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AGRONOMY AND SOILS

Cotton Growth, Yield, and Fiber Quality Response to Irrigation and Water Deficit in Soil of Varying Depth to a Sand Layer

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ABSTRACT

Research was conducted in 2010 and 2011 at the West Tennessee Research and Education Center in Jackson, TN to investigate irrigation response in cotton. The objective of this study was to evaluate plant response to four different irrigation regimes by using main-stem node counts, quantification of canopy light interception, and canopy temperature, while making comparisons across two soils that vary in depth to a sandy layer. PHY 375 WRF cottonseed was planted in a no-tillage system in 9-m rows on 97-cm spacing with 10.5-12 seed m^{-1} of row. Irrigation was applied from drip tape lying in the row furrow at rates of 0, 1.27, 2.54, and 3.81 cm $week^{-1}$. Comparisons were made across deep soils (no sand layer within the top 89 centimeters of soil) and shallow soils (sand layer within the top 61 centimeters of soil). Plant height, number of nodes, nodes above white flower (NAWF), canopy light interception, and canopy temperature were monitored during the blooming period of the crop each year to determine differences in irrigation response. Cotton plants grown in deep soils had higher vegetative biomass, total number of nodes, plant height, light interception, fiber quality, yield, and reduced canopy temperature compared to plants grown in the shallow soil. Similarly, irrigation increased cotton plant vegetative biomass, total number of nodes, plant height, light interception, fiber quality, yield, and reduced canopy temperature compared to dryland cotton. Results from this trial indicate that differences in physiological growth patterns, canopy density, canopy temperature, lint yield, and fiber quality are evident when compared across irrigation amounts and soil depths.

Cotton (*Gossypium hirsutum* L.) producers in the humid Midsouth and Southeastern United States have observed mixed outcomes with the irrigation of upland cotton varieties. This is due in part to the cotton plant's indeterminate growth pattern, where the plant continues to grow vegetatively during reproduction (Eaton, 1955; Quisenberry and Roark, 1976). The level of indeterminacy is related to such growth altering parameters as available moisture, heat accumulation, and quality of growing environment. Research has found that supplemental irrigation often has a positive effect on the crop, but may have a negative effect in some situations (Guinn and Mauney, 1984a; Gwathmey et al., 2011).

In the absence of adequate and timely rainfall, stress due to water deficit is detrimental to a cotton production system (Pettigrew, 2004a). Water can be the most limiting factor in some cropping systems and is needed throughout the cotton plant's life to grow and develop from emergence to harvest (Gerik et al., 1996; Howell, 2001). Water deficit stress symptomology can be readily identified, as the lack of water will typically reduce the plant's ability to establish and retain blooms and fruiting structures, having a direct negative impact on yield (Guinn and Mauney, 1984a; Guinn and Mauney, 1984b; Pettigrew, 2004a; Whitaker et al., 2008). Water stress can also result in stunted plants with reduced leaf area, limiting the transpiration and photosynthesis rate of the crop. Lack of leaf area reduces the ability of cotton to transpire and cool itself, commonly resulting in the shedding of leaves and fruiting structures (Spooner et al., 1958). Thus, plants suffering from water stress result in a crop with a diminished yield potential. However, it can prove beneficial to impose water-deficit stress in cotton at certain times during the growing season. Typically supplemental irrigation will be terminated toward the end of the growing season, reducing further growth to aid in the defoliation process (Guinn and Mauney, 1984a).

High temperatures can be detrimental for both vegetative and reproductive growth in upland cotton

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varieties (Ashraf et al., 1994). This is particularly true for regions of the southern United States that experience both high temperatures and humidity. When water availability in a leaf becomes limited, transpiration slows and the plant loses its ability to cool its tissues (Keener and Kircher, 1983). Often, leaf temperatures in these situations reach ambient air temperatures or higher (Keener and Kircher, 1983; Reddy et al., 1999). Crops growing under stress due to water deficits and high temperatures have a smaller plant canopy (Reddy et al., 1997). Canopy development plays an essential role in determining the amount of photosynthetically active radiation (PAR) that can be intercepted by the plant. Canopy interception is directly related to cotton growth and development (Reddy et al., 1991); reduced interception of PAR ultimately reduces yields.

Both canopy temperature and leaf area can be readily determined in a cropping system. Infrared thermometers are an effective means for collecting canopy temperatures (Hatfield, 1990). Crop water stress indices have been created from gathering canopy temperature data and ambient air temperatures (Jackson et al., 1981; Wanjura et al., 1984). These indices have been suggested as an irrigation scheduling tool (Howell et al., 1984). However, PAR interception measurements can be more difficult to acquire, but these measurements are pertinent to the growth and development of the cotton plant.

Supplemental irrigation is generally accepted as a beneficial contribution to a cotton production system, but a positive plant response is not always the result. Typical responses include enhancing the plant's ability to establish and retain more fruiting structures throughout the growing season (Pettigrew, 2004b) and the promotion of a healthier, more vigorous growing crop. This increase in plant structure generally has a positive influence on yield, as yield is highly correlated with the number of bolls produced and overall plant health (Gerik et al., 1996; Guinn and Mauney, 1984b). However, supplemental irrigation has also proved to be detrimental in certain environments, this is especially true in production areas where there is a shorter growing season (Gwathmey et al., 2011). Additional irrigation has been documented to add an excessive amount of vegetative growth, leading to a reduced boll load, boll diseases, and delays in maturity (Gwathmey et al., 2011, Spooner et al., 1958).

Various measurement techniques have been developed and used for assessment of cotton growth and are utilized at various times throughout the growing season (Bourland et al., 2001). Main stem node counts are often associated with morphological and phenological events in the cotton plant (Bednarz and Nichols, 2005). This type of data collection is easily acquired throughout the growing season without excessive disturbance to the plant population and can provide pertinent information about such parameters as growth rate, plant structure, and plant maturity.

Additional irrigation research in areas of high soil variability in the Midsouth is needed to aid producers in these areas in making better management decisions, as these inputs can be costly. Therefore, the objective of this study was to evaluate plant response to four different irrigation regimes by using main-stem node counts, quantification of canopy light interception, and canopy temperature, while making comparisons across two soils that vary in depth to a sandy layer.

MATERIALS AND METHODS

An experiment to determine the effects of physiological plant response to supplemental irrigation and water deficit was conducted at the West Tennessee Research and Education Center in Jackson, TN, during the 2010 and 2011 growing seasons in a single field. The field consisted of a Lexington series silt loam (fine-silty, mixed, active, thermic Ultic Hapludalf) and a Dexter series (fine-silty, mixed, active, thermic Ultic Hapludalf). PHY 375 WRF was planted into existing crop residue using a no-tillage system. The trial was conducted as a randomized incomplete block design with a three factor factorial arrangement of treatments with 3 replications. Factors evaluated were irrigation amount, irrigation timing, and soil depth. Depth of soil was the incomplete blocking factor in this experiment; limited by space and variability in the field. However, soil depths evaluated in this study are considered fixed effects as they were replicated in the field and plots remained the same across both years of the study. Plots were six rows by 9.1 m, with a row spacing of 97 cm. Irrigation treatments were applied using surface drip tape at rates of 0 cm, 1.27 cm, 2.54 cm, and 3.81 cm per week minus rainfall. Irrigation initiation timings of at pin-head square and at first bloom were evaluated. Depth to a sandy layer was also evaluated in a highly variable soil and was quantified by extracting soil cores from the plot areas. Comparisons were made across deep soils (no sand layer within the top 89 centimeters of soil) and shallow soils (sand layer within the top 61 centimeters of soil). All other production practices followed University of Tennessee Extension Service recommendations for cotton production.

Evaluations of physiological growth response in cotton were conducted weekly for four weeks, starting when plots began to bloom. This was accomplished by recording weekly main-stem node counts, including number of nodes, plant height, height of first fruiting branch, and nodes above white flower (NAWF). Data were recorded from ten plants selected at random from each plot. Additional measurements recorded during each growing season included canopy light interception and canopy temperature differences across treatments. Canopy light interception was measured twice during the blooming period, 14 and 28 days after the plots began to bloom, using a calibrated LI-COR quantum point sensor placed above the crop canopy and line sensor placed under the canopy. The data were recorded by a LI-COR 1400 data logger (LI-190 Quantum point sensor, LI-191 Quantum line sensor, LI-1400 Data logger; LI-COR Environmental; Lincoln, NE). Measurements were obtained as close to solar noon as possible, as this is when there is the least amount of variation in sunlight intensity. At the same time, canopy temperature differences were measured utilizing a RAYTEK infrared thermometer (ST™ ProPlus; Raytek Corporation; Santa Cruz, CA).

Water use efficiency was calculated from total lint yield (kg ha^{-1}) and a summation of irrigation applied during the blooming and fruiting cycle (cm) and accumulated precipitation during the growing season (cm), where:

$$[WUE = \frac{Lint\ Yield\ (kg\ ha{-}1)}{Total\ Water\ Applied + Precipitation\ (cm)}].$$

The center two rows of each six-row plot were harvested using a spindle cotton picker adapted for small-plot harvesting. A sample of mechanically harvested seed cotton was collected from each plot and used to determine lint percentage and fiber quality. Seed cotton was ginned on a laboratory gin without lint cleaning, and fiber upper half mean length, fiber length uniformity index, fiber strength, and micronaire were determined by high volume instrumentation testing (Sasser, 1981).

Data were subjected to analysis of variance using the PROC MIXED procedure of SAS (ver. 9.2; SAS Institute; Cary, NC). Means were separated using Fishers Protected LSD procedure at a 0.05 significance level. Additionally, regression analysis was used to determine the relationships between canopy light interception, canopy temperature, and water use efficiency of irrigation treatments and soil depths. The coefficient of determination (r^2) was calculated for each parameter analyzed by regression. Data were pooled across the two years of the study, and each year was considered as an environment. Replications were considered random; whereas soil depth, irrigation treatment amounts, and interactions of these effects were considered fixed effects. Irrigation initiation time did not impact results, thus data were pooled across pin-head square and first bloom initiation timings. Year of the study was not significant for any measured parameters based on ANOVA results, as both years accumulated adequate heat units and precipitation to produce a high yield potential cotton crop (NOAA, 2001) (Table 1).

Table 1. Irrigation rates, irrigation totals, total rainfall, and total water for Jackson, TN during 2010 and 2011 growing seasons, along with historical average rainfall.

		------------------- 2010 -------------------			------------------- 2011 -------------------			
Irrigation Initiation	**Irrigation Rate (cm)**	**Total Irrigation (cm)**	**Total Rainfall (cm)[Z]**	**Total Water (cm)**	**Total Irrigation (cm)**	**Total Rainfall (cm)**	**Total Water (cm)**	**Historical Average Rainfall[Y]**
Pinhead Square	**1.27**	**7.04**	**57.58**	**64.62**	**6.93**	**35.74**	**42.67**	
Pinhead Square	**2.54**	**14.05**	**57.58**	**71.63**	**13.84**	**35.74**	**49.58**	
Pinhead Square	**3.81**	**21.08**	**57.58**	**78.66**	**20.77**	**35.74**	**56.51**	
First Bloom	**1.27**	**6.12**	**57.58**	**63.7**	**5.61**	**35.74**	**41.35**	**49.78**
First Bloom	**2.54**	**12.27**	**57.58**	**69.85**	**11.23**	**35.74**	**46.96**	
First Bloom	**3.81**	**18.39**	**57.58**	**75.97**	**16.84**	**35.74**	**52.55**	
Dryland	**0**	**0**	**57.58**	**57.58**	**0**	**35.74**	**35.74**	

[Z] Total rainfall collected from May to September for 2010 and 2011.

[Y] Historical average rainfall from May to September from 1971-2000.

RESULTS AND DISCUSSION

Cotton Growth and Development. Cotton plant growth and development varied due irrigation treatments and depth of soil to a sandy layer; the interaction of irrigation amount and soil depth was not a significant factor. Plant response to irrigation treatments and depth of soil varied, but, as in Pettigrew (2004b), the most obvious soil moisture deficit response is a reduction in plant growth and development. Likewise, plots receiving supplemental irrigation increased in total number of nodes and plant height. The highest weekly irrigation rate, 3.81 cm per week, resulted in the greatest number of total nodes and plant height (Table 2). Plant stunting and a reduction of growth and development were evident in dryland plots. Plants in irrigated plots maintained vegetative growth longer than the plants of the dryland plots, as in Pettigrew (2004a). These results verify that supplemental irrigation is beneficial in areas where water is limiting in establishing and maintaining plant growth and development. This high level of growth and development will lead to a healthy and robust crop, increasing yield potential.

Soil depth also had a significant impact on the plant growth and development during the evaluation period. Total number of nodes and plant height were higher on plants grown in a deep soil profile than on the shallow soil (Table 2). These deeper soil profiles have greater water holding capacities that allow the crop to utilize the moisture applied over a longer period of time, which is beneficial in times of sporadic precipitation. Since a deep silt loam soil is able to adequately maintain and establish a healthy growing crop in times of adequate rainfall, these results suggest that producers utilizing supplemental irrigation in their production scenarios should focus water inputs on areas where water is a more limiting factor. Cotton planted in shallow soils, with reduced water holding capacities, would benefit from supplemental irrigation by establishing and maintaining plant growth and development and increasing yield potential. Therefore, producers could potentially benefit from site-specific management tactics in areas like this where variable soils are present to ensure that valuable water resources are utilized in the most efficient manner.

Maturity. Cotton maturity was determined by irrigation amount and soil depth; the interaction of irrigation amount and soil depth was not a significant factor. Maturity was recorded throughout the evaluated blooming period by monitoring NAWF. Measurements of NAWF in the Midsouth can vary due to available moisture, insect pressure, and other stresses. Therefore, NAWF was evaluated throughout the peak blooming period to determine differences in maturity due to irrigation treatments and depth of soil. Plots receiving irrigation treatments resulted in higher NAWF values (Table 2), suggesting a delay in maturity. Dryland cotton had fewer NAWF at each evaluation time, similar to the results of Whitaker et al. (2008). Application of irrigation allowed plants to continue growing

Table 2. Average plant nodes, plant height, and NAWF of a cotton crop grown in a soil varying in depth to a sandy layer and receiving varying amounts of irrigation during the first four weeks of bloom.

		Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4
Irrigation (cm)	**Soil Depth**	-------- Plant Nodes (no.) --------				------- Plant Height (cm) -------				------------- NAWF^{Z} -------------			
0		13.8	15.7	15.6	16.2	89.0	89.8	94.4	93.8	4.9	2.1	1.2	0.6
1.27		14.9	16.8	16.8	17.6	96.3	104.5	107.3	108.9	5.8	2.9	1.7	1.1
2.54		15.0	17.1	17.3	17.6	98.6	106.1	110.4	110.6	6.1	3.3	2.1	1.3
3.81		14.9	16.9	17.3	17.9	93.5	102.9	106.4	106.7	6.1	3.5	2.1	1.2
LSD (0.05)		0.7	0.7	0.8	0.8	NS	8.6	9.2	9.1	0.7	0.6	0.3	0.4
	Shallow^{Y}	14.2	15.9	16.0	16.5	88.2	94.7	96.4	95.6	5.2	2.5	1.4	0.6
	Deep^{X}	15.1	17.4	17.5	18.2	100.5	106.9	112.7	114.4	6.2	3.5	2.2	1.5
	LSD(0.05)	0.5	0.5	0.6	0.6	5.8	6.1	6.6	6.5	0.5	0.4	0.2	0.3

^{Z}NAWF = Main stem Nodes Above White Flower.

^{Y}Shallow soil = < 61 cm to a sandy soil layer.

^{X}Deep soil = >89 cm to a sandy soil layer.

vegetatively and delayed maturity, whereas the reduced moisture received by dryland treatments caused plants to mature earlier due to earlier cutout and boll maturation. Depth of soil also impacted maturity, as plots grown in the deep soil resulted in higher NAWF values than that of the shallow soil. Similar to results of irrigation application, cotton grown in the deeper soil profile grew vegetatively longer. Consequently, cutout was delayed by seven days from applying supplemental irrigation or from being grown in a deeper soil profile. Results from Gwathmey et al. (2011) concluded that maturity was delayed ten days from similar nominal irrigation amounts, but this was in a deeper silt loam soil than the soil evaluated in this experiment. This indicates that variation in soil type may be an important component when determining maturity differences due to irrigation. Producers may face implications due to variations in soil depth or irrigation amounts. These implications can make management decisions for nitrogen application, plant growth regulators, and harvest aids more difficult and increase the need for site-specific application.

Canopy Light Interception and Temperature. Canopy density and canopy temperature varied across irrigation treatments. Canopy light interception varied based on irrigation amount, soil depth, and the interaction of irrigation amount and soil depth. Results of light interception measurements were similar to results found in Pettigrew (2004b), where dryland plots intercepted significantly less PAR (Figure 1.). Light interception by the crop in the deep soil ranged from 85% to 93%, at 0 cm and 3.81cm of water applied weekly, respectively. Light interception by the crop in the shallower soil ranged from 48% at the 0 cm irrigation treatment to 78% at the highest irrigation treatment. Plants in the limiting soil lacked moisture to transpire and cool plant tissue, making them susceptible to water deficit stress and diminished yield. Water stress in these trials decreased the amount of light intercepted in the canopy as in Gerik et al. (1996). However, cotton in the shallower plots did benefit the most from supplemental irrigation by increasing PAR interception by 16% from the dryland to the 1.27 cm per week treatment; suggesting once again that the greatest focus of water inputs should be on the most limiting production areas to obtain a more uniform and profitable crop.

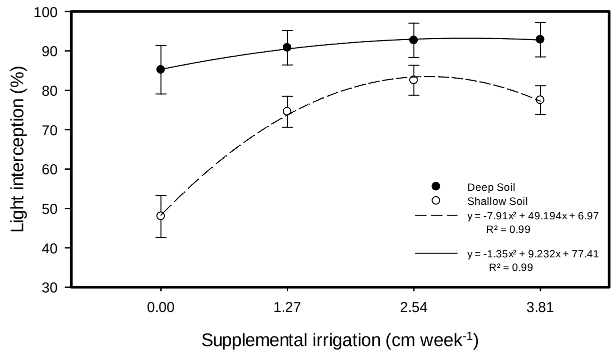

Figure 1. Canopy light interception of a cotton crop grown in a soil varying in depth to a sandy layer and receiving varying amount of irrigation.

Canopy temperature differed across irrigation amounts and depth to sand, but no interaction between irrigation and depth to sand occurred. Canopy temperature varied across soil type with the cotton grown on shallow soil having a higher average temperature than plants grown in deep soil (Figure 2.). As in Pettigrew (2004b), dryland treatments had significantly higher canopy temperatures during the blooming period. The application of supplemental irrigation reduced canopy temperature significantly from the dryland treatments. Dryland treatments averaged a canopy temperature of 32.6°C. The temperature of plants in the irrigated plots was 30.6°C, 30.3°C, and 30.0°C with 1.27 cm, 2.54 cm, and 3.81 cm of irrigation applied, respectively (Figure 2.).

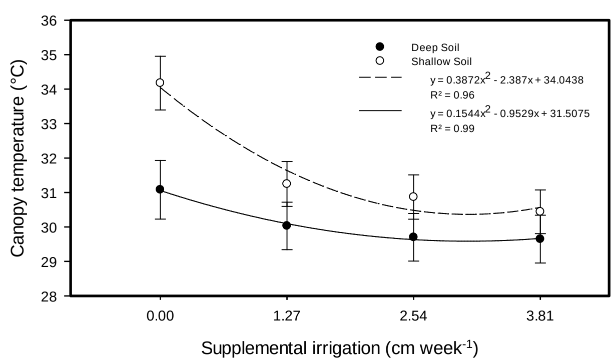

Figure 2. Average canopy temperature of a cotton crop grown in a soil varying in depth to a sandy layer and receiving varying amounts of irrigation.

Lint Yield and Fiber Quality. Lint yield and fiber quality were influenced by irrigation amount and soil depth; the interaction of irrigation amount and soil depth was not a significant factor. Supplemental irrigation increased yield and fiber quality. However, lint percentage decreased by 1%. As observed by Gwathmey et al. (2011), yield response across irrigation treatments was more quadratic in response than linear. Lint yield ranged from 1280 kg ha^{-1} in the dryland plots to 1560 kg ha^{-1} in an irrigated scenario (Figure 3.). The highest yield was the 2.54 cm irrigation treatment, where yield averaged 1560 kg ha^{-1}. Also, lint percent decreased significantly from the dryland plots with the addition of irrigation (Table 3). The dryland treatment averaged 40.4% lint, whereas the irrigated plots ranged from 39.8% to 39.1%. Micronaire, fiber length, fiber strength, and fiber length uniformity were influenced by irrigation rate. Dryland treatments averaged 4.6 micronaire, 1.10 in (27.9 mm) staple length, 30.0 g tex^{-1} (294 kN m kg^{-1}) strength, and 82.2% uniformity, while the application of 3.81 cm per week averaged 4.4 micronare, 1.15 in (29.2 mm) staple length, 31.4 g tex^{-1} (308 kN m kg^{-1}), and 83.2% uniformity. Yield and quality were also impacted by soil depth. The deeper soil plots averaged 1650 kg ha^{-1} of lint, while the shallow soil plots averaged 1310 kg ha^{-1} of lint. Fiber quality increased in the deeper soil verses the shallow soil. Staple length, fiber strength and uniformity were 1.11 in (28.2 mm) , 30.1 g tex^{-1} (295 kN m kg^{-1}), and 82.3%, respectively, in the shallow soil while they were 1.15 in (29.2 mm), 31.3 g tex^{-1} (306 kN m kg^{-1}), and 83.2% in the deeper soil.

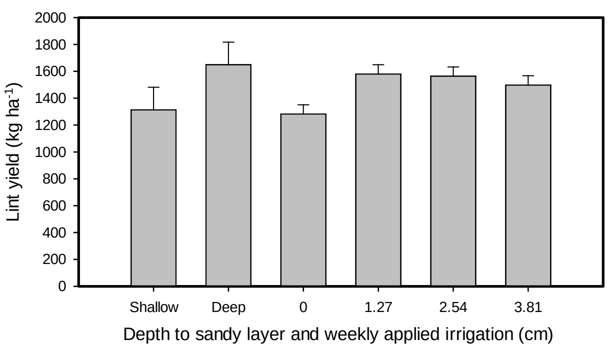

Figure 3. Lint yield of cotton grown a soil varying in depth to a sandy layer and receiving varying amounts of irrigation.

Water Use Efficiency. Differences were detected for depth to sand and irrigation treatment effects. Water use efficiency varied among years, as different amounts of precipitation and irrigation were accumulated during the growing season. Results show that in both years in the deep soil profile water use efficiency declined readily from the dryland WUE value. Values in the deeper soil during 2010 and 2011 ranged from 27.5 kg ha^{-1} to18.2 kg ha^{-1} and 47.17 kg ha^{-1} to 34.5 kg ha^{-1}, respectively (Figures 4.1 and 4.2). However, in the shallower soil, during both years of the study, WUE values increased. Water use efficiency values in the shallower soil ranged from 16.7 kg ha^{-1} to 16.8 kg ha^{-1} and 24.7 kg ha^{-1} to 26.7 kg ha^{-1} during the 2010 and 2011 growing season, respectively. The data for the shallow soil is represented by a parabolic function for both years, with the optimum water use efficiency value being reached with the supplemental application of 1.27 cm of irrigation per week. Since yield was not increased with more than 1.27 cm per week in the two years of this experiment, 1.27 cm per week was the most efficient irrigation rate.

Results from this trial in 2010 and 2011 indicate that irrigation amount and depth to a sand layer in soil will have an impact cotton production. Plant height and total number of nodes were greater in the deeper soil profile, resulting in a cotton crop with an increased yield potential. The dryland plots resulted in stunted plants with reduced amount of growth and development, restricting the potential for a high yield. Crop maturity was also affected from being grown

Table 3. Cotton lint percent and fiber quality analysis of a crop grown in a soil varying in depth to a sandy layer and receiving varying amounts of irrigation.

Irrigation (cm)	Soil Depth	Lint Percent (%)	Micronaire	Fiber Length (in.) [mm]	Fiber Strength (g tex^{-1}) [kN m kg^{-1}]	Fiber Uniformity (%)
0		40.4	4.6	1.10 [27.9]	30.0 [294]	82.2
1.27		39.8	4.5	1.13 [28.7]	30.1 [295]	82.8
2.54		39.2	4.4	1.14 [29.0]	30.1 [295]	83
3.81		39.1	4.4	1.15 [29.2]	31.4 [308]	83.2
LSD (0.05)		0.7	0.1	0.01 [0.3]	0.6 [6]	0.4
	Shallow[Z]	39.9	4.4	1.11 [28.2]	30.1 [295]	82.3
	Deep[Y]	39.4	4.5	1.15 [29.2]	31.3 [307]	83.2
	LSD (0.05)	NS	NS	0.01 [0.3]	0.5 [5]	0.3

[Z] Shallow = < 61 cm to sand layer, n = 56

[Y] Deep = > 89 cm to sand layer, n = 42 in the deep soils (Table 1). Soils with a shallow depth to sand benefit the most from supplemental irrigation, not only in plant growth and development, but yield, fiber quality, and WUE as well. This increased lint yield and improved fiber quality from efficient water use adds economic value to cotton grown on variable soils. Application of supplemental irrigation is generally thought to be beneficial in most cotton production scenarios and this was the case in this experiment by quantifying the increase in total number of nodes, plant height, canopy PAR interception, yield, and fiber quality. Supplemental irrigation lowered canopy temperature, also beneficial to a healthy, robust growing crop. However, some implications of applying irrigation do exist. Challenges associated with delaying cotton maturity in a short season environment can alter management practices that are in place today such as fertilizer, pesticide, and harvest aid applications. Moving forward, cotton producers in the Midsouth and rain-fed cotton producing areas will need to start making site-specific management decisions to obtain a manageable, uniform crop. These specific concerns will need to be addressed, particularly in areas where the amount of supplemental irrigation continues to increase. Also, it is pertinent to understand the variability that does exist in some soils to ensure the most efficient use of our valuable water resources; leading to a more sustainable and economic cotton production system.

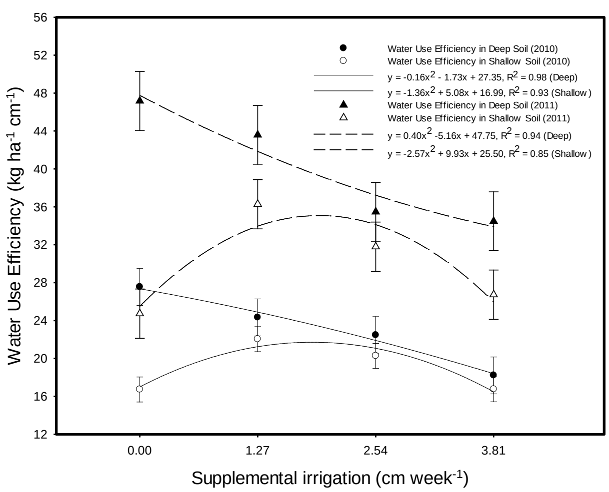

Figure 4 Water use efficiency in cotton grown in a soil varying in depth to a sandy layer during 2010 and 2011.

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