

AGRONOMY AND SOILS

A Deficit Irrigation Trial in Differing Soils Used To Evaluate Cotton Irrigation Scheduling For The Mid-South

Timothy J. Grant, Brian G. Leib, Heath A. Duncan, Chris L. Main, and David A. Verbree

ABSTRACT

Cotton (*Gossypium hirsutum* L.) irrigation management in the humid Mid-South is complicated by unpredictable rainfall and significant soil variability. Producers of irrigated cotton need guidance with making irrigation decisions to create conditions for optimal yield while efficiently managing irrigation water use. The objectives of this study were to demonstrate cotton yield response to varying irrigation across differing soils and to evaluate the ability of a water balance approach, and the use of soil moisture sensors to guide sound irrigation decisions. A three-year study was conducted in Jackson, TN where cotton was grown on soils ranging from primarily sandy-textured to deep silt loam soils and was drip-irrigated under several irrigation regimes. Three years of differing rainfall patterns demonstrated a need for different irrigation management between soils to optimize cotton yield each year. Sandy soils needed irrigation at a higher rate each year and an earlier initiation two of three years. A deficit between applied water and crop water use was especially important in silt loam soils, which required more judicious application of irrigation. A water balance approach to irrigation scheduling was a good indicator of soil and crop water status in sandy and silt loam soils. Soil moisture sensors often reflect the status of the water balance, however, in some cases soil moisture sensors could have triggered unnecessary irrigation based on suggested irrigation thresholds. While each method of irrigation scheduling has shortcomings, using a water balance in conjunction with soil moisture sensors is recommended, such that each can verify the other.

Irrigation of cotton in the Mid-South and Southeastern United States (US) has become an attractive option to protect against potential yield loss associated with irregular rainfall and episodic drought periods (Salazar et al., 2012; Schaible and Aillery, 2012). Irrigated cotton acreage in Tennessee (TN) has grown steadily over the last five to ten years, but still ranks well short of irrigated acreage in neighboring states (Gwathmey et al., 2011). In fact, according to the 2012 Census of Agriculture, only 6% of cotton acreage in Tennessee was irrigated, while neighboring states Arkansas, Louisiana, Mississippi, and Georgia irrigated 28–85% of cotton acreage (United States Department of Agriculture). The primary reason for the relatively small amount of irrigated cotton acreage in TN may be a lack of research-based understanding of appropriate irrigation management, i.e. water input required, and timing of application (Zhou et al., 2015). Tennessee shares challenges with other Mid-South and Southeastern US states in cotton irrigation management including irregular rainfall, yearly climactic variability, short growing season, soils with differing water holding capacity, soils with shallow root-limiting layers, and high degrees of variation in soils within fields (Vories and Evett, 2014).

Deficit irrigation has often proven to optimize cotton yields, while improving water use efficiency over full irrigation, i.e. full replenishment of evapotranspiration (ET) (Basal et al., 2009; Bronson et al., 2006; Tar et al., 1998). It has also been noted that water excess, along with stress-inducing water deficit, can be detrimental to yield (Balkcom et al., 2006; Geerts and Raes, 2009; Tar et al., 1998). In the Mid-South, deficit irrigation strives to apply water at a rate slightly below full ET, but its implementation may be considerably different than in more arid regions. Deficit irrigation in the Mid-South should take into account soil moisture carry-over from spring rains, often frequent in-season rainfall, and soil response to, and retention of rainfall. As in more arid regions, deficit irrigation has proven the optimal irrigation strategy for highest cotton yield with the

T.J. Grant* and B.G. Leib, Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, TN. 37996; H.A. Duncan, Fulghum, MacIndoe, & Associates, Inc., Knoxville, TN; C.L. Main, DOW AgroSciences, LLC, Medina, TN; and D.A. Verbree, Verbree International, Webster, NY.

*Corresponding author: tgrant7@vols.utk.edu

least amount of irrigation input in the Southeast and Mid-South (AbdelGadir et al., 2011; Dougherty et al., 2009; Pettigrew, 2004). It is important to note, however, that while irrigation is expected to improve cotton yields in slightly over half of years in the Mid-South, rainfall in some years can be sufficient to optimize cotton yields without supplemental irrigation (AbdelGadir et al., 2011; Gwathmey et al., 2011).

A critical question from producers' perspective in implementing deficit irrigation is how much water to apply and when to do so. Cotton water requirements are commonly based on replacement of water loss to evapotranspiration, whether through estimation or direct measurement (Bronson et al., 2006; Kebede et al., 2014). Irrigating to achieve a slight deficit compared to full ET is commonly found to be the best strategy, with optimal ET replacement values ranging from 74%-94% in more arid regions (Basal et al., 2009; Bronson et al., 2006; Tar et al., 1998) and around 75% in the humid Mid-South (AbdelGadir et al., 2011). Irrigation scheduling tools often use the water balance or checkbook approach when making irrigation decisions. In Tennessee, a spreadsheet-based tool, Management of Irrigation Systems in Tennessee (MOIST), is used by producers (Univ. of Tennessee, Knoxville, TN). MOIST calculates ET using the Turc method and FAO (Food and Agriculture Organization of the United Nations) crop coefficients with weather data from a station central to west TN. Location-specific rainfall and irrigation is entered and actual soil water depletion is compared to allowable soil water depletion, based on soil, crop, irrigation efficiency and other MOIST input parameters. This method is not free of error, however. A water balance approach depends on accurate measurements of effective rainfall, irrigation and crop water use. A water balance also does not account for confounding factors such as a shallow water table or subsurface water movement contributions. Soil moisture sensors can provide an additional perspective.

Soil moisture sensors are becoming more widely used by Mid-South cotton producers (Kebede et al., 2014). When installed at multiple depths, these sensors can give a producer a sense of water status throughout the soil profile. Used in conjunction with the water balance method, soil moisture sensors can provide verification of the status the water balance. Using soil water tension measurements as trigger points for irrigation decisions is a strategy often used, however, recommendations on what values to use as trigger points vary. Leib et al. (2015), recommend

setting irrigation thresholds at tensions of -30 to -40 kPa (cbar) in sandy loam soils and between -40 and -60 kPa in silt loam soils. Leib et al. (2015) also noted the importance of factors such as sensor site selection and placement, growth stage, and sensor depths. Vellidis et al. (2008) recommended trigger points of -40 kPa in the upper part of the soil profile and -50 kPa deeper in the profile. Flynn and Barnes (1998) observed optimal yield and water use when using a trigger of -60 kPa. Potential errors in using soil moisture sensors include faulty sensors giving erroneous readings, inadequate soil contact with the sensor, and localized soil irregularities (Leib et al., 2015; Kebede et al., 2014).

Studies have consistently shown positive yield and/or quality response of cotton to more frequent and lower volume water applications, irrigating multiple times per week as opposed to once every week or two (Chu et al., 1995; Enciso-Medina et al., 2000; Hunsaker et al., 1998). Gwathmey et al. (2011) and Duncan (2012) explored how much water TN cotton producers should expect to apply per irrigation to optimize yield. During critical growth stages between first square and cracked boll, approximately 40-120 days after planting, deep silt loam soils can be expected to respond to irrigation when rainfall <280 mm, a scenario expected to happen around 60% of years, according to historical rain in West TN (Gwathmey et al., 2011). Probability of response to irrigation can also increase with increasing irregularity of rainfall during the growing season, and as soil water holding capacity (WHC) decreases (Duncan, 2012).

Appropriate initiation timing of irrigation for cotton in TN needs research attention, as lack of knowledge could be limiting adoption of irrigation in the state. Irrigation before squaring is discouraged, and can actually limit yield (Buttar et al., 2007; Wanjura et al., 1996). Considering likely soil moisture carry-over from spring, irrigation in the Mid-South should not be required before squaring. From first square to first bloom, Snowden et al. (2014) found that significant water stress could lower yield, but fiber quality remained similar to well-watered treatments. Dekock et al. (1990), however, found cotton exposed to water stress during squaring was able to recover and yield similarly to well-watered cotton. Barber and Francis (2011) identified the week prior to first flower as a critical time to have sufficient crop available water. Studies are in agreement that once flowering has begun, and continuing through late bloom, yields and fiber quality can be significantly

diminished by damaging water stress conditions (Carvalho et al., 2015; Dekock et al., 1990; Snowden et al., 2014). In the Mid-South, appropriate initiation timing could vary depending on soil WHC. Low WHC soils could require earlier initiation because of their drainage loss of spring rain and/or smaller overall carry-over from spring rains. Duncan (2012), points out that irrigation decisions (amount and initiation time) for TN cotton producers depend heavily on site-specific soil properties.

Soil WHC variability, due to differential texture or depth to a restrictive soil layer, is known to have a significant impact on yield of cotton, whether irrigated or not (Booker et al., 2014; Ping and Green, 2000; Vories et al., 2015). Cotton yield response to irrigation in high WHC soils has been found to follow a positive quadratic function (Balkcom et al., 2006; Geerts and Raes, 2009; Gwathmey et al., 2011), while in sandy soils, yield tends to respond linearly to irrigation (Bronson et al., 2006; Detar, 2008; Tar et al., 1998). Research has consistently shown a need for higher water application in low WHC soils, compared to high WHC soils, to optimize cotton yield (English et al., 2002; Evans et al., 2013; Haghverdi et al., 2015), because of less inherent buffer in soil water or excessive drainage of soil water in a situation where soil texture is the primary cause of low WHC (Longwell et al., 1963). Cotton irrigation management across various soils in the Mid-South is complex because of early-season soil moisture carry-over and judgement of in-season rainfall effectiveness (Vories and Evett, 2014). Determining how irrigation decisions should be approached differently in various soils is of utmost importance to TN cotton producers with irrigation capability (Duncan, 2012; Haghverdi et al., 2015). The objectives of this study were to demonstrate cotton yield response to a range of irrigation regimes in soils differing in WHC, and to evaluate the potential of a water balance approach and soil moisture sensors to successfully demonstrate irrigation need.

MATERIALS AND METHODS

The effect of varying levels of deficit irrigation on cotton yield in various soils was evaluated in a three-year field study in Jackson, TN, at the West Tennessee Research and Education Center (WTREC). Soils of the test site were a Ruston-Dexter-Lexington complex. These soils are classified as Fine-loamy, siliceous, semiactive, thermic Typic

Paleudults, Fine-silty, mixed, active, thermic Ultic Hapludalfs, and Fine-silty, mixed, active, thermic Ultic Hapludalfs, respectively. While the soils all shared a silt cap layer over a primarily sand layer, they differed significantly in depth to sand and WHC. For the purposes of the study, soils were grouped based on electrical conductivity, ground-penetrating radar, and soil cores. The process of grouping soils of this test site is described in detail by Duncan (2012).

Cotton (PHY375) was planted in a no-till cropping system on 5 May 2010, 12 May 2011, and 24 April 2012. Plots were six rows wide by 9.1 m long. Row spacing was 97 cm. Nitrogen fertilizer was applied each year according to University of Tennessee recommendations for cotton production. Phosphorus (P) and potassium (K) application was dependent on University of Tennessee (UT) soil test recommendations from soil samples taken from study site. Management of the cotton crop, including pest management, growth regulator application, and application of defoliant followed UT Extension guidelines for cotton production.

The drip irrigation system was installed after cotton plants had emerged by placing the drip tape on the soil surface; one line of drip tape was placed alongside each row of cotton. Three flow ratings of drip tape were used to simultaneously apply three rates, 3.81, 2.54, and 1.27 cm/wk. Irrigation was applied three days per week, if necessary, as research has shown high-frequency, low-volume applications to yield higher than low-frequency, high-volume applications (Enciso-Medina et al., 2000; Hunsaker et al., 1998; Chu et al., 1995). This irrigation frequency also better replicates center-pivot irrigation frequency and capacity, which is most prevalent in TN. On Mondays, Wednesdays, and Fridays, 1.02, .76, and .76 cm were applied respectively (in the 2.54 cm/wk treatments) if complete irrigation time was necessary. Amount of supplemental irrigation applied was dependent upon rainfall. If there was no rainfall in the last seven days, the full amount of irrigation was applied. If 2.54 cm or more effective rainfall was recorded in the last seven days, no irrigation was applied. If an amount less than 2.54 cm was received, irrigation amount was determined based on the 2.54 cm/wk treatment reaching the full quota. Irrigation was initiated at either first square, first bloom, or two weeks past first bloom (in 2010 only) and all treatments were terminated at cracked boll. One line of drip tape was placed alongside each row of cotton. Applied irrigation treatments changed slightly in the three years of the study (Table 1).

Table 1: Applied irrigation (cm) for each treatment (initiation timing, cm/wk target) by year

	2010	2011	2012
Square 3.81	21.1	20.8	21.6
Square 2.54	14.0	13.8	14.4
Square 1.27	7.0	6.9	7.2
Bloom 3.81	18.4	16.8	12.4
Bloom 2.54	12.3	11.2	8.3
Bloom 1.27	6.1	5.6	-
Post-Bloom 3.81	14.9	-	-
Post-Bloom 2.54	9.9	-	-
Post-Bloom 1.27	5.0	-	-
Square 1.27, Bloom 3.81	-	-	15.5
Dryland	0.0	0.0	0.0
Rainfall 40-120 dap	37.3	19.1	30.0
30-yr Normal		27.2	
Rainfall Plant-Harvest	57.6	35.9	47.9

Precipitation data were collected from a standard National Oceanic and Atmospheric Administration (NOAA) weather station less than 400 m from the field of study. Daily ET values were calculated in MOIST, using temperature data from a weather station in Brownsville, TN, approximately 40 km from the field of study. Rainfall and irrigation records were input to MOIST after each season. Soil specific parameters used to calculate allowable soil water depletion were water holding capacity values of 18.3 cm/m for the silt loam soils and 8.3 cm/m for the sandy soils (Duncan 2012). In calculating actual soil water depletion, a crop-specific rooting depth of 0.91 m was used.

Soil moisture tension was measured using electrical resistance granular matrix sensors (Watermark) from Irrometer (Irrometer Company, Inc., Riverside, CA). For each plot monitored, sensors were placed at depths of 23 and 61 cm. Sensors were placed in spring of 2010 and remained in place until the end of 2012 growing season. Sensors and antennas remained in-field, and communicated wirelessly to a receiver upon significant (define this value) change in soil moisture.

The two center rows of each plot were harvested with a two-row spindle picker. Total seed cotton weight of each plot was measured by load cell in the field. A sample of seed cotton was taken from each plot, weighed, and air-dried. Each sample was ginned with a 20-saw gin assembly to determine lint turnout. Lint turnout was applied to the total

plot seed cotton weight, and with plot area a lint yield in kg/ha was calculated. While statistical analysis was conducted on calculated yields, lint yields are reported in the format of difference from rainfed yield. This numerical format compared each treatment yield in a given soil type and year to the rainfed yield for that soil type and year. Results from a portion of this dataset in 2010 and 2011 are presented by Wiggins et al. (2014), as are some additional physiological measurements. Previous analysis by Wiggins et al. (2014) examined four selected irrigation treatments and two soil groups and focused on the impact of irrigation amount applied on physiological measurements and lint yield. More detailed soil analysis was completed following the 2010 season (Duncan, 2012), which allowed for improvement in the grouping of plots by soil type. This re-grouping of plots and new analysis is the reason for some missing treatments in 2010.

The experiment was arranged as a randomized complete block design (RCBD) that was blocked by soils. Seven soil blocks were identified that transitioned from low to high WHC and shallow to deep depth to sandy soil (Duncan, 2012). Data were analyzed using the mixed procedure of SAS 9.4 (SAS Institute, Cary, NC). Preliminary analysis revealed a significant interaction between year, treatment, and soil. Therefore, the three years were analyzed separately, which is especially appropriate because of the dissimilar yearly rainfall patterns. Each year, a significant block by treatment interaction existed according to Tukey's single degree of freedom test for interaction ($\alpha=0.05$), indicating that cotton yield responded differently to irrigation treatments across soil blocks. To address this interaction, and achieve a better distinction between soil responses to irrigation, a variable "soil type" was added to the analysis. This variable grouped the seven soil blocks into three soil types - low, intermediate, and high WHC - based on soil textural and water holding capacity data presented by Duncan (2012). The grouping of soil blocks was the same in each year, block one was the low WHC (sandy soils), blocks two through four were intermediate WHC, and blocks five through seven constituted the high WHC (silt loam soils) soil type. Levene's test for equality of variance in each year reported an F-statistic of less than 3, therefore the pooled variance was used in mean separation. Mean separation was achieved using Fisher's LSD $p=0.10$.

RESULTS AND DISCUSSION

The three years of this study were markedly different from one another in rainfall amount and distribution, which is common in the Mid-South. The 2010 growing season was wetter than average during the critical irrigation period (Table 1), and rainfall was well distributed. The 2011 growing season was drier than average, and had a pronounced late dry period beginning in early to mid-July. The 2012 growing season was close to average in total rainfall, but had a pronounced early dry period from mid-June to early July. Whole season rainfall patterns, along with ET and soil moisture depletion, can be seen in MOIST outputs (Figure 1). The irrigation treatment that led to optimal lint yield in each soil and each year reflects the difference in rainfall in the three years of this study. The wettest year, 2010, saw no yield increase from irrigation in deep silt loam soils, while cotton grown in sandy soils yielded highest when irrigation was delayed until bloom, and then received irrigation at our highest rate (Table 2). In a year with a late dry period, 2011, cotton grown in deep silt loam soils did respond to irrigation and yielded highest when irrigation was initiated at bloom and applied at our highest rate. Cotton grown in sandy soils in 2011 required irrigation starting at square, at a high rate to yield highest. In a year with an early dry period, 2012, both deep silt loam soils and sandy soils needed irrigation beginning at square to optimize yield. However, while cotton grown in sandy soils needed our highest rate of irrigation, cotton grown in deep silt loam soils yielded optimally with 2.54 cm/wk supplemental irrigation. Another important observation from this study is the potential for over-irrigation to harm cotton yield in silt loam soils which has also been observed by Gwathmey et al. (2011) and Zhou et al. (2015). In all three years, we observed a reduction in lint yield when cotton in silt loam soils was irrigated at our highest irrigation treatment compared to the optimal treatment for that year.

A water balance approach in 2010 (Figure 1) confirms that actual soil water depletion remained above the allowable depletion for silt loam soil without irrigation. However, even in this wet year, the actual depletion without irrigation exceeded the allowable depletion for sandy soil, especially later in the year. Supplemental irrigation beginning at bloom was sufficient to keep the actual deple-

tion well above the allowable depletion level for sandy soils and subsequently increase yield over non-irrigated. Soil moisture sensors in the silt loam soils in 2010 seem to all read drier than expected, based upon the water balance and observed yields (Figure 2). The deep sensor in each treatment follows a similar drying trajectory through the year, but did so at dissimilar levels. The top sensor clearly shows wetter conditions when irrigated, compared to non-irrigated, but all observed treatments seem to violate suggested thresholds (Leib et al., 2015; Vellidis et al., 2008; Flynn and Barnes, 1998). Very dry conditions at the top sensor in the non-irrigated treatment suggest the cotton was able to use sufficient deep soil moisture to yield optimally. This reaffirms the sentiment in Leib et al. (2015), concerning averaging sensor readings across depths to trigger irrigation. In this case, extreme values in the upper part of the profile would likely trigger unnecessary irrigation. Sensors in the sandy soil show significant drying under non-irrigated conditions at both sensors (Figure 3). Cotton yielded highest in sandy soil with initiation at bloom and a rate of 3.81 cm/wk. Our observed plot of bloom 2.54 cm/wk shows more favorable conditions, however the levels are still allowed to drop below -100 kPa at both sensors for two short periods of time. With sensors in the bloom 3.81 cm/wk treatment, we expect we would have observed higher moisture levels during those periods.

A water balance approach in 2011 (Figure 1) shows actual depletion exceeding the allowable depletion for sandy and silt loam soils mid-late season. Supplemental irrigation beginning at bloom keeps the actual depletion well above the allowable depletion for silt loam soils until after the irrigation period. For sandy soils, the actual depletion nears the allowable depletion multiple times and exceeds the allowable depletion just after irrigation has ceased. When irrigation is initiated at square, the actual depletion stays significantly shy of the allowable depletion for sandy soil. Soil moisture sensors in the non-irrigated deep silt loam in 2011 show drying beyond the suggested thresholds for irrigation at both sensors (Figure 2). When irrigation was initiated at bloom, both sensors exceed -50 kPa for only a short period of time, and neither exceeds -100 kPa. Irrigation beginning at square and a high rate kept soil moisture levels above irrigation thresholds all season, but also resulted in yield loss. Others have observed yield loss from

over-irrigation (Gwathmey et al., 2011; Zhou et al., 2015), indicating perhaps cotton in silt loam soils can benefit from a deficit in soil moisture. Non-irrigated soil moisture in sandy soils in 2011 reveals extended periods of a thoroughly dry soil profile (Figure 3), leading to significant yield loss (Table 2). Initiating irrigation at bloom still allowed multiple periods where soil moisture was below -100 kPa at both sensors. Initiating irrigation at square and applying our highest rate kept at least one sensor above -60 kPa throughout the critical period, and led to optimal yield.

In 2012, the water balance clearly demonstrates the effect of a substantial early dry period (Figure 1). Actual soil water depletion exceeds the allowable depletion for both silt loam and sandy soils early in the season, and while the depletion does not grow significantly, it never recovers to an acceptable level without supplemental irrigation. Irrigation beginning at bloom improves the depletion late in the season, but does not erase a significant deficit early in the year. Cotton in both silt loam and sandy soils required irrigation beginning at square to yield optimally, as the MOIST output for square 3.81 cm/wk shows actual depletion within the range of allowable depletion for the silt loam soil and nearly all within the range for sandy soil. Sensors in the non-irrigated silt loam soil in 2012 (Figure 2) certainly do not reflect the severity of water deficit suggested by the water balance and yield loss suffered. Prior to irrigation initiation, the sensors in the bloom 2.54 cm/wk treatment are more indicative of probable conditions. Mostly favorable readings in the non-irrigated silt loam soil reveal potential shortcomings of relying solely on sensor data. As mentioned by Leib et al. (2015), faulty sensors, localized soil irregularities, and sensor proximity to crop row are factors that could contribute to unrealistic readings. Irrigation beginning at square was required to optimize yield, even in silt loam soils, and sensors show this earlier initiation alleviated dry conditions around first bloom stage. Sensors in sandy soil show drying beyond irrigation thresholds when non-irrigated and when irrigation was delayed until bloom (Figure 3). Irrigation beginning at square was necessary to optimize yield in sandy soils in 2012, however, sensor data is missing from an early initiation plot.

Table 2: Cotton lint yields compared to rainfed yield within soil type and year

2010				
Initiation Timing	Rate (cm/wk)	Yield Differential from Rainfed (kg/ha)		
		Low WHC (ns)	Intermediate WHC (ns)	High WHC (ns)
Square	3.81	377	171	-249
Square	2.54	-	544	-138
Square	1.27	-	580	-92
Bloom	3.81	543	374	-33
Bloom	2.54	225	620	111
Bloom	1.27	356	619	17
Mid-Bloom	3.81	-	634	-82
Mid-Bloom	2.54	-	480	172
Mid-Bloom	1.27	-	509	163
-	Rainfed	0 (519)	0 (789)	0 (1336)
2011				
Initiation Timing	Rate (cm/wk)	Yield Differential from Rainfed (kg/ha)		
		Low WHC	Intermediate WHC	High WHC
Square	3.81	1081 a	463 a	194 ab
Square	2.54	580 b	602 a	118 b
Square	1.27	204 bc	612 a	225 ab
Bloom	3.81	508 b	525 a	406 a
Bloom	2.54	501 b	614 a	292 ab
Bloom	1.27	437 bc	474 a	283 ab
-	Rainfed	0 (405) c	0 (900) b	0 (1385) b
2012				
Initiation Timing	Rate (cm/wk)	Yield Differential from Rainfed (kg/ha)		
		Low WHC	Intermediate WHC	High WHC
Square	3.81	949 a	383 b	254 bc
Square	2.54	166 bc	743 a	414 ab
Square	1.27	376 abc	203 bc	278 bc
Bloom	3.81	176 bc	424 ab	241 bc
Bloom	2.54	106 bc	378 b	319 abc
Sq/Bl	1.27, 3.81	676 ab	360 b	374 ab
-	Rainfed	0 (425) c	0 (872) c	0 (1108) c

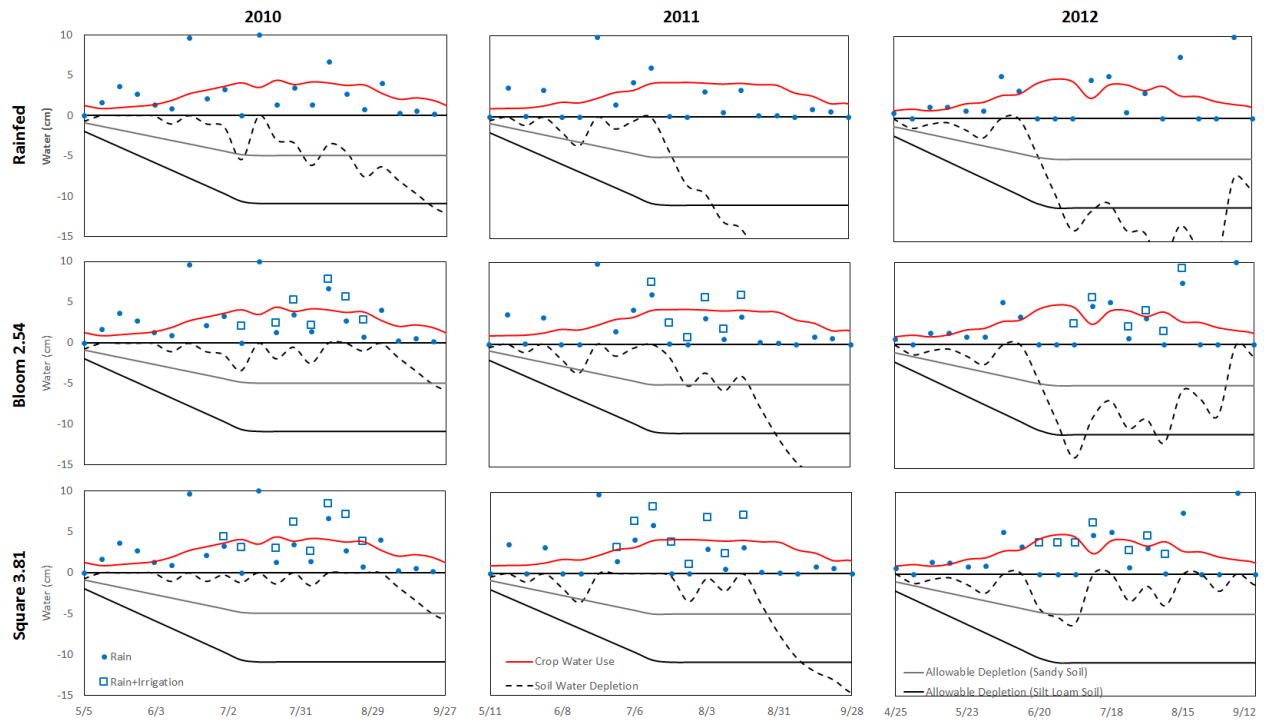


Figure 1: Seasonal water balance using MOIST irrigation scheduling tool for non-irrigated, irrigated beginning at bloom 2.54 cm/wk, and irrigated beginning at square 3.81 cm/wk for each of the three study years.

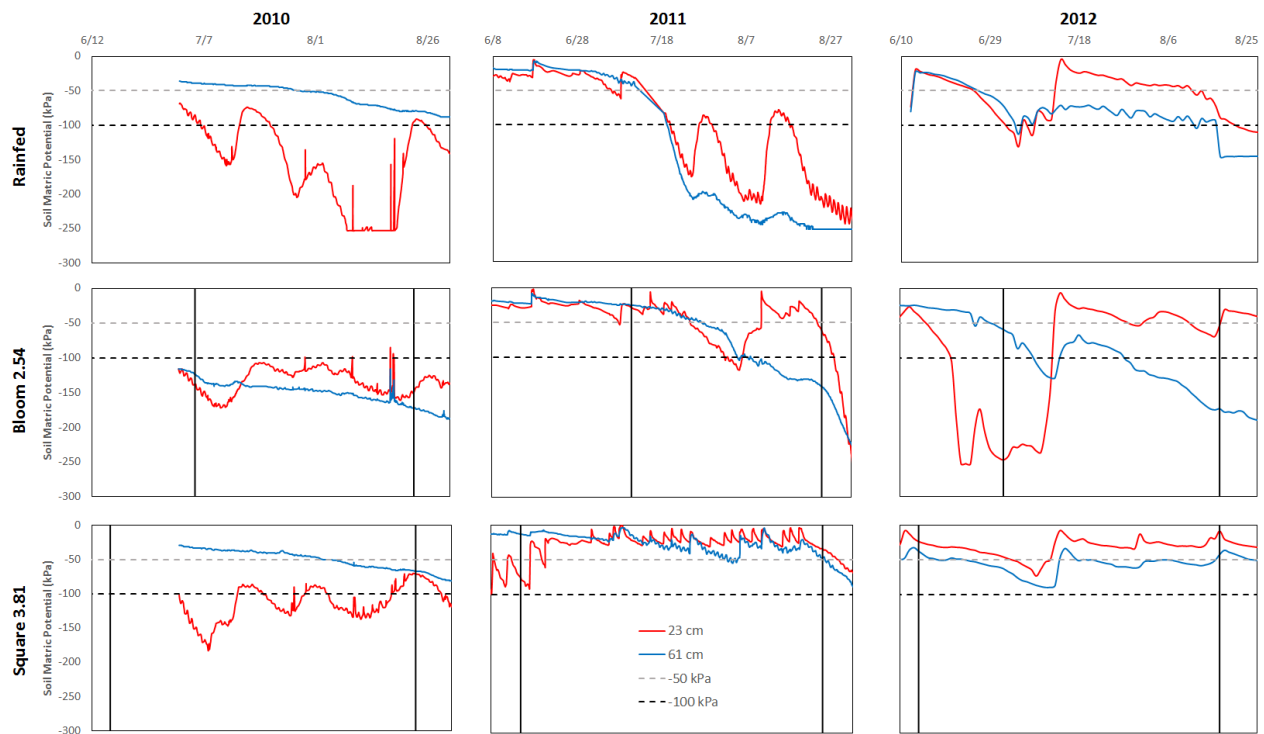


Figure 2: Soil moisture sensor data in silt loam soils. Vertical solid black lines, when present, indicate initiation and termination of irrigation.

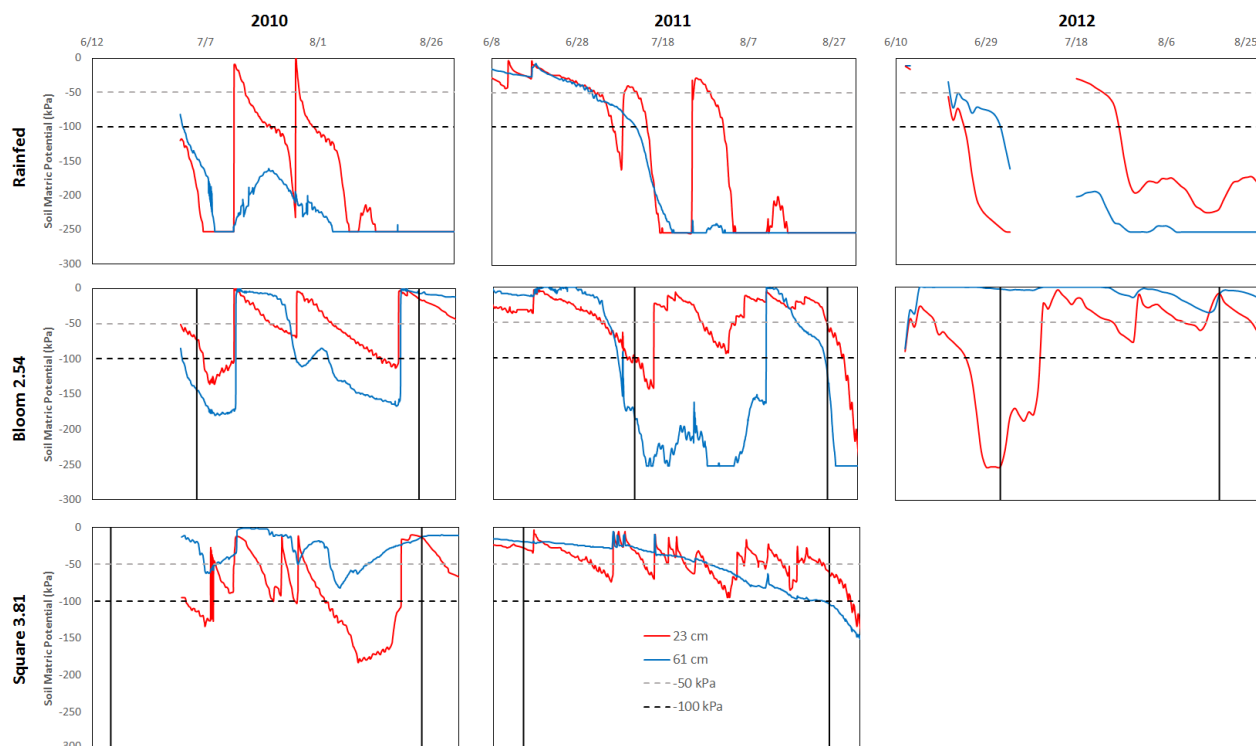


Figure 3: Soil moisture sensor data in sandy soils. Vertical solid black lines, when present, indicate initiation and termination of irrigation.

CONCLUSION

This study contributes further evidence of the need to irrigate cotton differently in soils that vary in texture and water holding capacity. In a wet year, this could mean not irrigating a silt loam soil, while supplying some irrigation to a sandy soil. In drier years, cotton grown in both soils could need irrigation to optimize yield, however, the initiation timing and rate of supplemental irrigation could need to be different. To encourage producers to do a good job irrigating, depending on soil, a source based on sound and proven methods is needed to make irrigation decisions. In this study, a water balance approach, using the MOIST scheduling tool, accurately predicted the need for irrigation and allowable depletions for silt loam and sandy soils were on target. Soil moisture sensors, in most cases, reflected the water balance status and revealed differential needs between soils and years. Irrigation thresholds, or trigger points, suggested in the literature, however, seem conservative compared to the values our sensors read, while still yielding optimally. There were also inconsistencies in sensor readings, and sometimes values that did not align with status of soil water indicated by the water balance and subsequent yields. Therefore, soil

moisture sensors can be recommended as a verification of a water balance approach, can demonstrate differences in water status between soils, and can alert one to significantly dry conditions. Multiple sensor locations could confirm that the sensors are representative of a larger area. While this study did not indicate difficulty with the water balance approach, it should be recognized that these plots were level and well-drained. Sloping ground and drainage issues as well as inaccurate measurements of rainfall/irrigation can cause the water balance to misdiagnose conditions. If both methods, soils moisture sensors and water balance, are in agreement there will be high confidence that irrigation scheduling is on track. If the methods diverge, it is important to discern the reason for the disparity in order to make good irrigation decisions.

ACKNOWLEDGEMENTS

This research was made possible with the assistance of the staff and supervisors at WTREC. Special thanks to Tyler Simmons, Matt Ross, and Matthew Wiggins. Statistical guidance and assistance were provided by Dr. Arnold Saxton. This research was supported by Cotton Incorporated and USDA-NRCS through a Conservation Innovation Grant.

REFERENCES

- AbdelGadir, A. H., J. P. Fulton, M. Dougherty, L. M. Curtis, E. van Santen, C. H. Burmester, H. D. Harkins, and B. E. Norris. 2011. Subsurface drip irrigation placement and cotton irrigation water requirement in the Tennessee Valley. *Crop Manag.* 10(1).
- Balkcom, K. S., D. W. Reeves, J. N. Shaw, C. H. Burmester, and L. M. Curtis. 2006. Cotton yield and fiber quality from irrigated tillage systems in the Tennessee Valley. *Agron J.* 98 (3): 596–602.
- Barber, T., and P. Francis. 2011. Achieving profitable cotton production: Irrigation initiation and termination. Research Series - Arkansas Agricultural Experiment Station. 589: 94–99.
- Basal, H., N. Dagdelen, A. Unay, and E. Yilmaz. 2009. Effects of deficit drip irrigation ratios on cotton (*Gossypium hirsutum* L.) yield and fibre quality. *J Agron Crop Sci.* 195 (1): 19–29.
- Booker, J. D., R. J. Lascano, S. R. Evett, and R. E. Zartman. 2014. Evaluation of a landscape-scale approach to cotton modeling. *Agron J.* 106 (6): 2263–79.
- Bronson, K. F., J. D. Booker, J. P. Bordovsky, J. W. Keeling, T. A. Wheeler, R. K. Boman, M. N. Parajulee, E. Segarra, and R. L. Nichols. 2006. Site-specific irrigation and nitrogen management for cotton production in the Southern High Plains. *Agron J.* 98 (1): 212–19.
- Buttar, G. S., M. S. Aujla, H. S. Thind, C. J. Singh, and K. S. Saini. 2007. Effect of timing of first and last irrigation on the yield and water use efficiency in cotton. *Agric Water Manage.* 89 (3): 236–42.
- Carvalho, H. Da Ros, C. J. Fernandez, J. C. Correa, J. T. Cothren, G. Morgan, and M. Krifa. 2015. Quantifying the effects of water deficit stress timing on cotton growth and yield under rain-sheltered controlled conditions. In Proc. Beltwide Cotton Conf., San Antonio, TX. 5-7 Jan. 2015. Natl. Cotton Counc. Am., Memphis, TN.
- Chu, C. C., T. J. Henneberry, and J. W. Radin. 1995. Effect of irrigation frequency on cotton yield in short-season production systems. *Crop Sci.* 35 (4): 1069–73.
- Dekock, J., L. P. Debruyne, and J. J. Human. 1990. The relative sensitivity to plant water-stress during the reproductive phase of upland cotton (*Gossypium hirsutum* L.). *Irrigation Sci.* 11 (4): 239–44.
- Detar, W. R. 2008. Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. *Agric Water Manage.* 95 (1): 69–76.
- Dougherty, M., A. H. AbdelGadir, J. P. Fulton, E. van Santen, L. M. Curtis, C. H. Burmester, H. D. Harkins, and B. E. Norris. 2009. Subsurface drip irrigation and fertigation for North Alabama cotton production. *J Cotton Sci.* 13 (4): 227–37.
- Duncan, H. A. 2012. Locating the variability of soil water holding capacity and understanding its effects on deficit irrigation and cotton lint yield. M.S. Thesis. University of Tennessee, Knoxville, TN.
- Enciso-Medina, J., B. Multer, and D. Porter. 2000. Optimizing cotton irrigation frequency for deficit irrigation. In Proc. National Irrigation Symposium, Phoenix, AZ. 14-16 Nov. 2000. Amer Soc Agr Engineers, St. Joseph, MI.
- English, M. J., K. H. Solomon, and G. J. Hoffman. 2002. A paradigm shift in irrigation management. *J Irrig Drain Eng.* 128 (5): 267–77.
- Evans, R. G., J. LaRue, K. C. Stone, and B. A. King. 2013. Adoption of site-specific variable rate sprinkler irrigation systems. *Irrigation Sci.* 31 (4): 871–87.
- Flynn, R. P. and C. E. Barnes. 1998. Timing first irrigations for cotton productivity and water conservation. In Proc. Beltwide Cotton Conf., San Diego, CA. 5-9 Jan. 1998. Natl. Cotton Counc. Am., Memphis, TN.
- Geerts, S., and D. Raes. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric Water Manage.* 96 (9): 1275–84.
- Gwathmey, C. O., B. G. Leib, and C. L. Main. 2011. Lint yield and crop maturity responses to irrigation in a short-season environment. *J Cotton Sci.* 15 (1): 1–10.
- Haghverdi, A., B. G. Leib, P. D. Ayers, M. J. Buschermohle, D. Verbree, and T. J. Grant. 2015. Studying cotton yield response to irrigation regimes and spatial soil variation in a humid region. In Proc. Beltwide Cotton Conf., San Antonio, TX. 5-7 January. 2015. Natl. Cotton Counc. Am., Memphis, TN.
- Hunsaker, D. J., A. J. Clemmens, and D. D. Fangmeier. 1998. Cotton response to high frequency surface irrigation. *Agric Water Manage.* 37 (1): 55–74.
- Kebede, H., D. K. Fisher, R. Sui, and K. N. Reddy. Irrigation methods and scheduling in the delta region of Mississippi: Current status and strategies to improve irrigation efficiency. *Am J Plant Sci.* 5 (20): 2917.
- Leib, B., J. Payero, L. Pringle, J. Bordovsky, W. Porter, and E. Barnes. 2015. Placement and interpretation of soil moisture sensors for irrigated cotton production in humid regions. Cotton Inc. [Online]. Available at <https://cottoncultivated.cottoninc.com/wp-content/uploads/2015/12/Soil-Moisture-Sensors.pdf>

- Longwell, T. J., W. L. Parks, and M. E. Springer. 1963. Moisture characteristics of Tennessee soils. In *Agric. Exp. Sta. Bull.* 367. University of Tennessee, Knoxville, TN.
- Pettigrew, W. T. 2004. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. *Agron J.* 96 (2): 377–83.
- Ping, J. L., and C. J. Green. 2000. Spatial Variability of Yield and Soil Parameters in Two Irrigated Cotton Fields in Texas. In *Proc. 5th International Conf. on Precision Agriculture*, Bloomington, MN. 16-19 Jul. 2000. American Society of Agronomy, Madison, WI.
- Snowden, M. C., G. L. Ritchie, F. R. Simao, and J. P. Bordo-vsky. 2014. Timing of episodic drought can be critical in cotton. *Agron J.* 106 (2): 452–58.
- Tar, W. R. de, S. J. Maas, and J. R. McLaughlin. 1998. Cotton irrigation using subsurface drip: Growth, cutout and yield depend on amount of water applied. In *Proc. Belt-wide Cotton Conf.*, San Diego, CA. 5-9 Jan. 1998. Natl. Cotton Counc. Am., Memphis, TN.
- Vellidis, G., M. Tucker, C. Perry, C. Kvien, and C. Bednarz. 2008. A real-time wireless smart sensor array for scheduling irrigation. *Comput Electron Agric.* 61 (1): 44-50.
- Vories, E. D., and S. R. Evett. 2014. Irrigation challenges in the sub-humid US Mid-South. *International Journal of Water.* 8 (3): 259–74.
- Vories, E. D., W. E. Stevens, K. A. Sudduth, S. T. Drummond, and N. R. Benson. 2015. Impact of soil variability on irrigated and rainfed cotton. *J Cotton Sci.* 19 (1): 1–14.
- Wanjura, D. F., J. R. Mahan, and D. R. Upchurch. 1996. Irrigation starting time effects on cotton under high-frequency irrigation. *Agron J.* 88 (4): 561–66.
- Wiggins, M. S., B. G. Leib, T. C. Mueller, and C. L. Main. 2014. Cotton growth, yield, and fiber quality response to irrigation and water deficit in soil of varying depth to a sand layer. *J Cotton Sci.* 18 (2): 145-152.
- Zhou, X., C. Boyer, J. A. Larson, B. G. Leib, and C. O. Gwathmey. 2015. Profit maximizing irrigation rates and timing for short-season cotton production. *Agron J.* 108: 1-10.