flexible hose with drip tube laterals connected using plastic adapters (Agricultural Products, Inc., Ontario, CA, model 400-B-06-LS). The drip tubing wall was 0.2-mm thick with emitters spaced at 30 cm (Streamline 630, NetafimUSA, Fresno, CA). Drip tube laterals were spaced in alternate row middles, 1.83-m apart. Drip tubing was buried approximately 5 cm beneath the soil surface. Emitter flow rate was 0.56 L h^{-1}. Drip laterals were removed each fall and new laterals installed each spring following crop emergence. Operating pressure was regulated between 70 to 100 kPa at the laterals (200 kPa at the pump) and water flow and irrigation depths were determined using mechanical water meters. Each irrigation treatment had its own mainline and water meter. Irrigation treatments were assigned in a randomized complete block design with three replications per treatment.

Land preparation was the same for all areas and for each year. The land was disk harrowed and deep ripped in the fall. Lime was applied in early spring at rates determined by soil test and incorporated using a field cultivator. Pre-plant herbicides and fertilizers were applied and incorporated using a 1.83-m wide field cultivator. Prior to planting each crop, the land was bedded using an experimental disk bedder (USDA-ARS National Peanut Research Laboratory) to make 1.83-m planting beds. All crop rows were planted in single rows 0.91-m apart on the 1.83-m beds using a commercial six-row vacuum type planter.

Cotton (PHY499, Dow AgroSciences LLC, Indianapolis, IN), was planted at a density of 106,300 seeds ha^{-1}. Prior to seeding, 22 kg N ha^{-1} of dry fertilizer was applied along with other recommended fertilizer as determined by soil test and incorporated. A total of 60 kg N ha^{-1} were applied to the plots through the drip system in two split applications (30 kg N ha^{-1} each application) using 32-0-0 liquid fertilizer. A total of 82 kg N ha^{-1} was applied each year. Herbicides, insecticides, and plant growth regulators were applied as recommended by field scouting.

Cotton was picked using a two-row spindle picker. Seed cotton from the picker basket was dumped into a weigh buggy, weights were recorded, a 1.0-kg subsample was collected, and a small 0.2-kg subsample was ginned on a table top gin. All ginned samples were sent to an official classing office to determine lint quality.

Irrigation IWUE as described by Lamb et al. (2015) was determined by subtracting the nonirrigated yield from the irrigated yield and dividing the sum by the total irrigation water applied. VWUE was determined by multiplying IWUE by lint price (Lamb et al., 2015). Cotton lint prices fluctuated across years with an average value of \$1.57 kg^{-1}.

Within each crop rotation area, a total of four irrigation treatments were replicated three times arranged in a randomized complete block. Irrigation events were dependent on when and how much rainfall occurred during the growing season. Variability of rainfall patterns from year to year will affect irrigation strategies. Therefore, each crop year was analyzed independently to identify which irrigation strategy would be best suited for that year's rainfall pattern. Crop yield, lint quality, and water-use-efficiency data versus either year or irrigation scheduling treatment were subjected to general analysis of variance (ANOVA) procedure in Statistix10 (Analytical Software, Tallahassee, FL). Lint yield and fiber quality data were pooled across years or irrigation treatments when ANOVA F-test showed no significance ($p \leq 0.05$). Differences between means of crop yield and quality were determined using Tukey's Honest Significant Difference (HSD) pairwise comparison when ANOVA F-test showed significance ($p \leq 0.05$).

RESULTS AND DISCUSSION

Figure 1 shows the cumulative rainfall for each year. Crop year 2013 had the most rainfall of the 4 yrs with almost double the average of the other 3 yrs. Rainfall in 2013 diverges from the other 3 yrs at approximately day of year (DOY) 150. There were 35 rainfall events greater than 5 mm compared with 22, 17, and 15 rainfall events in 2012, 2015, and 2016, respectively. Total rainfall amounts are shown in Table 1.

Table 1. Rainfall (dryland) received and total irrigation applied (irrigation events in parenthesis) during the 2012-2016 growing season for each irrigation treatment

Year	Dryland	I1[z]	I2	I3
	mm			
2012	442	547(12)	319(6)	439(9)
2013	635	143(5)	67(3)	118(5)
2015	249	493(11)	325(7)	315(9)
2016	350	581(14)	513(13)	306(10)
average	419	441	306	294
2013 removed	347	540	386	353

[z] Irrigation treatments I1 = -40 kPa; I2 = 70 kPa; I3 = -70/-40/-60 kPa

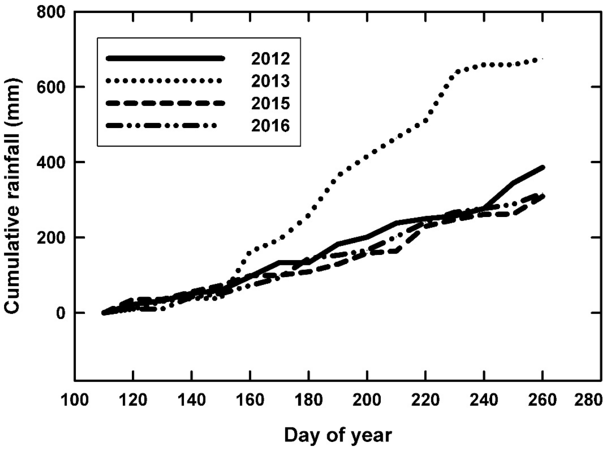

Figure 1. Cumulative rainfall measured between DOY (day of year) 110 to 260 for the cotton growing season 2012 to 2016.

Table 1 shows the total irrigation applied by year for each irrigation treatment. The average irrigation applied across all 4 yrs show that I2 and I3 applied less irrigation than I1. However, because 2013 was considered a wet year and little irrigation was needed, these data were removed from the irrigation analysis. In dryer years (2012, 2015, and 2016), more than three times more irrigation water was applied to I1 (540 mm) compared with I2 and I3 (170 mm). The total number of irrigation events and total water applied was also dependent on the amount of rainfall received. Consequently, more irrigation was applied in the dryer years of 2012, 2015, and 2016 compared to 2013. When comparing individual years, I2 received more irrigation than I3 (2015 and 2016), whereas in other years (2012 and 2013), I3 received more irrigation than I2. This can be explained by differences in rainfall patterns for each individual year. If more rainfall occurs during the middle of the growing season, then I1 and I3 treatments could be quite similar. Conversely, if rainfall events are less in the spring and fall then I2 and I3 would be similar.

With I1 being irrigated at greater soil water potential compared with the other two treatments (I2 and I3), there should be measurable soil water potential differences between the irrigation treatments throughout the year. Figure 2 shows the soil water potential measured at two soil depths during the 2015 growing season for the different irrigation treatment of I1 (A), I2 (B), and I3 (C). I1 (A) had multiple irrigation events at the beginning of the season compared with I2 (B) and I3 (C). Both I2 and I3 allowed more water to be removed at the 50-cm soil depth compared with I1 (A) before triggering an irrigation event. In 2015, I1 had 11 irrigation events (Table 1) compared with I1 and I3 having seven and nine events, respectively. These irrigation events can be counted in Fig. 2 by each upswing from low soil water potential to high. Figure 3 shows the dryland water potential for the two sensor depths of 25 and 50 cm. There was one rainfall at about DOY 230 that affected the 25-cm sensor to bring it back up to approximately field capacity but not the 50-cm sensor. Overall, soil water potential values show that each irrigation treatment had a slightly different irrigation scheduled except where irrigation trigger points were similar.

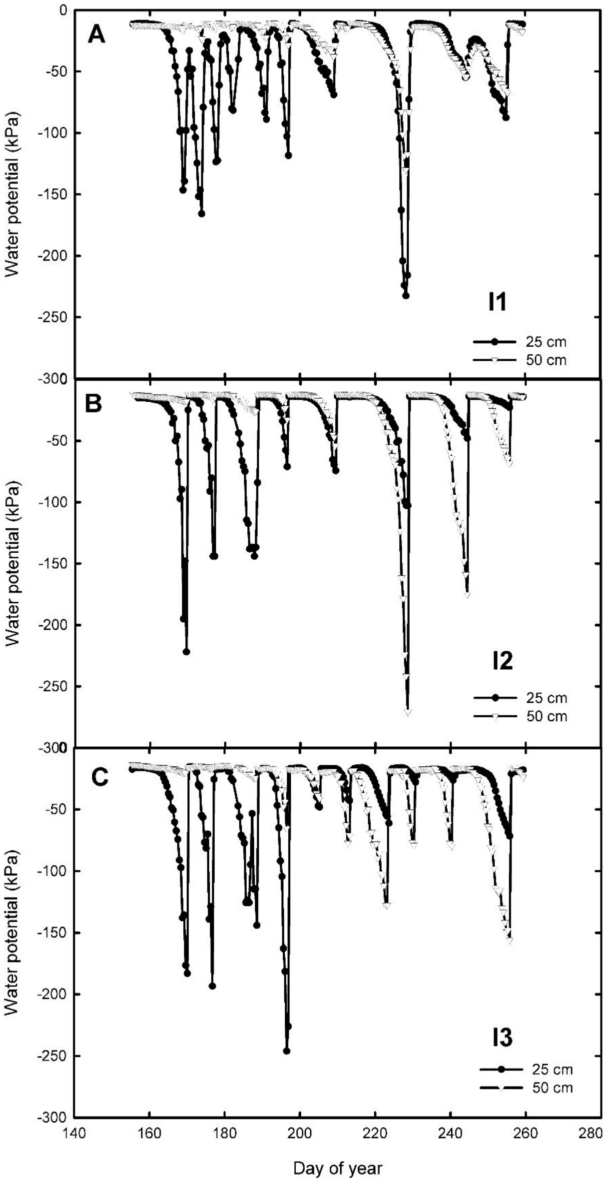

Figure 2. Soil water potential measured at two soil depths for I1, I2, and I3 treatments during the 2015 growing season.

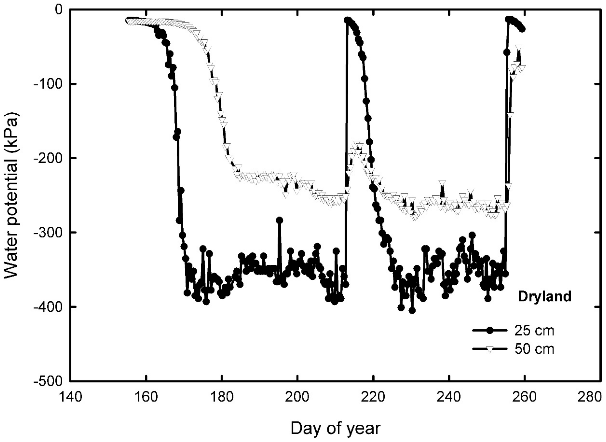

Figure 3. Soil water potential measured at two soil depths for dryland treatment during the 2015 growing season.

Lint yield values are shown in Table 2. Irrigated treatments had higher yield than nonirrigated yields except during the wet year of 2013. During 2013, there was no difference in lint yield across irrigation treatments compared with dryland. When comparing only irrigation treatments, that is, removing all dryland values, and comparing lint yield across years, 2013 (wet year) had lower yield (1516 kg ha^{-1}) compared with the other dry years (2042 kg ha^{-1}). When removing 2013 from the analysis and comparing only the irrigation treatments, there was no significant difference for lint yield across years (p = 0.07) or across irrigation treatments (p = 0.06). Lint yield for I1, I2, and I3 across the dry years (2012, 2015, and 2016) averaged 2068 kg ha^{-1}, whereas the dryland (2013 excluded) averaged 987 kg ha^{-1}. Lamb et al. (2015) showed that in dry years (rainfall less than average), 100% overhead irrigated cotton had an average yield of 1580 kg ha^{-1}, whereas the dryland treatment for the same dry years averaged 388 kg ha^{-1}. Drip irrigated cotton in dry years had greater lint yield than those reported for overhead irrigation in dry years (Lamb et al., 2015; Whitaker et al., 2008). These irrigation data imply that using any of the three irrigation treatments in dry years, with S3DI, can increase lint yield compared to dryland control. However, using irrigation treatment I2 or I3 can save approximately 170 mm of irrigation water compared to I1 without compromising yield, which would be a great savings to the grower in irrigation expenses.

Table 2. Cotton lint yield data by year and irrigation treatment

Year	Dryland	I1[z]	I2	I3
	------------------- kg ha^{-1}	-------------------		
2012	971b[y]	2213a	1945a	2157a
2013	1233a	1699a	1436a	1411a
2015	891b	2096a	2092a	2061a
2016	885b	1924a	1953a	1943a
average	987b	2060a	1885a	1981a
2013 removed	915b	2132a	1976a	2095a

[z] Irrigation treatments I1 = -40 kPa; I2 = 70 kPa; I3 = -70/-40/-60 kPa

[y] Lint yield means by year (rows) across irrigation treatments followed by the same letter are not statistically different ($p \leq 0.05$).

The decision to use I2 or I3 is dependent on rainfall patterns during the growing season and the end users comfort level. Treatment I3 would be equal to I2 if rainfall is adequate during the reproductive phenology period of 1st square to 1st cracked boll to maintain soil water potential less than the average -40 kPa. Conversely, if rainfall events do not occur during the reproductive period, the use of -70 kPa during this time period did not affect lint yield or quality. Therefore, using -40 kPa during the reproductive period could be more of a comfort factor for the grower to reduce possible drought and increase the feel better factor by irrigating a day or two earlier than recommended by the -70 kPa level.

Lower lint yield during 2013 can be explained by lower number of growing degree days (GDD) due to increased clouds during. University of Georgia weather network (www.weather.uga.edu) reported that from 10 April to15 September 2013 GDD was 2300, whereas 2012, 2015, and 2016 had 2598, 2720, 2734 GDD, respectively. Higher numbers of rainfall events in 2013 increased cloud cover explaining the lower GDD. Also, more rainfall events in 2013 could have affected flower pollination leading to decreased number of bolls and therefore lower yield compared with other years (Burke, 2003).

Differences in lint quality by year and by irrigation treatment are shown in Table 3. The dryland treatment had higher micronaire values, shorter fiber length, and lower fiber length uniformity compared with the irrigated treatments. Even though there were fiber differences across year and irrigation treatment, none of these differences caused large economic deductions to the value of the lint. When comparing just irrigation treatments (dryland data removed), there was no difference in lint quality. There is no benefit to the grower, as it relates to lint quality, when using any of these irrigation strategies with S3DI.

Table 3. Lint qualities of micronaire, fiber strength, fiber length, and fiber length uniformity by crop year and irrigation treatment

Treatment	Fiber quality			
	Micronaire	Strength	Length	uniformity
Year		g tex^{-1}	mm	%
2012	4.59b[z]	29.1b	29.1b	83.2c
2013	4.98a	32.4a	28.9b	83.4bc
2015	4.88a	33.2a	30.1a	84.5ab
2016	5.08a	33.6a	28.8b	85.0a
Irrigation treatment				
Dryland	4.98a	31.6a	28.4b	83.0b
I1[y]	4.67b	30.9a	29.5a	84.1a
I2	4.72b	30.9a	29.4a	84.0a
I3	4.76b	30.9a	29.5a	84.1a

[z] Means for fiber quality by year and irrigation treatment within columns followed by the same letter are not statistically different ($p \leq 0.05$).

[y] Irrigation treatments I1 = -40 kPa; I2 = -70 kPa; I3 = -70/-40/-60 kPa.

IWUE data are shown in Table 4. There was no significant difference for IWUE across year or irrigation treatment. However, a comparison of irrigated treatments (I1, I2, and I3) and dry years (2012, 2015, and 2016) showed IWUE for I2 and I3 was significantly greater than I1 ($p < 0.001$). IWUE for treatments I2 and I3 averaged 3.1 kg/mm, whereas I1 equaled 2.2 kg/mm water applied. Lamb et al. (2015) showed that with overhead irrigation, IWUE values were 3.32, 3.98 and 2.11 for 100, 66 and 33% irrigation rate, respectively. IWUE values for I2 and I3 were similar to the 66% irrigation rate, whereas I1 was similar to the 33% irrigation level.

Table 4. Irrigation water use efficiency (IWUE) for all years and irrigation treatments. Value water use efficiency (VWUE) for dry years and irrigation treatments

year	I1[z]	I2	I3
IWUE	------------------------	kg mm^{-1}	------------------------
2012	2.26a[y]	3.04a	2.70a
2013	3.26a	3.04a	1.51a
2015	2.45a	3.69a	3.71a
2016	1.79a	2.08a	3.46a
VWUE	------------------------	\$ mm^{-1}	------------------------
2012	4.07bc	5.66a	4.88ab
2015	3.84bc	5.80b	5.83a
2016	2.81c	3.27c	5.43a

[z] Irrigation treatments I1 = -40 kPa; I2= 70 kPa; I3= -70/-40/-60 kPa

[y] Means by mass (IWUE) or value (VWUE) followed by the same letter are not significant at the $p \leq 0.05$ level.

VWUE for dry years and the three irrigation treatments are shown in Table 4. These values show that I2 and I3 (except for I2 in 2016) have significantly great dollar value per unit of irrigation applied than for I1. The VWUE for I2 and I3 averaged \$5.14 mm^{-1}, whereas I1 had a VWUE of \$3.57 mm^{-1}. VWUE for I2 and I3 were similar to those determined by Lamb et al. (2015) for overhead irrigation at \$4.18 and \$5.52 mm^{-1} for irrigation rates 100 and 66, respectively.

CONCLUSION

Overall, by removing the wet year data (2013) when irrigation was minimal, all irrigation treatments increased lint yield compared with a dryland regime. Within irrigation treatments, I2 and I3 had the same lint yield and quality while reducing the total water applied by 170 mm compared with I1. Treatments I2 and I3 had greater IWUE (40%) and VWUE (44%) compared with I1. It is recommended to schedule irrigation events in cotton using an average value of -70 kPa during the whole season with soil water potential sensors installed at 25- and 50-cm soil depth. The use of I3 is also a recommended irrigation trigger. However, this treatment would provide more irrigation applied during the reproductive period, which would increase the number of irrigation events, increase cost, and reduce both IWUE and VWUE. In addition, I3 would help the comfort factor or feel better factor for the grower by irrigating a day or two earlier than recommended by I2 during the reproductive growth stage.

DISCLAIMER

Mention of proprietary product or company is included for the reader's convenience and does not imply any endorsement or preferential treatment by the USDA-ARS.

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