The *Journal of Cotton Science 17:10–22 (2013)*
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AGRONOMY & SOILS

Lint Yield, Lint Quality, and Economic Returns of Cotton Production under Traditional and Regulated Deficit Irrigation Schemes in Southwest Texas

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ABSTRACT

The urban water demand in Southwest Texas has grown rapidly in recent years due to steady increases in population. Improved irrigation schemes are needed to support new water-use plans as solutions to the conflict between municipal and agricultural water use. Deficit irrigation is one possible technique for conserving water while maintaining crop yield and/or economic returns. A field experiment was conducted at the Texas AgriLife Research and Extension Center at Uvalde, TX in the summers of 2008 and 2009 to examine the water saving potential of four traditional (T) and two regulated (R) deficit irrigation treatments against a full irrigation treatment. Two deficit irrigation treatments (80T and 70R) were found to be able to maintain lint yield similar to the full irrigation treatment for most cotton varieties tested. Although some differences were observed in lint quality parameters, these differences were not large enough to cause changes in the economic returns to the grower. In addition, a third treatment (50R) was able to maintain economic returns similar to the full irrigation treatment. These results indicate that the regulated deficit irrigation scheme could be further developed to achieve a possible increase in water conservation and economic sustainability for production in this region.

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The urban water demand in Southwest Texas has been increasing rapidly in recent years due to a steadily increasing urban population in a region with extremely limited water resources. This creates a critical need to develop and research sustainable water resource plans for both municipal and agricultural water supplies. One practical way to assist in solving the water demand conflict problem is to reduce agricultural water use through deficit irrigation. To maintain crop production, reduced amounts of water need to be applied in a manner that will maintain the ratio of production returns per unit of water consumed (i.e., agricultural water use efficiency, or water productivity). An improved irrigation scheduling plan for Southwest Texas would be beneficial to the region's agricultural sector and would have ancillary benefits to surrounding communities as well. Development of water-use efficient irrigation schemes requires large-scale field research conducted in this region.

In current deficit irrigation studies, fixed-ratio deficit irrigation schemes called traditional deficit irrigation (TDI) are widely used. Different TDI methods have been implemented by using soil water measurement, soil water balance calculations, and plant "stress" sensing approaches (Jones, 2004) to schedule irrigation. The soil water balance method, or evapotranspiration-based (ET-based) irrigation scheduling method, is a method that can be implemented easily. This method calculates soil moisture deficit (i.e., the net water loss through ET) and uses crop coefficients over the growing season to modify irrigation amounts for a given crop type. This method is commonly used in both research and farm production in the High Plains and Winter Garden areas of Texas with support of reference ET networks, as for example, the Texas High Plains ET Network and the Precision Irrigators Network. Several years of on-farm experiments were conducted in the Winter Garden area (Southwest Texas) on different crops using this irrigation scheduling method (Falkenberg et al., 2007; Ko and Piccinni, 2009). In these studies, 75% ET was reported to be a good deficit irrigation alternative to full irrigation without reducing crop yields. However, because only two deficit irrigation treatments (75% and 50% ET) were examined, the threshold level of TDI for maintaining crop production in this region remains unclear.

Although TDI is easy to implement and widely used in recent years, some doubts on its efficacy still exist. Applying the same deficit rate in different crop growth stages might not be optimal, because plants show different sensitivity to drought stress in particular stages (Meng et al., 2007). In a stage where the crop is highly sensitive to water deficit, the TDI scheme is likely to introduce drought stress that can lead to significant yield loss (Kang et al., 2000). Regulated deficit irrigation (RDI) is an alternative irrigation scheduling scheme to TDI and was started in the 1970s in Australia (Meng et al., 2007). The first application of an RDI scheme was on peach trees (*Prunus persica* (L.) Batsch) to improve water use efficiency through decreasing irrigation amounts while maintaining fruit yields (Chalmers and Vandenende, 1975; Chalmers and Wilson, 1978). The principle of the RDI scheme is to apply different deficit irrigation amounts timed to particular plant growth stages, thereby providing sufficient water during stages when the plant is sensitive to drought stress, and saving water during stages when the crop is more drought-tolerant and plant reproduction is less affected. More complicated calculations are involved in the RDI scheme; thus, intensive research into defining drought-sensitive crop growth stages and appropriate irrigation amounts are required.

The field study of corn by Kang et al. (1998, 2000) might be the earliest report of a detailed RDI experiment conducted in a full-scale field crop production environment and included measurements of several key physiological parameters besides grain yield. Many more RDI studies on field crops have been conducted in China since 2000, including corn (*Zea mays* L.) (Du et al., 2006; Guo and Kang, 2000; Kang et al., 2000; Tan et al., 2009; Tang et al., 2005), cotton (*Gossypium hirsutum* L.) (Gao et al., 2004; Meng et al., 2007, 2008; Pei et al., 2000), spring wheat (*Triticum aestivum* L.) (Zhang et al., 2006), and broad beans (*Vicia faba* L.) (Ding et al., 2007). However, similar studies in the U.S., especially in Texas, are rarely found. Because local climate conditions and soil types have great impacts on RDI thresholds of different growth stages, it is necessary to obtain local parameters to improve RDI practice. The quantitative relationship between drought stress sensitivity and RDI rate remains a challenge, which adds to the difficulty in RDI practice.

A key component in evaluating the success of any water management scheme is the calculation of economic return to the producer. This determines the sustainability of the technique in the agricultural environment. Although lint yield is the major goal in cotton production, the maximum profit might not be guaranteed even when lint yield is maximal because of offsets in economic returns caused by the quality parameters of the lint itself. From this perspective, the profit, rather than the lint yield, should be used to evaluate which irrigation scheme (full irrigation, TDI, or RDI) performs optimally. Although implementing a reduced irrigation scheme might not necessarily produce the same lint yield as the full irrigation scheme, the loss in lint production can be compensated by the reduced cost of irrigation application. Therefore, it is important to include both the cost of water and other fees, such as the electricity cost for pumping and running the irrigation system. To conduct an economic evaluation of TDI and RDI, the lint price for each growing season (at the harvest time) is needed. Lint quality has a direct impact on the economic return to the producer because these parameters determine the classification of lint, and the prices for these different classifications vary. Taking the standard lint of upland cotton [white with color grade of strict low middling (SLM), leaf level 4, and staple length level 34 (2.7 cm)] as an example, the loan rate (the bottom price set by the USDA) in 2010 was approximately \$1.15 kg^{-1} if the micronaire reading is between 4.3 and 4.9. However a sample with the micronaire reading of 5.0 to 5.2 had a return of only \$1.09 kg^{-1} (\$0.06 kg^{-1} discount) even if all the other characteristics were the same. Further, the economic costs associated with applying irrigation (electricity or diesel pumping costs) must be included in any economic evaluation of an irrigation system. Therefore, the lint yield, quality, and cost of applying the water must all be included in the final economic evaluation of an irrigation management scheme.

In this study, one of the major agronomic crops in Southwest Texas—cotton—was chosen to test the performance of two types of irrigation schemes (TDI and RDI). The objectives of this study were to determine the optimum amount and timing of irrigation application to maintain lint yield and economic returns of cotton in South Texas, and to develop recommendations for irrigation scheduling that have the potential to maintain sustainability in Southwest Texas cotton production.

MATERIALS AND METHODS

Experimental Design. A field experiment was conducted at the Texas AgriLife Research and Extension Center at Uvalde (29°13′03″N, 99°45′26″E, 283 m ASL) in the summers of 2008 and 2009 under a center pivot irrigation system. The soil type in the experimental field of the research farm was Uvalde silty clay loam (Fine-silty, mixed, active, hyperthermic Aridic Calciustolls) (Ko and Piccinni, 2009).

Plots were established within a quarter section (91° wedge, ~ 4.7 ha) of a center pivot field (~250 m in diameter) in 2008 and rotated to another quarter in 2009 to avoid problems associated with continuous cropping of cotton. A strip-plot design was assigned to the experimental field with seven irrigation treatments and four upland cotton varieties that were replicated four times along the center pivot spans (Fig. 1). Irrigation treatments were applied by a center pivot with a low energy precision application (LEPA) system (Lyle and Bordovsky, 1981) with an irrigation efficiency of 95%. The irrigation treatments were applied to seven equally divided wedges (13° each) within the quarter section of the field. Radially, the field was further divided into five sections (called spans) delineated by the five tire-tracks formed by the irrigation spans themselves, such that each was approximately 50 m in width. The inner span closest to the pivot point, i.e. the first span, and the area outside the fifth span served as buffer zones to avoid disturbance from routine farm maintenance activities. The second through fifth spans were used as four blocks (four replications). Within each span, the field was bedded in a circle with 48 rows, which were divided into four 12-row plots, and four cotton varieties were assigned to these plots randomly.

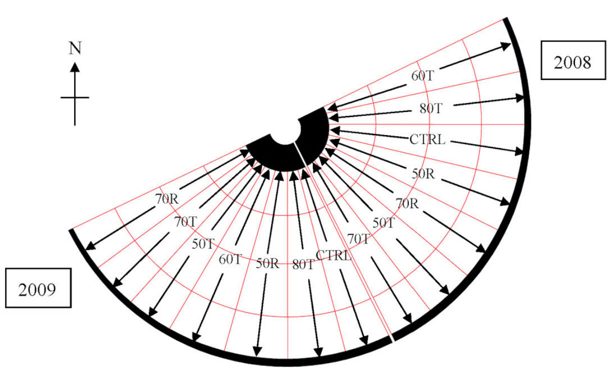

Figure 1. Field layout of experimental treatments including: control (CTRL), four traditional deficit irrigation treatments (80T, 70T, 60T, and 50T), and two regulated deficit irrigation treatments (70R and 50R).

Multiple varieties were chosen to test irrigation effects on a diverse array of genotypes for the production region. The commercial varieties selected were predicted to be the best adapted to this region for each year: ‘DP164’, ‘DP555’, ‘FM0989’ and ‘FM9063’ in 2008, and ‘DP555’, ‘DP935’, ‘DP949’ and ‘FM9180’ in 2009. These varieties were planted on 15 April 2008 and 20 April 2009, and harvested on 22 September 2008 and 25 September 2009. All other agronomic inputs, such as pesticides, herbicides, and fertilizers, were applied based on the extension recommendations for the study area.

Irrigation Scheduling. The irrigation scheduling in this study was based on the daily crop evapotranspiration (ET_c) of the well-watered crop, which was calculated as the product of the daily reference evapotranspiration (ET_o) and the related cotton crop coefficient (K_c) determined at Uvalde (Ko and Piccinni, 2009; Ko et al., 2009). The ET_o was reported daily on the PET network website of the Winter Garden area. In the full irrigation scheme (CTRL), the cumulative water loss (CWL) on the n^{th} day after the last irrigation application was computed as:

$$CWL_{(CTRL)n} = CWL_{(CTRL)n\text{-}1} + ET_C - P \qquad [1]$$

where $CWL_{(CTRL)n}$ and $CWL_{(CTRL)n\text{-}1}$ are cumulative water loss on the n^{th} and $(n\text{-}1)^{th}$ day, respectively; P is precipitation received on the n^{th} day.

For the deficit irrigation treatments, a deficit ratio (r_d) was applied to the daily ET_c, and the residual terms remained the same:

$$CWL_{(deficit)n} = CWL_{(deficit)n\text{-}1} + r_d \times ET_C - P \qquad [2]$$

Notice that Equation 2 was used to calculate suboptimal irrigation amounts for both TDI and RDI treatments. In TDI schemes, r_d was fixed through the entire growing season; in RDI schemes, r_d was adjusted based on the growth stages. For Equations 1 and 2, where calculated CWL values became negative (due to excessive precipitation), CWL was reset to zero for that day, because the excessive water would not be stored in the soil when the soil moisture exceeded its field capacity. When CWL of the CTRL reached a preset critical value (25.4 mm), irrigation was triggered and each treatment was compensated according to its CWL. The crop ET of the irrigation day was estimated based on the previous day’s ET and then added into the irrigation amount. On the next day the “actual” ET value of the irrigation day was calculated, and the

CWL was adjusted accordingly and accumulated from then on.

Besides the control, four TDI and two RDI treatments were selected to evaluate the effects of two types of deficit irrigation. The TDI treatments included 80%, 70%, 60%, and 50% of ET_c (80T, 70T, 60T, and 50T), which means the r_d values were 0.8, 0.7, 0.6, and 0.5 for the entire growing season, respectively. The RDI treatments in this study involved application of water during the following three morphological stages: planting to first flower (S1), first flower to 25% open boll (S2), and 25% open boll to 75% open boll (S3). In 2008 and 2009, the inception of S2 was 13 June and 19 June, respectively, and the inception of S3 was 14 August and 1 August, respectively. The two RDI treatments were 70R and 50R, indicating the deficit ratios in S1 were 0.7 and 0.5, respectively (Table 1). During S2, the deficit ratios for both RDI treatments were set to 1.0; during S3 the deficit ratios were reduced to 0.1 for both treatments. After 75% open boll (S4), the irrigation was terminated for all seven treatments (Table 1).

Soil Moisture. Soil moisture differences among irrigation treatments were measured using a neutron probe in 2008 and a capacitance probe in 2009. In 2008, two weeks after planting, one soil access tube (7 irrigation treatments × 4 varieties × 4 replications = 112 total tubes) was installed in the center of each plot for soil moisture monitoring. A neutron hydroprobe (530DR Hydroprobe, Campbell Pacific Nuclear Corp. Int. Inc., Pacheco, CA) was used to measure the count ratios at seven depths (20, 40, 60, 80, 100, 120, and 140 cm). The count ratios were measured seven times (19, 26, and 30 June; 10, 18, and 28 July; 5 August) and all count ratios were converted to volumetric water content (in percentage) using a group of linear equations obtained through neutron probe calibration (Ko, unpublished data). Due to changes in the regulations regarding the neutron probe, soil moisture was measured in 2009 using a Profiler capacitance probe (type PR2, Delta-T Device Ltd., Cambridge, UK) and an associated moisture meter (HH2, Delta-T Device Ltd., Cambridge, UK) that served as a data logger. Use of the capacitance probe allowed more frequent soil moisture measurement due to the faster data acquisition procedure of the capacitance probe. The same number of PR2 access tubes were installed in the center of each plot as with the neutron probe accessing tubes. The PR2 readings were measured 11 times (23, 26, and 29 June; 6, 10, 13, 23, 27, and 29 July; 5 and 12 August) at seven depths (10, 20, 30, 40, 60, 80, and 100 cm).

Lint Yield and Quality. To determine the lint yield in each irrigation treatment/variety combination, 12-m^2 areas were randomly selected in each experimental plot and all seed cotton was harvested with a two-row cotton picker (C-622 with customized platform; Case IH USA, Racine, WI). After weighing the seed cotton samples, 150- to 200-g subsamples were taken randomly from each harvested sample sack and then table ginned (using a research tabletop gin with 10 saw blades; Dennis Manufacturing Company, Athens, TX) to determine the lint percentage; this percentage was used to estimate lint yield (in $kg\cdot ha^{-1}$) in each plot .

The ginned samples were sent to the Fiber and Biopolymer Research Institute (Texas Tech Univ., Lubbock, TX) for USDA standard HVI tests. The micronaire, fiber length, fiber uniformity index, fiber strength, elongation, fiber grayness, and fiber yellowness were analyzed.

Calculation of Economic Returns. A general financial budget model for cotton production can be described as follows (based on one hectare) using basic microeconomic theory:

1. The profit (PF) is the difference between the revenue (REV) and the total cost:
2. (TC): PF = REV– TC.
3. The gross income is the production of the current lint price (p_L) and the lint yield: (LY): REV = $p_L \cdot$LY.

Table 1. Deficit ratios (r_d) of each irrigation treatment during different cotton growth stages. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively

Growth Stage	r_d						
	CTRL	80T	70T	60T	50T	70R	50R
Planting to 1st Flower (S1)	1.0	0.8	0.7	0.6	0.5	0.7	0.5
1st Flower to 25% Open Boll (S2)	1.0	0.8	0.7	0.6	0.5	1.0	1.0
25% Open Boll to 75% Open Boll (S3)	1.0	0.8	0.7	0.6	0.5	0.1	0.1
75% Open Boll onwards (S4)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

4. The total cost includes two portions: fixed cost (FC) and variable cost (VC). The fixed cost is associated with the equipment depreciation and field management, which is not a function of the irrigation water and does not change among different irrigation treatments. The variable cost is the product of the water price (including electricity cost) (p_W) and the irrigated water amount (WI). Thus:
5. $TC = FC + VC = FC + p_W \cdot WI$.
6. According to (1) through (3), the model can be rewritten as:

$$PF = p_L \cdot LY - p_W \cdot WI - FC. \quad [3]$$

The base lint price was set to $1.44/ kg, and the water price was $0.15/ m^3, as reported by Dagdelen et al. (2009). The lint price was adjusted based on lint quality parameters using the USDA published loan rate table (USDA-FSA, 2009). The FC was estimated to be $750/ha in this study, based on the 2007 to 2009 balance sheets of some farms in nearby counties (data not published). However, because FC was not a function of WI, the value per se had no impact on the selection of irrigation regime. Using Equation 3 and inserting the values stated above, we calculated the PF of each plot on a 1-ha basis.

Data Analysis. The lint yield, lint quality, profit, as well as volumetric soil water content data were analyzed using PROC GLM (for MANOVA and homoscedasticity tests) and PROC MIXED in SAS 9.2.1 (SAS, Inc., Cary, NC), against irrigation treatments, varieties, and irrigation-variety interaction. The mean separation results were computed using a macro named pdmix800, which was updated by Saxton (see http://animalscience.ag.utk.edu/FacultyStaff/ArnoldSaxton.html) based on pdmix612 (Saxton, 1998). Both equal and unequal variance situations were considered and the best model was selected based on the Akaike Information Criterion (AIC) values. Furthermore, the Pearson's correlation coefficients between lint yield and soil moisture at each soil depth for each measurement were calculated using PROC CORR in SAS 9.2.1 (SAS, Inc., Cary, NC).

RESULTS AND DISCUSSION

Environmental Patterns and Volumetric Soil Water Content. The daily temperatures of the 2008 growing season (Fig. 2A) were generally lower than the daily temperatures of the 2009 season (Fig. 2B). The maximum daily temperatures between 15 June and 15 August 2009 were consistently 38 to 40°C, which were approximately 2 to 3°C higher than the maximum daily temperatures of the same duration in 2008. Compounding the high temperatures, total precipitation of both years was lower than the 30-yr average of the study area. Precipitation received during the 2008 growing season was approximately 20% less than the 30-yr average (Ko and Piccinni,

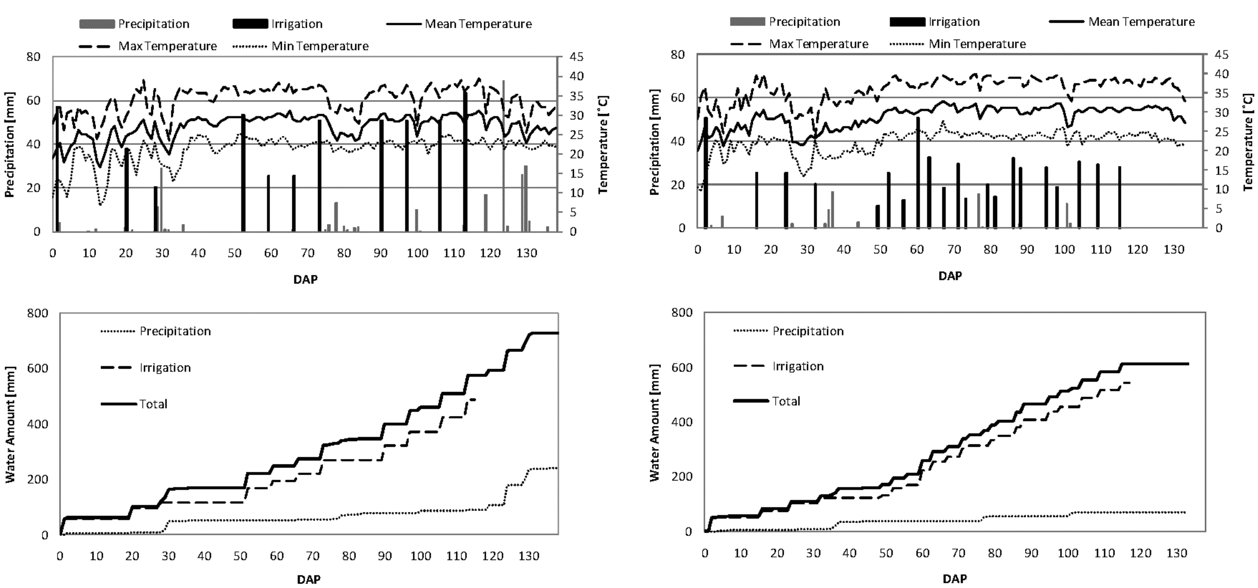

Figure 2. Climatic conditions and water input components (precipitation and irrigation) in 2008 and 2009 during the growing season. The top two graphs illustrate the maximum/ minimum/ average daily temperatures, daily precipitation and irrigation amounts in 2008 and 2009, respectively. The bottom two graphs show the cumulative precipitation, irrigation, and total water received in the field during the growing seasons of 2008 and 2009, respectively.

2009) (Table 2) with peak events occurring in mid-May, early-July, and late-August (including two excessive events, which were 68.6 and 61.0 mm, respectively), making a marked contribution to the cotton water demand. Much less rainfall occurred in the 2009 growing season (approximately a quarter of the 30-yr average), and a major portion of the total precipitation occurred before 50 d after planting (DAP) (approximately the first flower stage). It is likely that not all precipitation received during the growing season was used by plants because once soil moisture reaches field capacity, the excess precipitation goes to deep drainage (and in some cases runoff as well in the field with slope) and would not be held in the soil. This implies the total water consumption by plants in the CTRL was less than the sum of the applied irrigation water and precipitation because only part of precipitation is stored in the soil for plant to use. In both years, the actual total water consumption by plants in the CTRL was 594 and 560 mm, respectively (the sum of irrigation and precipitation that was actually used; see Table 2). Also, due to technical problems, the 60T treatment in 2008 received more irrigation than the planned amount. All data associated with this treatment in 2008 were thus excluded in the statistical analysis.

The volumetric soil water content was shown at four different soil depths: 20, 40, 60, and 100 cm. Three treatments [CTRL, TDI (50T) and RDI (70R) schemes] were selected for comparison (Figs. 3 and 4) to better demonstrate the soil moisture differences. In 2008, the highest soil water content fluctuation was found at the 20-cm layer (Fig. 3). In general, slight decreasing trends in soil moisture over the growing season could be observed at all four soil depths. The largest differences between the CTRL and the most severe water deficit treatment, 50T, were seen at the 20- and 40-cm depths, indicating a difference in water application and perhaps crop water use. Temperatures were also much higher in 2009 as compared to 2008, which could have caused greater water consumption by plants and loss in the soil, as evidenced by larger differences among treatments in soil moisture in 2009 (Fig. 4). In general, the 70R treatment showed intermediate soil moisture levels between the CTRL and the 50T treatments at all soil depths. Only at the 40-cm depth did the 70R treatment show lower soil water content than the other two treatments. This might indicate a major portion of plant water uptake by the 70R plants occurred at the depth between 40 and 60 cm.

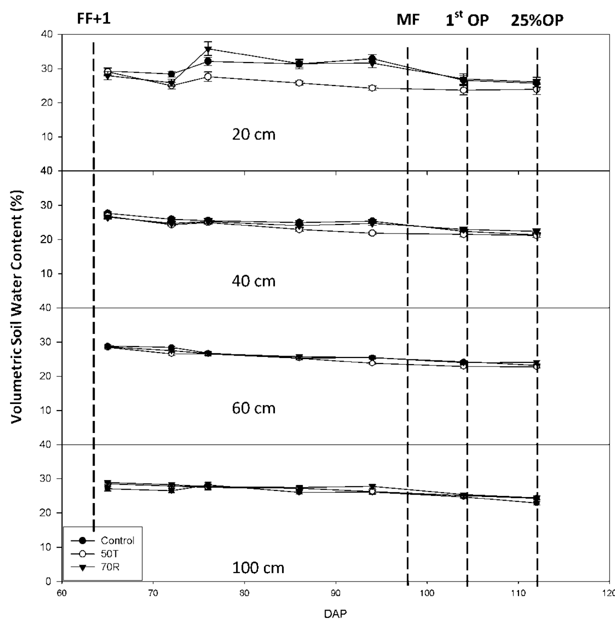

Figure 3. Relative volumetric soil water content at depths of 20, 40, 60, and 100 cm during the 2008 growing season. FF+1, MF, 1st OP, and 25% OP signify 1 wk after first flower, maximum flower, first open boll, and 25% open boll, respectively. DAP signifies day after planting.

Table 2. Irrigation applied in each treatment and total precipitation during the cotton growing seasons in 2008 (15 April to 31 August) and 2009 (20 April to 31 August) at Uvalde, TX. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively

Year	Irrigation Applied							Precipitation	Total Crop Water Use of CTRL
	CTRL	80T	70T	60T	50T	70R	50R		
	mm							mm	mm
2008	429	337	283	> 245^y	189	337	315	241	594
2009	492	390	315	266	222	358	334	68	560
30-year^z	-	-	-	-	-	-	-	315	-

^z According to Ko and Piccinni (2009). The duration used to calculate the 30-year (1971-2000) annual mean precipitation was from 23 April to 10 September.

^y The 60T treatment was excluded from the analysis.

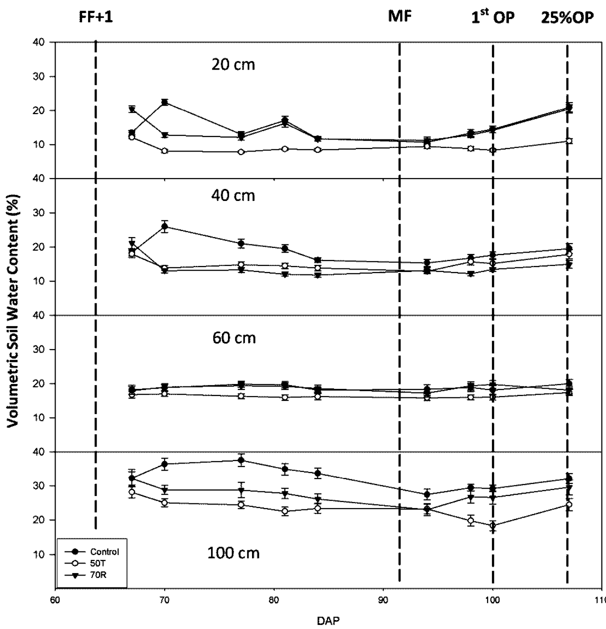

Figure 4. Relative volumetric soil water content at depths of 20, 40, 60, and 100 cm during the 2009 growing season. FF+1, MF, 1st OP, and 25% OP signify 1 wk after first flower, maximum flower, first open boll, and 25% open boll, respectively. DAP signifies day after planting.

Lint Yield and Percentage. The varieties that produced the highest lint yields in 2008 and 2009 were DP555 (1,446 kg·ha^{-1}) and DP935 (1,598 kg·ha^{-1}), respectively (Table 3). Because different varieties were grown in 2008 and 2009, and considering that the interaction of irrigation and variety was not significant in either year, the irrigation effects for each year are discussed separately. In 2008, the lint yields of the 80T treatment (1,243 kg·ha^{-1}) and the CTRL (1,312 kg·ha^{-1}) were not significantly different, but both were significantly higher than the lint yields of the 70T and 50T treatments. The 70R treatment produced 1,152 kg·ha^{-1} lint, which was not significantly different from the lint yield of the CTRL; the 50R treatment, however, showed a significantly reduced lint yield of approximately 1,039 kg·ha^{-1} or 21% less than the lint yield of the CTRL. In 2009, the CTRL yielded 2,022 kg·ha^{-1}, which was significantly higher than the lint yield of all TDI treatments. Within the TDI treatments, the lint yields of the 80T and 70T treatments were not significantly different (1,509 and 1,335 kg·ha^{-1}, respectively), and both were significantly higher than that of the 60T and 50T treatments. Both the 70R and 50R treatments showed significantly lower lint yield (approximately 28% and 33% less, respectively) compared to the CTRL across all varieties. Two varieties (DP555 and DP935) demonstrated similar patterns to those detected in 2008, with both the 80T and 70R treatments having lint yields similar to the CTRL. The other two varieties showed significantly reduced lint yields in comparison to the CTRL by as much as 30 to 40% in the 80T and 70R treatments, indicating both irrigation treatments were inadequate for these two varieties.

A previous study at the same site in Uvalde, TX showed that a 75% ET irrigation replacement regime (i.e., 75T in our TDI scheme) yielded similarly compared to the fully irrigated treatment (equivalent to the CTRL in this study) (Falkenberg et al., 2007). Thus, it seems that the threshold deficit ratio for a TDI scheme falls between 0.70 and 0.75 for cotton production in Southwest Texas under a LEPA sprinkler irrigation system. Because the 70R treatment in our study also performed well in maintaining lint yields in some of the cotton varieties, RDI might be a productive and possibly less extreme alternative to the TDI scheme for water savings.

Singh (2007) summarized several studies (Oosterhuis, 1999; Reddy et al., 1992a, 1992b; Singh, 2007; Snider, 2009) and concluded that cotton plants have an optimal temperature range around 30°C for growth and development. However, he argued that the optimal temperature might be variety specific. This argument might explain the differences among varieties for lint yield in 2009. The separation of the yield patterns in 2009 implies that some cotton varieties (e.g., DP164 and FM9180) might not respond to a deficit irrigation scheme well enough under hot and dry climatic conditions (such as the 2009 summer) to maintain lint yield.

In both years, the highest lint percentages were observed in DP555, which were 46.4% of the seed cotton yield in 2008, and 48.7% of the seed cotton yield in 2009 (Table 4). No significant irrigation or irrigation-by-variety interaction was detected. However, the minimum irrigation treatment in our study was 50% ET replacement; below this level of irrigation, varietal response might become separated as seen in other studies. Pettigrew (2004) reported that two out of eight cotton varieties had variation in lint percentage responses between irrigated and dryland treatments, which in general were less than 50% ET. Meng et al. (2008) also showed that under severe water deficits (less than 50% ET), lint percentage increased, whereas no significance was detected between moderate or slightly stressed and stress-free treatments. Thus, at least for the current study's moderate level irrigation treatments (i.e., 80T and 70R), the influence on lint percentage appears to be negligible.

Table 3. Lint yield means in 2008 and 2009. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively

	Lint Yield							
	2008				2009			
	kg·ha^{-1}				kg·ha^{-1}			
BY VARIETY	DP555	DP164	FM0989	FM9063	DP935	DP555	FM9180	DP949
CTRL	1952.1 A^z	1247.8 A	1041.9 A	1006.1 AB	2290.8 A	1870.8 A	1857.3 A	2069.0 A
80T	1712.6 AB	1247.6 A	1018.6 A	991.6 AB	1814.0 AB	1471.5 AB	1282.5 B	1466.7 AB
70T	1151.3 BC	918.0 AB	732.8 B	765.6 ABC	1518.2 BC	1483.4 AB	1138.9 B	1199.8 B
60T	- -	- -	- -	- -	1224.1 BC	759.6 C	835.2 B	973.1 B
50T	984.1 C	747.6 B	643.3 B	587.4 C	967.8 C	783.6 C	862.0 B	874.2 B
70R	1345.6 ABC	1111.8 AB	1102.6 A	1045.9 A	1642.1 ABC	1710.2 AB	1205.3 B	1254.5 B
50R	1653.6 AB	943.8 AB	842.6 AB	715.8 BC	1732.2 AB	1310.5 B	1105.4 B	1296.4 B
MEANS ACROSS MAIN FACTORS								
Irrigation	CTRL	1312.0 A			CTRL	2022.0 A		
	80T	1242.6 AB			80T	1508.7 B		
	70T	891.9 C			70T	1335.1 B		
	60T	- -			60T	948.0 C		
	50T	740.6 D			50T	871.9 C		
	70R	1151.5 AB			70R	1453.0 B		
	50R	1038.9 CD			50R	1361.1 B		
Variety	DP555	1446.4 A			DP935	1598.4 A		
	DP164	1042.8 B			DP555	1341.4 B		
	FM0989	892.6 BC			FM9180	1304.8 B		
	FM9063	860.3 C			DP949	1183.8 B		
ANOVA		Pr > F				Pr > F		
	Irrigation (I)	< 0.01 **			Irrigation (I)	< 0.01 **		
	Variety (V)	< 0.01 **			Variety (V)	0.013 *		
	I × V	0.99 ns			I × V	0.90 ns		

**: highly significant ($p < 0.01$). *: significant ($p < 0.05$). ns: not significant.

^{z} Mean values with the same letter group were not significantly different from each other by column.

Table 4. Lint percentage for varieties in 2008 and 2009

2008				2009			
Variety		Lint Percentage %		Variety		Lint Percentage %	
	DP555	46.4	A^z		DP555	48.7	A
	FM0989	41.0	B		DP949	47.7	B
	DP164	40.3	BC		DP935	47.6	B
	FM9063	39.6	C		FM9180	43.1	C
ANOVA		Pr > F		ANOVA		Pr > F	
	Irrigation (I)	0.74	ns		Irrigation (I)	0.30	ns
	Variety (V)	< 0.01	**		Variety (V)	< 0.01	**
	I × V	0.91	ns		I × V	0.51	ns

**: highly significant ($p < 0.01$). *: significant ($p < 0.05$). ns: not significant.

^{z} Mean values with the same letter group were not significantly different from each other.

Lint Quality. The MANOVA results of the lint quality parameters in this study showed that both irrigation ($p < 0.01$ for 2008 and 2009) and variety ($p < 0.01$ for 2008 and 2009) effects were significant, whereas the interaction of these two factors was not significant. Thus, only the effects of the two main factors are discussed for each separate year.

The lint quality characteristics tended to decrease with increasing water deficit severity in the TDI treatments in 2008 (Table 5). The micronaire values ranged from 4.86 to 5.07. No significant differences of micronaire values were detected between the TDI/RDI treatments and the CTRL. For the other lint quality parameters, most significant differences were between the 50T treatments and the CTRL. The 50T treatment showed significantly shorter fibers (0.03 mm decrease) than the CTRL (1.14 mm); and fiber strength of the 50T treatment was 275 $kN \cdot m \cdot kg^{-1}$, which was significantly lower than the fiber strength of the CTRL (284 $kN \cdot m \cdot kg^{-1}$). The grayness of the 50T treatment was approximately 62.5% Rd, which was significantly lower than the value of CTRL (65.5% Rd). For yellowness, the 50T treatment showed a significantly higher value (8.10) than the CTRL (7.66). No other significant difference was found between the TDI/RDI treatments and the CTRL.

In 2009, there were few differences among irrigation treatments for fiber quality traits. The TDI treatments showed decreasing trends with water deficit severity except for grayness and yellowness (Table 5). The micronaire ranged from 4.78 to 5.06, with the highest micronaire value for the 50R treatment (5.06), which was significantly higher than the CTRL value (4.78). The fiber length, uniformity, fiber strength, and elongation of the CTRL were significantly greater than all other treatments. The grayness of the CTRL and the 50T treatments was the lowest (51.75% Rd) and the highest (58.61% Rd), respectively, and 70R and 50R treatments showed significantly higher grayness than the CTRL. For yellowness, the 70T, 50T, and 70R treatments demonstrated significantly higher values (~7.3) than the CTRL (~7.0).

In general, the response of lint quality to irrigation treatment in our study was quite stable in both 2008 and 2009. The numerical trend is obvious: the less water applied, the lower the fiber quality. The largest differences detected in fiber quality parameters were between the 50T and the CTRL treatments, indicating the 50T treatment has a greater risk in reducing fiber quality than other irrigation treatments in this study. In contrast, Pettigrew (2004) reported inconsistency in the response of fiber quality to irrigation treatments, which might be attributed to the inconsistent

Table 5. The effect of irrigation treatments on fiber quality parameters. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively

Year	Variety	Micronaire		Length		Uniformity		Strength		Elongation		Grayness		Yellowness	
		--		--mm--		--		-$kN \cdot m \cdot kg^{-1}$-		--		%Rd		Hunter's +b	
2008															
	CTRL	5.01	AB[z]	1.14	A	82.16	ABC	284.60	AB	6.28	A	65.48	A	7.66	BC
	80T	5.00	AB	1.12	AB	81.76	BC	281.85	ABC	6.31	A	65.19	A	7.75	ABC
	70T	4.89	AB	1.13	AB	81.61	C	280.48	ABC	6.24	A	64.40	AB	7.66	BC
	60T	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	50T	4.86	B	1.11	B	81.71	C	275.87	C	6.29	A	62.51	B	8.10	A
	70R	5.00	AB	1.14	A	82.63	A	287.93	A	6.14	A	65.31	A	7.61	C
	50R	5.07	A	1.14	A	82.56	AB	284.01	ABC	6.25	A	64.44	AB	7.80	ABC
2009															
	CTRL	4.78	B	1.09	A	81.56	A	273.52	AB	6.03	A	51.75	D	7.03	C
	80T	4.83	AB	1.06	BC	80.98	AB	274.30	AB	5.89	AB	55.99	BC	7.05	BC
	70T	4.89	AB	1.04	CDE	80.79	AB	264.89	BC	5.73	AB	55.94	BC	7.32	A
	60T	4.96	AB	1.04	DE	80.53	B	269.89	ABC	5.89	AB	57.88	AB	7.23	ABC
	50T	4.83	AB	1.03	E	80.61	B	260.28	C	5.66	B	58.61	A	7.33	A
	70R	5.01	AB	1.06	BCD	80.91	AB	273.91	AB	5.98	AB	55.66	C	7.30	AB
	50R	5.06	A	1.07	B	81.54	A	278.91	A	5.98	AB	55.79	C	7.14	ABC

[z] Mean values with the same letter group were not significantly different from each other.

precipitation total among different growing seasons under dryland conditions in that study.

It should be emphasized that although some significant differences were detected among irrigation treatments and varieties in our study, the variation of each lint quality parameter did not introduce significant premiums or discounts that caused the lint prices to differ, according to the 2008 and 2009 loan rate references of upland cotton (USDA-FSA, 2009).

Economic Returns. The results of mean comparisons by variety, and across variety and irrigation treatment in both growing seasons (Table 6) showed that in 2008, the 80T treatment produced the highest profit ($574.96 ha^{-1}). Compared to the profit of the CTRL treatment ($460.63 ha^{-1}), the profit obtained from the 70R and 50R treatments ($414.77 ha^{-1} and $321.26 ha^{-1}, respectively) were not significantly different. The 70T treatment showed a significantly lower profit ($135.08 ha^{-1}) than the profit of the CTRL. However in 2009, the CTRL showed a significantly higher profit ($1423.23 ha^{-1}) than all the other treatments. The profit of the 70T treatment ($699.96 ha^{-1}) was not significantly different from the profit of the 80T treatment ($838.02 ha^{-1}). Further, profit for the 80T treatment was not significantly different from either RDI treatments (70R: $800.86 ha^{-1} and 50R: $708.92 ha^{-1}). These economic results indicate that the 80T and 70R treatments are likely to maintain profits similar to full irrigation under years with typical (non-severe) climatic conditions. The 50R

Table 6. Profit means by variety, across variety and irrigation in 2008 and 2009. The values of the 60T treatment in 2008 were excluded from the analysis

	Lint Yield							
	2008				2009			
	$ ha^{-1}				$ ha^{-1}			
BY VARIETY	DP555	DP164	FM0989	FM9063	DP935	DP555	FM9180	DP949
CTRL	1382.40 A[z]	368.25 AB	71.73 A	20.14 B	1810.32 A	1205.57 A	1490.98 A	1186.04 A
80T	1251.79 AB	582.14 A	252.44 A	213.46 A	1277.62 AB	784.46 A	777.61 B	512.37 B
70T	508.63 AB	172.64 B	-94.03 A	-46.19 B	963.66 BC	913.53 A	505.17 BC	417.50 B
60T	- -	- -	- -	- -	613.12 BC	-55.76 B	251.80 BC	53.16 B
50T	397.77 B	57.18 B	-93.05 A	-173.61 B	309.86 C	44.64 B	175.13 C	157.45 B
70R	1206.35 AB	357.62 AB	344.40 A	262.77 A	1073.08 B	1171.20 A	514.98 BC	444.18 B
50R	694.31 AB	184.28 B	38.53 A	-144.12 B	1243.29 AB	635.97 AB	615.74 BC	340.66 B
MEANS ACROSS MAIN FACTORS								
Irrigation	CTRL	460.63 A			CTRL	1423.23 A		
	80T	574.96 A			80T	838.02 B		
	70T	135.08 BC			70T	699.96 B		
	60T	- -			60T	215.58 C		
	50T	47.07 C			50T	171.77 C		
	70R	414.77 A			70R	800.86 B		
	50R	321.26 AB			50R	708.92 B		
Variety	DP555	906.87 A			DP935	1041.57 A		
	DP164	287.02 B			DP555	671.37 A		
	FM0989	86.67 B			FM9180	618.77 A		
	FM9063	21.96 B			DP949	444.48 A		
ANOVA		Pr > F				Pr > F		
	Irrigation (I)	< 0.01 **			Irrigation (I)	< 0.01 **		
	Variety (V)	< 0.01 **			Variety (V)	0.41 ns		
	I × V	0.32 ns			I × V	0.66 ns		

**: highly significant ($p < 0.01$). ns: not significant.

[z] Mean values with the same letter group were not significantly different from each other by column.

treatment, from an economic perspective, might be able to maintain profits in years with optimal conditions but under hot and dry conditions such as 2009, the maximum profits were seen in the full replacement treatment (CTRL), which was demonstrated in both lint yield and profit comparisons. Using the results of profit analysis seems to be a more reasonable method to evaluate the performance of deficit irrigation regimes due to its inclusive characteristics of yield and irrigation costs.

Correlations Between Volumetric Soil Water Content and Lint Yield. The volumetric soil water content showed differing correlations to lint yield by depth and timing in the two growing seasons (Table 7). In 2008, the soil moisture at the 20-cm depth was significantly correlated with lint yield across the flowering and boll-opening stages (65-112 DAP), whereas at all other deeper depths no significant correlations were observed. In 2009, the soil moisture at the 100-cm depth was significantly correlated with lint yield across the flowering and boll-opening stages (67-114 DAP), whereas at other depths significant correlations existed mainly at 70 DAP (mid-flower stage).

The relatively high daily temperature and low precipitation levels during the growing season of 2009 (Table 2 and Fig. 2) might have encouraged deeper rooting systems, resulting in greater water uptake at these levels and leading to the significant correlations with lint yield for the 100-cm depth. This is not uncommon for many crops, as root growth has been shown to influence production in maize (Comin et al., 2009), chickpea (Kashiwagi et al., 2006), and rice (Henry et al., 2011). Further studies regarding the relationship between soil moisture at different depths and crop yield would be useful to understand how crop yield is affected by soil moisture patterns over the growing season.

CONCLUSION

In this study, four traditional (TDI) and two regulated (RDI) deficit irrigation treatments were evaluated against a full irrigation treatment for lint yield and economic returns among several cotton varieties over two growing seasons. For TDI, the threshold deficit ratio appears to fall between 0.70 and 0.75 of ET_c for lint yield in Southwest Texas under a LEPA sprinkler irrigation system. One RDI treatment, 70R, can also be applied for water savings while maintaining lint yield. The lint yield seemed to be affected by soil water content at different depths, depending on the weather conditions during a particular year. The lint percentage and lint quality showed minor differences between irrigation treatments and/or varieties, but was not sufficient enough to affect the lint price. Because of this, economic returns matched the patterns in lint yield, with the exception of the 50R treatment. In this case, the 50R treatment might be profitable in years with more mild environmental conditions of temperature and rainfall (such as 2008). The approach taken in this

Table 7. Pearson correlation coefficients (r) between the lint yields and the soil moisture at each soil depth

(a) 2008

Soil Depth (cm)	r						
	DAP65	DAP72	DAP76	DAP86	DAP94	DAP104	DAP112
20	ns	0.21*	0.24*	ns	0.23*	ns	0.23*
40	ns	ns	ns	ns	ns	ns	ns
60	ns	ns	ns	ns	ns	ns	ns
100	ns	ns	ns	ns	ns	ns	ns

*: significant (p < 0.05). ns: not significant.

(b) 2009

Soil Depth (cm)	r										
	DAP67	DAP70	DAP77	DAP81	DAP84	DAP94	DAP98	DAP100	DAP107	DAP114	DAP119
20	ns	0.48**	0.20*	0.30**	ns	ns	ns	ns	0.19*	ns	ns
40	ns	0.27**	ns	ns	ns	ns	ns	ns	ns	ns	ns
60	ns	0.22*	ns	ns	ns	ns	ns	ns	ns	ns	ns
100	0.20*	0.36**	0.29**	0.35**	0.28**	ns	0.21*	0.25*	ns	0.22*	ns

**: highly significant (p < 0.01). *: significant (p < 0.05). ns: not significant.

study where both profit and yield were assessed was useful for determining the efficacy of different irrigation treatments because it took into account the pumping costs associated with each treatment. These costs can be considerable and will critically impact the economic returns to the producer. Based on the current results the 80T and 70R treatments could be considered as viable deficit irrigation regimes for most years in this region. The RDI scheme could be further developed in future studies to refine deficit levels and durations for optimal irrigation management recommendations for Southwest Texas.

ACKNOWLEDGMENTS

This study was funded by Monsanto Company, TWRI USGS Graduate Research Grant #USGS-2009TX328B, TWRI Mills Scholarship and Tom B. Slick Graduate Research Fellowship. Submitted to the Texas A&M University as part of a PhD dissertation.

REFERENCES

Chalmers, D.J., and B. Vandenende. 1975. Productivity of peach trees: Factors affecting dry-weight distribution during tree growth. Ann. Bot. 39:423–432.

Chalmers, D.J., and I.B. Wilson. 1978. Productivity of peach trees: Tree growth and water stress in relation to fruit growth and assimilate demand. Ann. Bot. 42:285–294.

Comin, J.J., J. Barloy, V. Hallaire, F. Zanette, and P.R.M. Miller. 2009. Effects of alumnium on the adventitious root system, aerial biomass and grain yield of maize grown in the field and in a rhizotron. Exp. Agric. 42:351–366.

Dagdelen, N., H. Basal, E. Yilmaz, T. Gurbuz, and S. Akcay. 2009. Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey. Agric. Water Manage. 96:111–120.

Ding, L., Z. Cheng, Y. Zhao, and F. Wang. 2007. Influence of regulated deficit irrigation on water consumption rule and water use efficiency of broad bean. Jie Shui Guan Gai [Water Saving Irrigation] 2007-05:27–30.

Du, T.S., S.Z. Kang, J.H. Zhang, F.S. Li, and X.T. Hu. 2006. Yield and physiological responses of cotton to partial root-zone irrigation in the oasis field of northwest China. Agric. Water Manage. 84:41–52.

Falkenberg, N.R., G. Piccinni, J.T. Cothren, D.I. Leskovar, and C.M. Rush. 2007. Remote sensing of biotic and abiotic stress for irrigation management of cotton. Agric. Water Manage. 87:23–31.

Gao, Y.P., Dong, X. Zhang, S. Chen, and M. Liu. 2004. Effects of water deficit on yield and yield components of cotton. Chinese Journal of Eco-Agriculture 12:136–139.

Guo, X., and S. Kang. 2000. After-effect of regulated deficit irrigation (RDI) on maize. Trans. CSAE 16:58–60.

Henry, A., V.R.P. Gowda, R.O. Torres, K.L. Mcnally, and R. Serraj. 2011. Variation in root system architecture and drought response in rice (*Oryza sativa*): Phenotyping of the OryzaSNP panel in rainfed lowland field. Field Crops Res. 120:205–214.

Jones, H.G. 2004. Irrigation scheduling: Advantages and pitfalls of plant-based methods. J. Exp. Bot. 55:2427–2436.

Kang, S., W. Shi, and X. Hu. 1998. The effects of regulated deficit irrigation on physiological parameters and water use efficiency of corn. Trans. CSAE 14:82–87.

Kang, S., W. Shi, and J. Zhang. 2000. An improved water-use efficiency for maize grown under regulated deficit irrigation. Field Crops Res. 67:207–214.

Kashiwagi, J., L. Krishnamurthy, J.H. Crouch, and R. Serraj. 2006. Variability of root length density and its contributions to seed yield in chickpea (*Cicer arietinum* L.) under terminal drought stress. Field Crops Res. 95:171–181.

Ko, J., and G. Piccinni. 2009. Corn yield responses under crop evapotranspiration-based irrigation management. Agric. Water Manage. 96:799–808.

Ko, J., V. Piccinni, W. Guo, and E. Steglich. 2009. Parameterization of EPIC crop model for simulation of cotton growth in South Texas. J. Agric. Sci. 147:169–178.

Lyle, W.M., and J.P. Bordovsky. 1981. Low energy precision application (LEPA) irrigation system. Transactions of the American Society of Agricultural Engineers 26:1241–1245.

Meng, Z., X. Bian, A. Liu, H. Pang, and H. Wang. 2007. Physiological responses of cotton to regulated deficit irrigation and its optimized agronomic techniques. Trans. CSAE 23:80–84.

Meng, Z., X. Bian, A. Liu, H. Pang, and H. Wang. 2008. Effect of regulated deficit irrigation on growth and development characteristics in cotton and its yield and fiber quality. Cotton Sci. 20:39–44.

Oosterhuis, D.M. 1999. Yield response to environmental extremes in cotton. p. 30–38 *In* D.M. Oosterhuis (ed.) Proc. 1999 Cotton Research Meeting Summary Cotton Research in Progress. Report 193. Arkansas Agric. Exp. Stn., Fayetteville, AR.

Pei, D., X. Zhang, and R. Kang. 2000. Effects of water deficit on cotton growth, physiology and yield. Eco-agriculture Research 8:52–55.

Pettigrew, W.T. 2004. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. Agron. J. 96:377–383.

Reddy, K.R., H.F. Hodges, J.M. Mckinion, and G.W. Wall. 1992a. Temperature effects on pima cotton growth and development. Agron. J. 84:237–243.

Reddy, K.R., H.F. Hodges, and V.R. Reddy. 1992b. Temperature effects on cotton fruit retention. Agron. J. 84:26–30.

Saxton, A.M. 1998. A macro for converting mean separation output to letter groupings in PROC MIXED. Proc. 23rd Annual SAS Users Group International Conf.:1243–1246, 1626.

Singh, R.P. 2007. Influence of high temperature and breeding for heat tolerance in cotton: A review. Adv. Agronomy 93:73.

Snider, J.L. 2009. Heat stress-induced limitations to reproductive success in *Gossypium hirsutum L.* Physiol. Plant. 137:125–138.

Tan, G., L. Zhao, L. Zhang, H. Zhao, X. Fang, X. Meng, W. Yan, C. Xu, X. Han, and S. Bian. 2009. Researches on regulated deficit irrigation at seeding stage of maize. J. Jilin Agric. Sci. 34:3–5.

Tang, L.S., Y. Li, and J.H. Zhang. 2005. Physiological and yield responses of cotton under partial rootzone irrigation. Field Crops Res. 94:214–223.

USDA-FSA, 2009. Online loan rate. Currently only 2010-2012 loan rate sheets are available at http://www.apfo.usda.gov/FSA/webapp?area=home&subject=prsu&topic=lor. Historical data of 2008 and 2009 loan rate can be found at http://www.cottoninc.com/fiber/AgriculturalDisciplines/AgriculturalEconomics/Cotton-Farming-Decision-Aids/ and check 2008/2009 Cotton Loan Valuation Model.

Zhang, B.C., F.M. Li, G.B. Huang, Z.Y. Cheng, and Y.H. Zhang. 2006. Yield performance of spring wheat improved by regulated deficit irrigation in an arid area. Agric. Water Manage. 79:28–42.