COTTON PRODUCTION UNDER TRADITIONAL AND REGULATED DEFICIT IRRIGATION SCHEMES IN SOUTHWEST TEXAS

A Dissertation

by

YUJIN WEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2011

Major Subject: Agronomy

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ABSTRACT

Cotton Production under Traditional and Regulated Deficit Irrigation Schemes in Southwest Texas. (August 2011)

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The urban water demand in Southwest Texas has grown rapidly in recent years due to the population increases in urban areas, which caused conflict between municipal and agricultural water use. Deficit irrigation is one important measure for solving this problem. A field experiment with seven different irrigation treatments and four cotton varieties was conducted at the Texas AgriLife Research and Extension Center at Uvalde in the summers of 2008 and 2009 to examine the water saving potential and related phenological/ physiological responses in Southwest Texas. The results showed that: 1) The threshold deficit ratio for a traditional deficit irrigation scheme falls between 0.7 and 0.8 for cotton production in Southwest Texas under a low energy precision application (LEPA) sprinkler irrigation system. The 70% evapotranspiration (ET)-initialled regulated deficit irrigation scheme (70R) performed well in maintaining lint yield in most cotton varieties tested. The significant changes detected in lint quality failed to introduce premiums or discounts in cotton price. 2) The phenological parameters (plant height, node number and flower/fruit number) showed clear trends that illustrate the relationship between increased stress level and decreased plant growth and development. The observed inconsistency of the physiological responses in the two growing seasons may imply that physiological parameters are not good direct predictors of lint yield if measurements are conducted only on a point basis. The partitioning coefficients of boll dry weight in both years failed to show a significant difference between deficit irrigation treatments and the control, indicating that reallocation of carbohydrates may not be the major factor of maintaining lint yield for the deficit irrigation treatments. 3) Economic analysis showed that due to the low water price, it is not currently profitable to adopt deficit irrigation. In case that water price is increased, it may become more profitable to adopt deficit irrigation. This work provides reference information to water authorities and policy makers to set quotas for municipal and agricultural water use and to value water properly through setting different water prices.

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NOMENCLATURE

AIC	Akaike Information Criterion
A_n	net carbon assimilation rate
ANOVA	analysis of variance
ASL	above sea level
CTRL	control, or the full irrigation scheme
CWL	cumulative water loss
DAP	day after planting
$ET_{(i)}$	evapotranspiration at stage i
ET	evapotranspiration
ET_c	crop evapotranspiration
ET_o	reference evapotranspiration
FC	fixed cost
GLM	general linear model
HVI	high volume index
I_o	total irrigation amount of the CTRL
I_t	total irrigation amount of the TDI treatment
K_c	crop coefficient
LEPA	low energy precision application
LY	lint yield
MANOVA	multivariate analysis of variance

P	precipitation
P_e	effective precipitation
PF	profit
p_L	lint price
p_W	water price
r_d	deficit ratio
$\bar{r}_d$	average deficit ratio
RDI	regulated deficit irrigation
r_i	irrigation efficiency
TC	total cost
TDI	traditional deficit irrigation
Tr	transpiration rate
USDA	United States Department of Agriculture
VC	variable cost
WI	irrigated water amount
WUE	water use efficiency
WUE_i	instantaneous water use efficiency
φ_r	actual water saved from RDI treatment
φ_t	actual water saved from TDI treatment

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CHAPTER I

INTRODUCTION

The urban water demand in Southwest Texas has been increasing rapidly in recent years due to the population increases in urban areas. Since the water resources in this area are limited, it is crucial to create 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. In order to maintain crop production and the farmers' profit, water needs to be applied wisely for more economic return per unit consumption (i.e., higher agricultural water use efficiency/ higher water productivity). This improved irrigation scheduling plan for Southwest Texas will in turn maximize the whole community's benefit. However, in order to achieve these benefits well-designed on-farm research is needed.

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 one method that can be implemented easily. This method calculates soil moisture deficit (i.e., the net water loss through ET) and uses detailed 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

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The format and style of this dissertation follow Crop Science.

Texas with support of well-maintained reference ET networks, as for example, the Texas High Plains ET Network (TXHPET) and the Precision Irrigators Network (PIN). 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, 2009b). In their studies, 75% ET was reported to be a good deficit irrigation alternative to the full irrigation without reducing crop yields. However, since only two deficit irrigation treatments (75% and 50% ET) were examined in these studies, the appropriate level of TDI for maintaining crop production in this region remains unclear. In addition, crop ET and precipitation amount vary over growing seasons, thereby greatly influencing the required irrigation amounts. Consequently, the actual water saved on irrigation through a TDI scheme differs from year to year, which is rarely discussed quantitatively. From an economic aspect, the decision of irrigation scheduling should be based on the profit instead of total crop production, an issue which is seldom mentioned in deficit irrigation studies. Yield quality is another key factor that influences profit, and needs to be integrated into an overall evaluation of an irrigation scheduling system.

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 may not be optimal, because plants show different sensitivity to drought stress in these stages (Meng et al., 2007). In a stage that the crop is highly sensitive to water deficit, the TDI scheme is likely to introduce severe drought stress and cause significant yield loss in the end. Regulated deficit irrigation (RDI) is an alternative irrigation scheduling scheme to TDI and was started in the 1970's in Australia (Meng et al., 2007). The first application of an RDI scheme was on peach trees (*Prunus persica*) to improve water use efficiency (WUE) 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 different 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 calculation is involved in the RDI scheme; thus intensive irrigation management is 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 were 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*) (Zhang et al., 2006) and broad beans (*Vicia faba*) (Ding et al., 2007). However, similar studies in the US, especially in Texas, are rarely found. Since 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.

In this study, one of the major agronomic crops – cotton – in Southwest Texas is chosen to test the performance of two types of irrigation schemes (TDI and RDI). The objectives of this study were to: 1) determine the optimum amount and timing of irrigation application to maintain yield and quality of cotton production in Southwest Texas; 2) detect levels of plant stress among irrigation treatments using measurements of crop carbon assimilation, water use and phenology, and discuss the possible allocation change of the assimilated carbon to the vegetative and reproductive organs, and 3) develop recommendations for irrigation scheduling that maximize profitability and sustainability in Southwest Texas cotton production.

CHAPTER II

MATERIALS AND METHODS

Experimental Design

A field experiment was conducted at the Texas AgriLIFE Research and Extension Center at Uvalde (29^{o}13'03"N, 99^{o}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, 2009b).

Plots were established within a quarter section (91^{o} 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 with an irrigation efficiency of 95%. The irrigation treatments were applied to seven equally divided wedges (13^{o} 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 very 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 the 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.

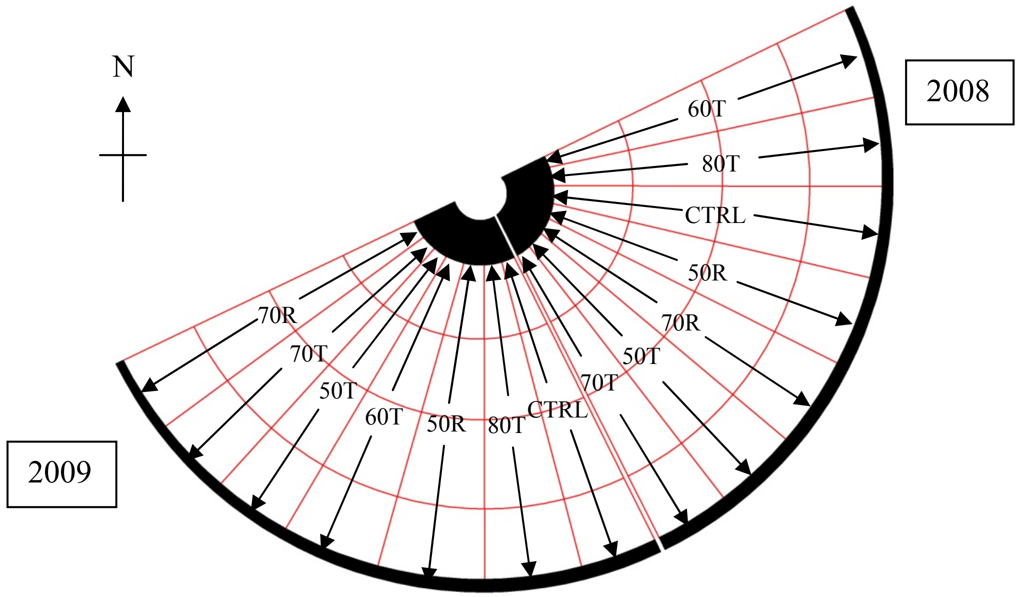

Figure 1. Experimental layout. The irrigation treatments were labeled as control (CTRL), four traditional deficit irrigation treatments (80T, 70T, 60T and 50T), and two regulated deficit irrigation treatments (70R and 50R).

The commercial varieties were selected among varieties 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 April 15, 2008 and April 20, 2009, and harvested on September 22, 2008 and September 25, 2009. Multiple varieties were chosen to test irrigation effects on a diverse array of varieties for the production region. 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, 2009b; Ko et al., 2009). The ET_o was reported daily on the PET network website of the Winter Garden area. In the full irrigation treatment (CTRL), the cumulative water loss (CWL) on the n^{th} day after the last irrigation application was computed as:

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

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

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

$$CWL_{(deficit)n} = CWL_{(deficit)n-1} + r_d \cdot ET_c - P \qquad [2]$$

Notice that Eq.[2] was applied to both traditional and regulated deficit irrigation treatments. In traditional deficit irrigation (TDI) scheme, r_d was fixed through the whole growing season; in regulated deficit irrigation (RDI) scheme, r_d was adjusted based on the growth stages. For Eqs. [1] and [2], where calculated CWL values became negative (due to excessive precipitation), CWL was reset to zero for that day, since the excessive water would not be stored in the soil when the soil moisture rises beyond its field capacity. When CWL of the CTRL reached a preset critical value (38.1 mm in 2008 and 25.4 mm in 2009), irrigation was triggered and each treatment was compensated according to its CWL. The crop ET of the irrigation day was neglected, and the CWL was accumulated again from the following day.

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 whole growing season, respectively. The RDI treatments in this study involved application of water during the following three phenological 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 June 13 and June 19, respectively, and the inception of S3 was August 14 and August 1, 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. The 0.1 RDI ratios in stages 3 were chosen arbitrarily for more water saving during boll maturity.

Table 1. Deficit ratios (r_d) of each irrigation treatment during different 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

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, 112 soil access tubes (7 irrigation treatments × 4 varieties × 4 replications) were installed in the center of each plot for soil moisture monitoring. A neutron hydroprobe (530DR Hydroprobe, Campbell Pacific Nuclear Corp. Int. Inc., USA) 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 (June 19, 26 and 30; July 10, 18 and 28; August 5) 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). In 2009, soil moisture was measured using a Profiler capacitance probe (type PR2, Delta-T Device Ltd., UK) and the moisture meter (HH2, Delta-T Device Ltd., 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 amount of PR2 access tubes were installed in the center of each plot as with the neutron probe accessing tubes. The PR2 readings were measured eleven times (June 23, 26 and 29; July 6, 10, 13, 23, 27 and 29; August 5 and 12) at seven depths (10, 20, 30, 40, 60, 80 and 100 cm).

Plant Measurements

A portable photosynthesis system (LI-6400, LICOR, Lincoln, NE) with a CO_2 injector and red/blue LEDs light chamber were used to measure two key physiological parameters (net carbon assimilation rate, A_n, in μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$; and transpiration rate, Tr, in mmol $H_2O \cdot m^{-2} \cdot s^{-1}$) on three plants (recorded from the most recent fully expanded leaf) in each experimental unit of the second span, i.e. not all experimental units were measured due to limited time. These parameters were measured five times in 2008 (June16 and 25; July 11, 17 and 29) and three times in 2009 (June 25; July 9; August 5) from 1100 h to 1400 h (CST) of sunny days. The chamber conditions used to obtain these parameters were: PAR of 2,000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, CO_2 of 400 $\mu mol \cdot mol^{-1}$, and chamber temperature being set identical to the outside air temperature. Instantaneous water use efficiency (WUE_i, in μmol $CO_2 \cdot$ mmol^{-1} H_2O) was defined as the ratio of A_n to Tr (Ko and Piccinni, 2009b), indicating the assimilated CO_2 amount through photosynthesis per unit water loss.

The phenological parameters were obtained through field sampling and/or measurement of three to five plants per plot. These phenological parameters included plant height (in cm), node number (in node·plant^{-1}), and flower/fruit number (in flower/fruit·plant^{-1}). The leaves, stems and flower/fruit were separated and dried in an oven at 60 °C for 72 hours and weighed to obtain the dry weight (in g) of each biomass component. The partitioning coefficient of boll dry weight, defined as the ratio of boll dry weight to total biomass dry weight, was computed for each plot. A summary of the parameters collected from each sampling/ measurement is provided in Table 2.

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 sub-samples were taken randomly from each harvested sample sack and then table ginned (using a research tabletop gin with 10 saw blades) to determine the lint percentage (%), through which the lint yield (in $kg \cdot ha^{-1}$) in each plot was estimated.

The ginned samples were sent to the Fiber & Biopolymer Research Institute (Texas Tech. Univ., Lubbock, TX) for USDA standard HVI tests. The micronaire (dimensionless), fiber length (in mm), fiber uniformity index (dimensionless), fiber strength (in $g \cdot tex^{-1}$), elongation (dimensionless), fiber reflectance (dimensionless) and fiber yellowness (dimensionless) were analyzed.

Data Analysis

The lint yield, lint quality, physiological and morphological parameters, dry biomass, and 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., 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. The outputs of the selected models were used as the results reported in tables and figures.

Table 2. Morphological parameters collected through each plant sampling.

Date (2008)	DAP†	Sample Size	Parameters Collected	Approximate Stage‡
6/12	58	5	height, node, stand	FS+2
6/23	69	5	height, node, fruit number	FF
7/9	85	5	height, node, fruit number	FF+2
7/23	99	3	height, node, fruit number, dry biomass	MF
Date (2009)	**DAP**	**Sample Size**	**Parameters Collected**	**Approximate Stage**
6/3	44	5	height, node, stand	FS
6/22	63	3	height, node, dry biomass	FF
7/13	84	3	height, node, fruit number	FF+2
8/10	112	3	height, node, fruit number, dry biomass	25%OP

† DAP: day after planting.
‡ FS: first square; FS+2: two weeks after first square; FF: first flower; FF+2: two weeks after first flower; MF: maximum flower; 25%OP: 25% open boll.

CHAPTER III

LINT YIELD, LINT QUALITY, MORPHOLOGICAL AND PHYSIOLOGICAL RESPONSES

Results

Environmental patterns and volumetric soil water content

The daily temperatures of the 2008 growing season were generally lower than the daily temperature of the 2009 season (Fig. 2). The maximum daily temperatures between June 15 and August 15, 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. Precipitation received during the 2008 growing season was approximately 20% less than the 30-year average (Ko and Piccinni, 2009b) (Table 2). The peak precipitation events occurred in mid-May, early-July and late-August (two excessive events, which were 68.6 and 61.0 mm, respectively), making a marked contribution to the cotton water demand. Much less rainfall was observed in the 2009 growing season (about 25% of the 30-year average), and a major portion of the total precipitation was occurred before the DAP 50 (approximately the first flower stage). The total irrigation amounts of all seven treatments are presented in Table 3. Notice that not all precipitation received during the growing season was used by plants, which implies the total water consumption by plants in the CTRL was less than the sum of the applied irrigation water and precipitation. In both years, the actual total water consumption by plants in the CTRL was approximately 600 mm.

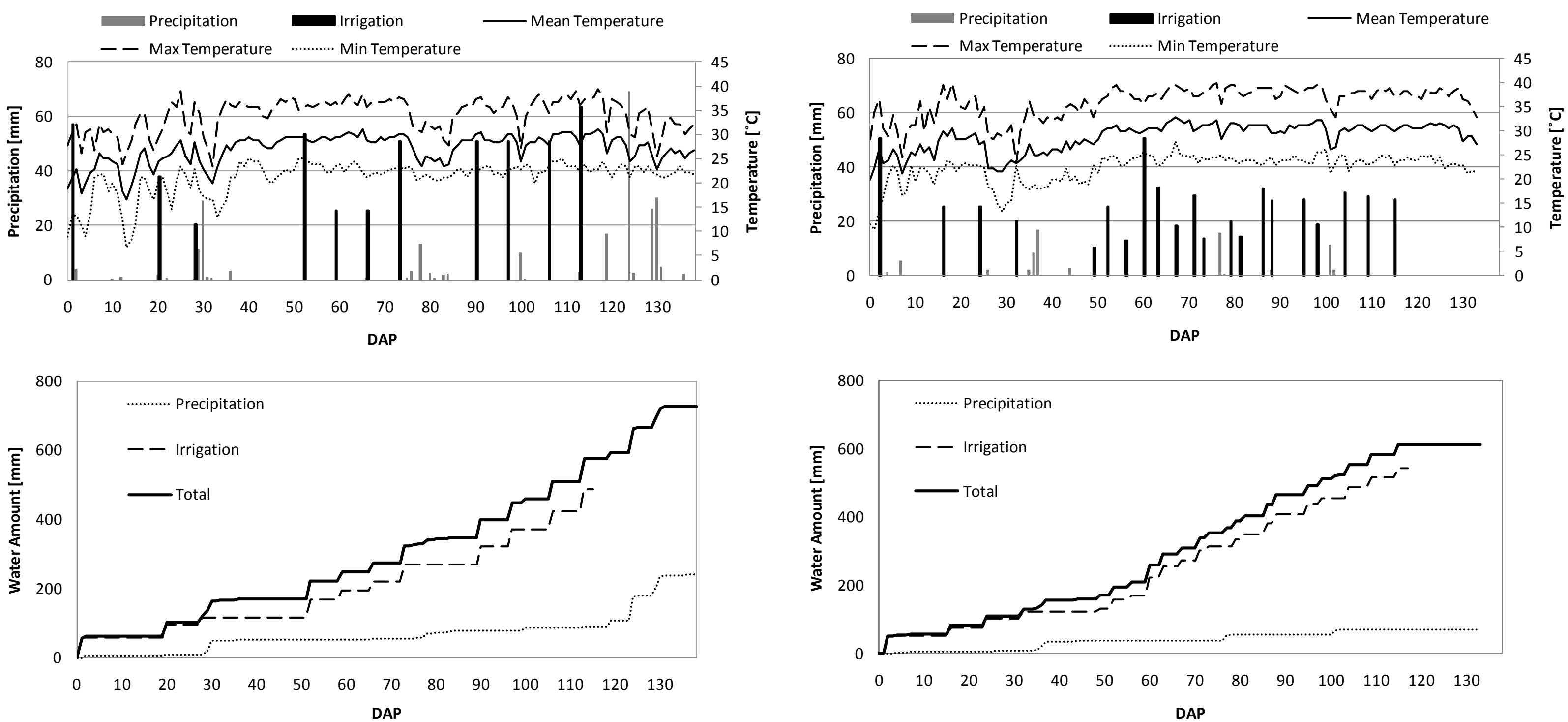

Figure 2. Climatic conditions and water input components (precipitation and irrigation) in summers of 2008 and 2009. The top two graphs illustrate the maximum/ minimum/ average daily temperatures, daily precipitation and irrigation amounts in 2008 (left) and 2009 (right), respectively. The bottom two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

Table 3. Irrigation applied in each treatment and total precipitation during the cotton growing seasons in 2008 (Apr 15 to Aug 31) and 2009 (Apr 20 to Aug 31) at Uvalde, TX. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively. Due to erroneous irrigation, the actual water amount applied on the 60T treatment in 2008 is larger than the calculated amount (245 mm).

Year	Irrigation Applied							Precipitation
	CTRL	80T	70T	60T	50T	70R	50R	
	---------------------------mm---------------------------							-----mm-----
2008	429	337	283	> 245	189	337	315	241
2009	492	390	315	266	222	358	334	68
30-year†	-	-	-	-	-	-	-	315

† According to Ko and Piccinni (2009). The duration used to calculate the 30-year (1971-2000)

The relative volumetric soil water content is presented for four different soil depths: 20, 40, 60 and 100 cm. Three treatments that represent the CTRL, TDI (50T) and RDI (70R) schemes are selected for comparison (Figs. 3 and 4). The reason for choosing the three treatments to demonstrate the soil moisture differences will be given later (see P30-31). In 2008, the highest soil water content fluctuation was found at the 20-cm layer (Fig. 3). In general, a slight decreasing trend in soil moisture over time could be observed in all four layers. 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. In 2009, the high temperature condition was severer than in 2008, which might cause more water consumption by plants and soils. This difference is illustrated by the larger differences among treatments in soil moisture (Fig. 4). 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 does the 70R treatment show lower soil water content than the other two treatments. This may indicate the effective rooting depth for this treatment was between 40 and 60 cm, where a major portion of the 70R-plants water uptake occurred. The soil water content plots also confirmed the irrigation scheduling through ET-based estimation was accurate.

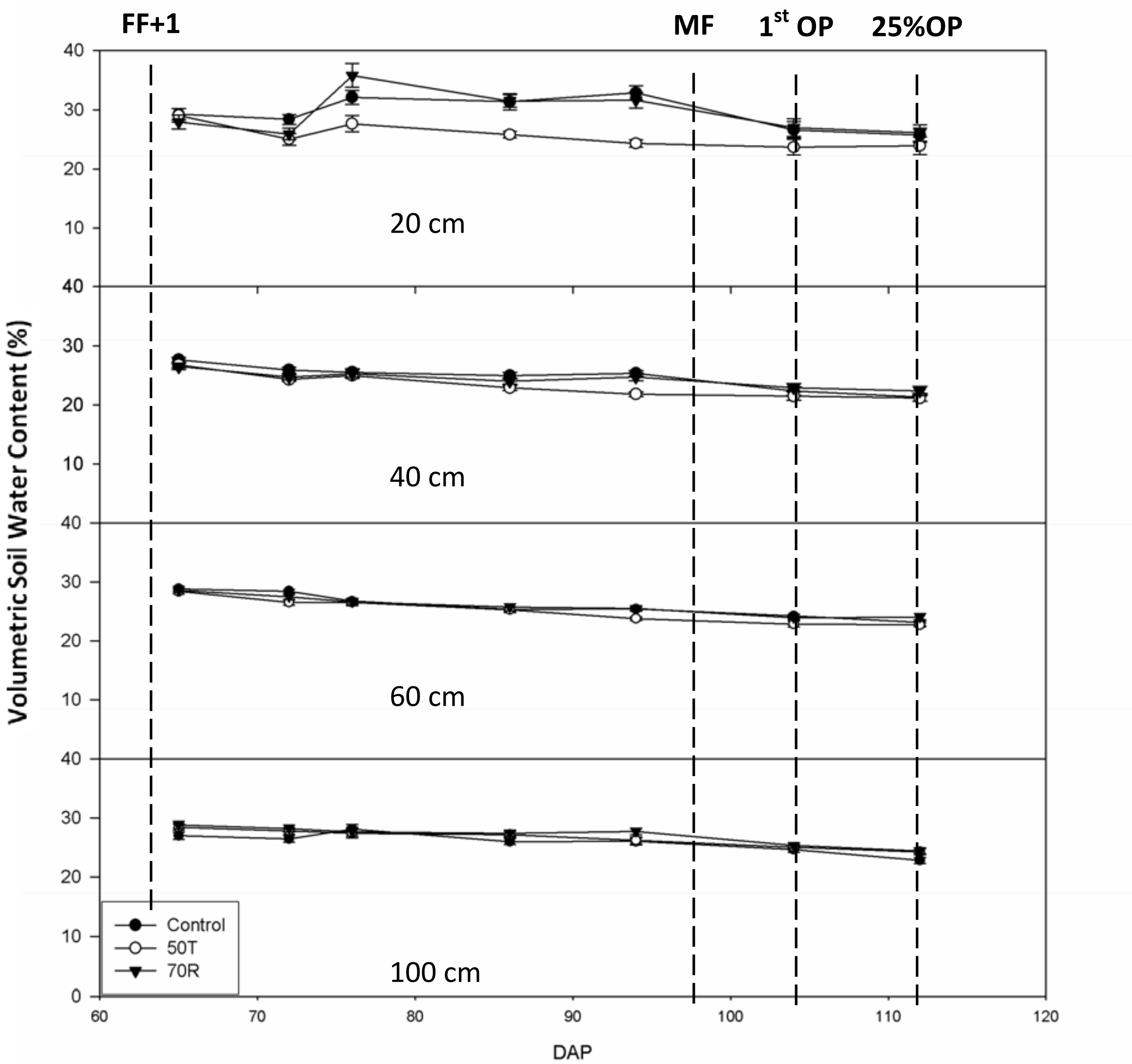

Figure 3. Volumetric soil water content (relative) at depths of 20, 40, 60 and 100 cm during the 2008 growing season. FF+1, MF, 1st OP and 25% OP signify one week after first flower, maximum flower, first open boll, and 25% open boll, respectively. DAP refers to day after planting.

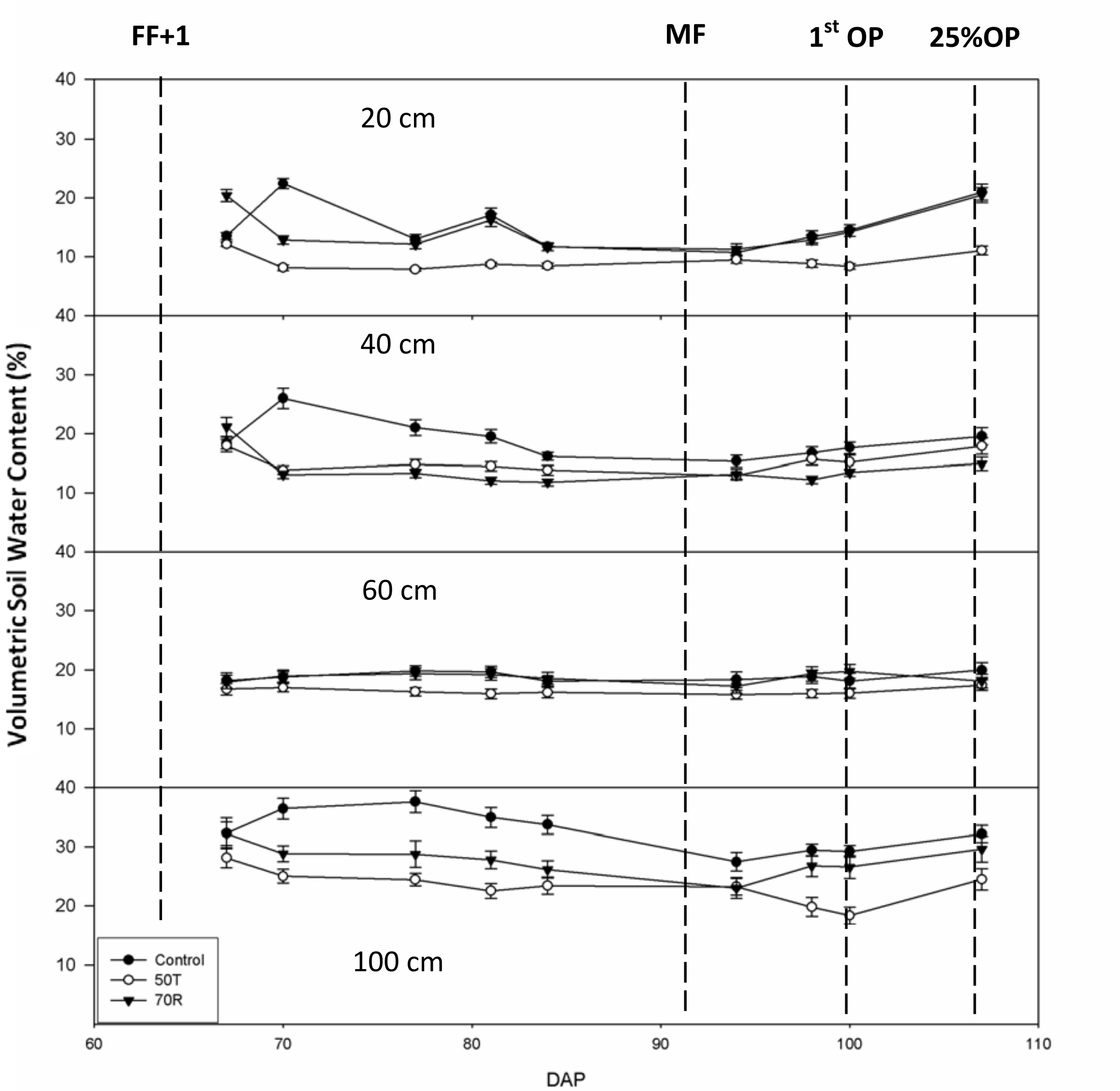

Figure 4. Volumetric soil water content (relative) at depths of 20, 40, 60 and 100 cm during the 2009 growing season. FF+1, MF, 1st OP and 25% OP signify one week after first flower, maximum flower, first open boll, and 25% open boll, respectively. DAP refers to day after planting.

Lint yield and lint percentage

Results of the effects of the irrigation scheme and variety on lint yield are shown in Table 4. The varieties that produced the highest lint yields in 2008 and 2009 were

DP555 (1446.4 kg·ha^{-1}) and DP935 (1598.4 kg·ha^{-1}), respectively. 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 will be discussed separately. In 2008, the lint yield of the 80T treatment (1242.6 kg·ha^{-1}) and the CTRL (1312.0 kg·ha^{-1}) were not significantly different, but both were significantly higher than the lint yields of the 70T and 50T treatments. The yields of the 60T treatment were excluded from the mean comparison due to erroneous irrigation application. The 70R treatment produced 1151.5 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 1039 kg·ha^{-1} or 21% less than the lint yield of the CTRL.

In 2009, the CTRL yielded 2022 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 (1508.7 and 1335.1 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.

With a further examination of the lint yield results in 2009 by variety, the 80T treatment on three out of four varieties (except FM9180) showed no significant lint yield difference to the CTRL. On the contrary, the 70T treatment presented non-significant lint yield difference to the CTRL only for DP555. For RDI, the 70R treatment on DP555 and DP935 demonstrated no statistical difference in lint yield compared to the CTRL;

under the 50R treatment, DP935 was the only variety that failed to show a significant lint yield difference from the CTRL.

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 5). No significant irrigation or irrigation-by-variety interaction was detected.

Lint quality

The MANOVA results of the lint quality parameters (Table 6) showed that both irrigation and variety effects were significant ($p < 0.05$) while the interaction of these two factors was not. 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 7). 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 28 $g \cdot tex^{-1}$, which was significantly lower than the fiber strength of the CTRL (29 $g \cdot tex^{-1}$). The reflectance of the 50T treatment was approximately 62.5 units, which was significantly lower than the value of the CTRL (65.5 units). 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.

Table 4. 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. The yields of the 60T treatment in 2008 were excluded from the mean comparison due to erroneous irrigation application.

	Lint Yield															
	2008								2009							
	kg·ha^{-1}								kg·ha^{-1}							
BY VARIETY	DP555		DP164		FM0989		FM9063		DP935		DP555		FM9180		DP949	
CTRL	1952.1	A†	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

		2008		2009		
MEAN						
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. † Mean values with the same letter group were not significantly different from each other.

Table 5. Lint percentage in 2008 and 2009.

2008				2009			
Variety		Lint Percentage		Variety		Lint Percentage	
		%				%	
	DP555	46.4	A†		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.
† Mean values with the same letter group were not significantly different from each other.

Table 6. Wilks' Lambda test of MANOVA for fiber quality parameters.

Year	Effect	λ	F	Pr>F	
2008					
	Irrigation (I)	0.3294	2.35	<0.01	**
	Variety (V)	0.0269	26.98	<0.01	**
	I × V	0.2813	0.88	0.80	ns
2009					
	Irrigation (I)	0.1675	4.08	<0.01	**
	Variety (V)	0.0135	37.21	<0.01	**
	I × V	0.2208	1.07	0.30	ns

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

Table 7. 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		Reflectance		Yellowness	
		--		--mm--		--		-g·tex^{-1}-		--		--		--	
2008															
	CTRL	5.01	AB†	1.14	A	82.16	ABC	29.02	AB	6.28	A	65.48	A	7.66	BC
	80T	5.00	AB	1.12	AB	81.76	BC	28.74	ABC	6.31	A	65.19	A	7.75	ABC
	70T	4.89	AB	1.13	AB	81.61	C	28.60	ABC	6.24	A	64.40	AB	7.66	BC
	60T	4.95	AB	1.13	A	81.76	BC	28.32	BC	6.28	A	62.59	B	8.05	AB
	50T	4.86	B	1.11	B	81.71	C	28.13	C	6.29	A	62.51	B	8.10	A
	70R	5.00	AB	1.14	A	82.63	A	29.36	A	6.14	A	65.31	A	7.61	C
	50R	5.07	A	1.14	A	82.56	AB	28.96	ABC	6.25	A	64.44	AB	7.80	ABC
2009															
	CTRL	4.78	B	1.09	A	81.56	A	27.89	AB	6.03	A	51.75	D	7.03	C
	80T	4.83	AB	1.06	BC	80.98	AB	27.97	AB	5.89	AB	55.99	BC	7.05	BC
	70T	4.89	AB	1.04	CDE	80.79	AB	27.01	BC	5.73	AB	55.94	BC	7.32	A
	60T	4.96	AB	1.04	DE	80.53	B	27.52	ABC	5.89	AB	57.88	AB	7.23	ABC
	50T	4.83	AB	1.03	E	80.61	B	26.54	C	5.66	B	58.61	A	7.33	A
	70R	5.01	AB	1.06	BCD	80.91	AB	27.93	AB	5.98	AB	55.66	C	7.30	AB
	50R	5.06	A	1.07	B	81.54	A	28.44	A	5.98	AB	55.79	C	7.14	ABC

† Mean values with the same letter group were not significantly different from each other.

In 2009, there were again few differences among irrigation treatments for fiber quality parameters. The TDI treatments showed decreasing trends with water deficit severity except for reflectance and yellowness (Table 7). 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 reflectance of the CTRL and the 50T treatments was the lowest (51.75) and the highest (58.61), respectively, and 70R and 50R treatments showed significantly higher reflectance than the CTRL. For yellowness, the 70T, 50T, and 70R treatments demonstrated significantly higher values (~7.3) than the CTRL (~7.0).

Plant height

In both years, irrigation and variety effects on plant height were highly significant across all measurements without significant interaction (Table 8). In 2008, significant difference among the irrigation treatments was detected after the second measurement (DAP 69). Starting from DAP 85, the average plant height of the 50T treatment was significantly shorter (14% less at DAP 85 and 15% less on DAP 99) than the height of the CTRL. The plant height of the 70T treatment was about 10% lower than the CTRL at DAP 99. For RDI, the plant height of the 70R treatment was not significantly different from the CTRL, while the 50R treatment showed a similar reduction in plant height as the 50T treatments in comparison to the CTRL.

In 2009, all TDI schemes showed significantly shorter plant heights than the CTRL starting at DAP 84 (Table 8). For RDI, the height of the 50R treatment was significantly shorter (~6% less) than the CTRL since DAP 63, whereas the average plant height of the 70R was significantly shorter at DAP 84. The plant height of the 70R treatment showed no significant difference from the heights of the 80T and 70T treatments. The plant height of the 50R treatment was not significantly different from the plant heights of the 60T and 50T treatments.

Node, flower, and boll number

Both irrigation treatment and variety effects on node number were highly significant in 2008 and 2009, and no significant interaction was detected (Table 9). In 2008, the 50T and 70T treatments showed significantly reduced node numbers (~1 node) than the node numbers of the CTRL at DAP 85 (about two weeks after first flower) and DAP 99 (maximum flower). The 70R treatment had equal numbers of nodes as the CTRL, while the 50R treatment followed a similar pattern as the 50T treatment with two nodes fewer than the CTRL per plant. Flower and boll number was not significantly affected by irrigation but was significantly different among the varieties grown in 2008 (data not shown).

In 2009, the CTRL surpassed all the TDI and RDI treatments in node numbers at DAP 84 (FF+2). Flower and boll number were significantly affected by irrigation and variety (Table 10) with the CTRL showing relatively lower numbers of flowers. The boll numbers at the first open boll and the 75% open boll stages demonstrated that the 60T and 50T treatments had significantly decreased boll numbers in comparison to all the other treatments. However, the RDI treatments showed no reduction in flowers or bolls.

Table 8. The mean plant heights of traditional (T) and regulated (R) deficit irrigation treatments at different days after planting (DAP). CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively.

Year	**Irrigation**	**DAP58**		**DAP69**		**DAP85**		**DAP99**	
2008	CTRL	34.76	A†	49.03	AB	54.91	A	54.12	A
	80T	35.20	A	47.42	B	53.25	A	53.02	AB
	70T	33.75	A	49.47	AB	52.09	A	48.45	BC
	60T	37.00	A	52.92	A	54.63	A	51.50	AB
	50T	33.22	A	47.28	B	47.05	B	44.95	C
	70R	36.65	A	48.08	B	51.66	A	51.14	AB
	50R	36.91	A	45.28	B	46.92	B	45.87	C
Year	**Irrigation**	**DAP44**		**DAP63**		**DAP84**		**DAP112**	
2009	CTRL	31.44	A	60.33	AB	89.77	A	84.47	A
	80T	30.91	A	62.20	A	77.66	B	72.71	B
	70T	30.16	A	60.54	ABC	78.58	B	72.68	BC
	60T	30.83	A	58.82	BC	69.48	C	60.62	D
	50T	29.97	A	58.02	BC	63.47	D	61.49	D
	70R	29.97	A	59.58	ABC	76.41	B	69.09	BC
	50R	30.15	A	56.62	C	68.47	CD	65.15	CD
ANOVA	**Effect**	**2008**		**2009**					
	Irrigation (I)	**		**					
	Variety (V)	**		**					
	I×V	ns		ns					
	DAP (D)	**		**					
	I×D	*		**					
	V×D	**		**					
	I×V×D	ns		ns					

**: highly significant ($p < 0.01$); *: significant ($p < 0.05$); ns: not significant.
† Mean values with the same letter group were not significantly different from each other.

Table 9. The mean node numbers of traditional (T) and regulated (R) deficit irrigation treatments at different days after planting (DAP). CTRL signifies the full irrigation treatment (control).

Year	Irrigation	DAP58		DAP69		DAP85		DAP99	
2008	CTRL	13.26	AB†	13.96	A	15.48	A	16.73	A
	80T	13.00	B	13.46	A	15.19	AB	16.35	AB
	70T	13.10	AB	13.54	A	14.59	ABC	15.15	CD
	60T	14.04	A	14.50	A	15.38	ABC	16.31	ABC
	50T	12.98	B	13.26	A	13.63	C	14.44	D
	70R	13.64	AB	13.36	A	14.30	BC	15.92	ABC
	50R	13.65	AB	13.09	A	13.46	C	15.38	BCD
Year	**Irrigation**	**DAP44**		**DAP63**		**DAP84**		**DAP112**	
2009	CTRL	7.14	A	12.43	A	16.78	A	15.28	A
	80T	6.96	AB	12.88	A	14.37	B	14.10	B
	70T	6.85	AB	12.31	A	13.42	BC	13.36	B
	60T	6.92	AB	12.54	A	12.66	C	12.24	C
	50T	6.83	AB	12.07	A	12.78	C	11.95	C
	70R	6.75	B	12.41	A	14.10	B	13.35	B
	50R	6.89	AB	12.08	A	13.41	BC	13.49	B
ANOVA	**Effect**	**2008**		**2009**					
	Irrigation (I)	**		**					
	Variety (V)	**		**					
	I×V	ns		ns					
	DAP (D)	**		**					
	I×D	ns		**					
	V×D	**		**					
	I×V×D	ns		ns					

**: highly significant ($p < 0.01$); ns: not significant.
† Mean values with the same letter group were not significantly different from each other.

Table 10. The mean flower/ boll numbers of traditional (T) and regulated (R) deficit irrigation treatments at different days after planting (DAP) in 2009. CTRL signifies the full irrigation treatment (control).

Year	Irrigation	Flower Number at DAP63		Boll Number at First Open Boll (DAP84)		Boll Number at 75% Open Boll (DAP112)	
		$Plant^{-1}$		$Plant^{-1}$		$Plant^{-1}$	
2009	CTRL	2.05	B†	12.39	A	14.54	A
	80T	2.69	A	11.24	AB	15.41	A
	70T	2.11	AB	10.44	ABC	13.48	A
	60T	2.34	AB	8.26	D	10.26	B
	50T	2.29	AB	8.63	CD	9.85	B
	70R	2.20	AB	12.50	A	13.16	A
	50R	2.38	AB	9.37	BCD	13.70	A
ANOVA	**Effect**						
	Irrigation (I)	ns		**		**	
	Variety (V)	**		ns		**	
	I×V	ns		ns		ns	

**: highly significant ($p < 0.01$); *: significant ($p < 0.05$); ns: not significant.
† Mean values with the same letter group were not significantly different from each other.

Partitioning coefficient of boll dry weight

In 2008, the highest partitioning coefficient (% of total aboveground dry biomass) of boll dry weight was found in the 50T treatment. The partitioning coefficients of the other deficit irrigation treatments did not significantly differ from the coefficient of the CTRL. DP555 presented a significantly lower partitioning coefficient than the other three varieties. Other treatments were not significantly different from each other. No significant difference was detected among irrigation treatments in 2009. Again, DP555 presented to be the most significant variety that has the lowest partitioning coefficient.

Table 11. Partitioning coefficients (% of total above ground dry biomass) of boll dry weight across irrigation treatments (I) and varieties (V) in 2008 and 2009. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively.

2008				**2009**			
		Partitioning Coefficient				**Partitioning Coefficient**	
Irrigation				Irrigation			
	CTRL	52.57%	B†		CTRL	53.99%	A
	80T	55.14%	B		80T	55.65%	A
	70T	55.33%	B		70T	54.83%	A
	60T	53.31%	B		60T	50.73%	A
	50T	60.28%	A		50T	54.14%	A
	70R	54.37%	B		70R	56.09%	A
	50R	56.11%	AB		50R	53.96%	A
Variety				Variety			
	DP555	51.12%	B		DP935	55.18%	A
	DP164	55.68%	A		DP555	50.88%	B
	FM0989	55.60%	A		FM9180	54.24%	A
	FM9063	58.81%	A		DP949	56.49%	A
ANOVA		**Pr > F**		**ANOVA**		**Pr > F**	
	Irrigation (I)	0.03	*		Irrigation (I)	0.11	ns
	Variety (V)	< 0.01	**		Variety (V)	< 0.01	**
	I × V	0.94	ns		I × V	0.89	ns

**: highly significant (p < 0.01); *: significant (p < 0.05); ns: not significant.
† Mean values with the same letter group were not significant different from each other.

Leaf gas exchange

In both 2008 and 2009, irrigation and variety had significant effects on carbon assimilation rate (A_n), transpiration rate (Tr) and instantaneous water-use efficiency (WUE_i) (Table 12). The interaction between these two factors was significant for Tr and WUE_i in 2008 and for A_n and Tr in 2009. As expected, DAP and its interaction with irrigation and variety had significant effects on all gas exchange parameters which reflect the seasonal development of the crop and its physiological performance with age.

Table 12. ANOVA table for net carbon assimilation rate (A_n), transpiration rate (Tr) and instantaneous water use efficiency (WUE_i).

Year	Effect	A_n	Tr	WUE_i
2008	Irrigation (I)	**	**	**
	Variety (V)	**	**	**
	I×V	ns	*	**
	DAP (D)	**	**	**
	I×D	**	**	**
	V×D	**	**	**
	I×V×D	ns	**	**
2009	Irrigation (I)	**	**	**
	Variety (V)	**	**	ns
	I×V	**	**	ns
	DAP (D)	**	**	**
	I×D	**	**	**
	V×D	**	**	**
	I×V×D	**	**	**

**: highly significant ($p < 0.01$); *: significant ($p < 0.05$); ns: non-significant.

In all gas exchange figures, three treatments (CTRL, 50T and 70R) are shown to illustrate the significant differences between the three classes of treatments: CTRL, TDI, and RDI. The CTRL and 50T treatments are chosen because they represent drought stress free and severe drought stress conditions, which served as two extreme conditions of drought stress; the 70R treatments performed well in maintaining lint yield in both years, and thus were selected to evaluate its physiological responses against the two extreme conditions. In 2008, the highest A_n values were detected at DAP 93 (approximately maximum flower stage) for the CTRL and the 70R treatments while the 50T treatment showed decreasing values throughout the growing season (Fig. 5). Overall, the 70R treatment showed no significant difference in A_n values from the CTRL. In 2009, the A_n values were maximal for all treatments at DAP 80 (Table 13). The A_n value of the 50T treatment was significantly lower than the value of the CTRL at DAP 107 (about 25% open boll). Surprisingly for 2009, the 70R treatment showed significantly lower A_n values across the growing season compared to both the 50T treatment and the CTRL.

The transpiration rates in 2008 peaked for all treatments at DAP 87 (Table 13). The 50T treatment demonstrated significantly lower transpiration rates from DAP 87 to DAP 105 (Fig. 6). The transpiration rates of the 70R treatment and the CTRL were not significantly different across the growing season. In 2009, the transpiration rates were maximal at the first measurement (DAP 66) and decreased across the growing season. Of the three selected treatments, the 50T treatment had a higher transpiration rate at DAP 66 (FF+1) but a relatively lower rate at DAP 107 (25%OP). Similar to its A_n rates, the 70R treatment had the lowest transpiration rates compared to the 50T treatment and the CTRL across all three measurement periods.

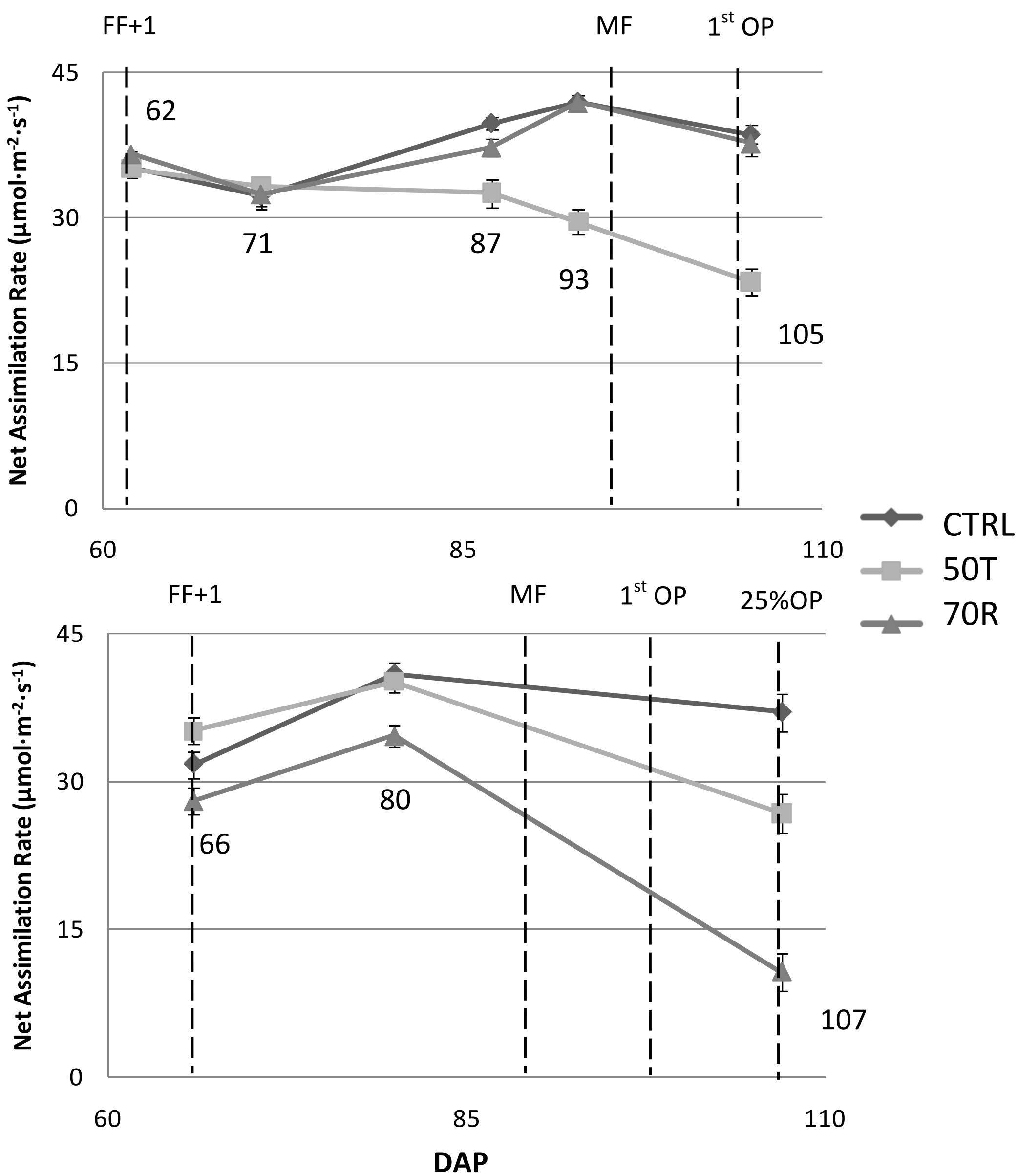

Figure 5. Net carbon assimilation rate (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$) over growing seasons in 2008 (upper) and 2009 (lower). CTRL, 50T and 70R signify the full irrigation (the control), 50%ET traditional deficit irrigation, and 70%ET-initiating regulated deficit irrigation treatments. FF+1, MF, 1st OP and 25% OP signify one week after first flower, maximum flower, first open boll and 25% open boll, respectively.

Instantaneous water use efficiency (WUE_i) in 2008 under TDI and RDI peaked at DAP 93 (about maximum flower stage) and was maintained at the same level till the last measurement (DAP 105) (Table 13). The WUE_i of the 50T treatment was significantly higher than the 70R treatment and the CTRL at DAP 93 and 105 (Fig. 7) while the 70R treatment and the CTRL showed no significant differences. In 2009, WUE_i values peaked at the last measurement (DAP 107) (Table 14). The WUE_i of all three treatments (CTRL, 50T and 70R) increased in a similar pattern and had statistically similar values during the growing season (Fig. 7).

Because the interaction term between irrigation and variety for transpiration rate was significant in both 2008 and 2009 years (Table 12), variability within individual cotton varieties grown in each year was evaluated. These differences were most apparent at DAP 105 (1^{st} open boll) in 2008 and DAP 107 (25% open boll) in 2009; thus, these two times were selected to closely examine the irrigation effects on each variety.

In 2008 for the TDI treatments, all varieties showed an overall pattern of decreasing transpiration rates with increasing water deficit severity with minor exceptions (Fig. 8). Quite consistently, the transpiration rates of the 50T treatments were significantly lower than the rates of the CTRL. No significant difference between the transpiration rates of the RDI (70R and 50R) treatments and the CTRL was detected for that year except for DP555, where the 50R treatment had a higher rate than the CTRL.

Table 13. The means of net carbon assimilation rate, net transpiration rate and instantaneous water use efficiency of each irrigation treatment on different days after planting (DAP) in 2008. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively.

Parameter	Irrigation	DAP62		DAP71		DAP87		DAP93		DAP105	
A_n	CTRL	35.1	AB†	32.3	AB	39.7	A	41.9	AB	38.6	AB
(μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)	80T	36.5	AB	29.9	B	37.4	ABC	43.1	A	38.0	B
	70T	35.5	AB	32.0	AB	38.9	AB	39.3	B	33.5	CD
	60T	35.3	AB	32.0	AB	38.4	AB	39.0	B	33.1	D
	50T	35.1	AB	33.2	A	32.5	D	29.6	C	23.3	E
	70R	36.6	A	32.4	AB	37.3	BC	41.9	AB	37.7	ABC
	50R	34.9	B	29.8	B	35.4	CD	41.9	AB	40.9	A
Tr	CTRL	13.1	AB	11.1	A	18.2	A	11.5	A	11.7	A
	80T	13.4	AB	9.6	B	16.4	B	11.5	A	11.4	A
(mmol $H_2O \cdot m^{-2} \cdot s^{-1}$)	70T	13.8	A	10.4	AB	17.4	AB	10.6	B	9.2	B
	60T	13.6	A	10.5	AB	16.4	B	10.1	B	9.0	B
	50T	12.8	BC	11.3	A	14.1	C	7.1	C	5.9	C
	70R	13.7	A	11.2	A	17.1	AB	11.9	A	11.4	A
	50R	12.3	C	9.6	B	16.2	B	11.4	A	12.5	A
WUE_i	CTRL	2.7	BC	3.0	BC	2.2	C	3.6	D	3.3	C
(μmol $CO_2 \cdot$ $mmol^{-1}$ H_2O)	80T	2.8	BC	3.1	AB	2.3	AB	3.8	C	3.3	C
	70T	2.6	D	3.1	AB	2.2	BC	3.8	BC	3.7	B
	60T	2.6	CD	3.1	AB	2.3	A	3.9	B	3.7	B
	50T	2.8	AB	2.9	C	2.4	A	4.2	A	4.1	A
	70R	2.7	C	2.9	C	2.2	BC	3.5	E	3.3	C
	50R	2.9	A	3.2	A	2.2	BC	3.7	CD	3.3	C

† Mean values with the same letter group were not significantly different from each other.

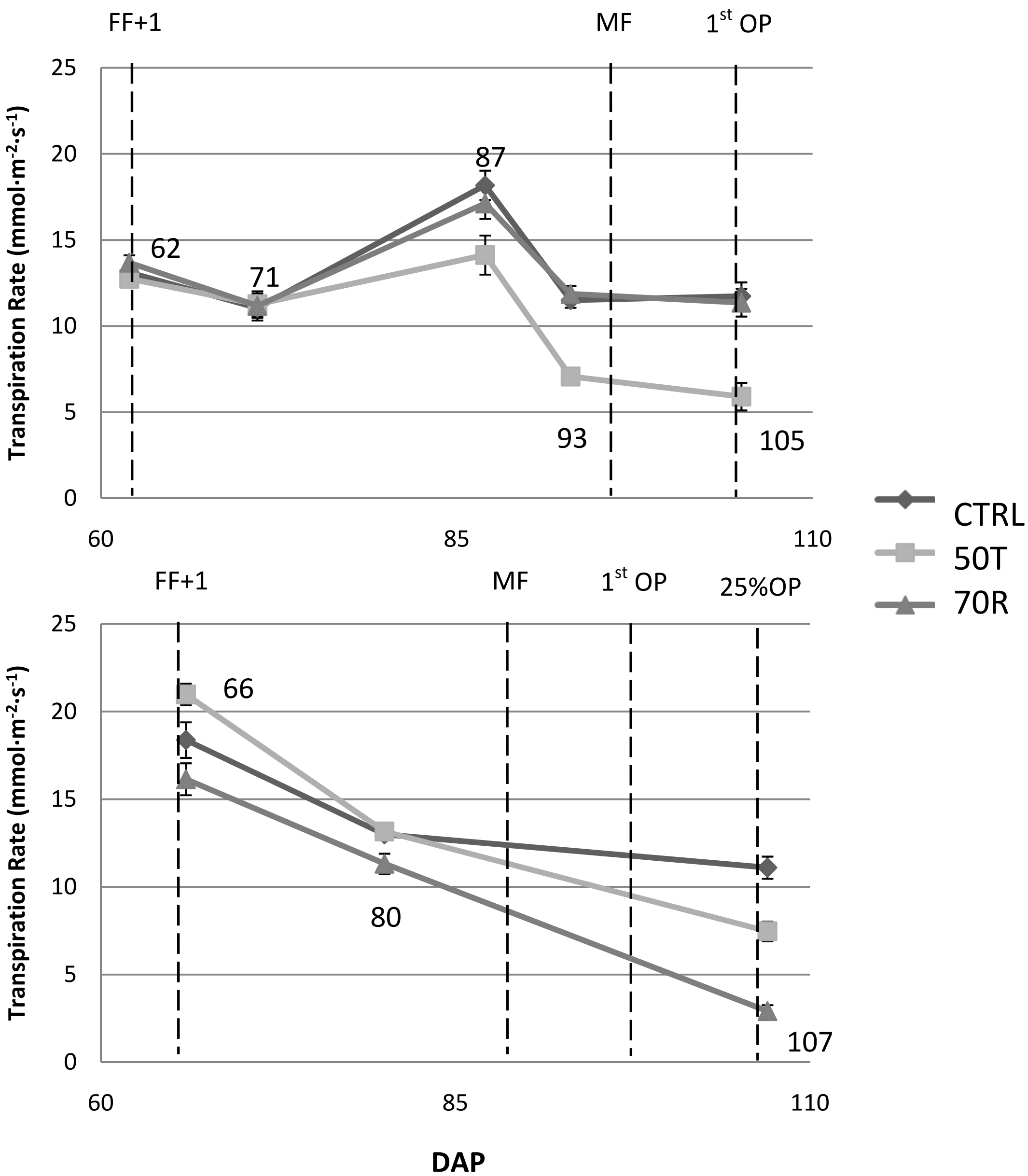

Figure 6. Transpiration rate (mmol $H_2O \cdot m^{-2} \cdot s^{-1}$) over growing seasons in 2008 (upper) and 2009 (lower). CTRL, 50T and 70R signify the full irrigation (the control), 50%ET traditional deficit irrigation, and 70%ET-initiating regulated deficit irrigation treatments. FF+1, MF, 1st OP and 25% OP signify one week after first flower, maximum flower, first open boll and 25% open boll, respectively.

Table 14. The means of net carbon assimilation rate, net transpiration rate and instantaneous water use efficiency of each irrigation treatment on different days after planting (DAP) in 2009. CTRL signifies the full irrigation treatment (control). T and R signify the traditional and regulated deficit irrigation treatments, respectively.

Parameter	Irrigation	DAP66		DAP80		DAP107	
A_n	CTRL	31.7	BCD†	40.9	AB	37.0	A
(μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)	80T	35.7	A	43.4	A	20.4	C
	70T	33.6	ABC	39.0	BC	16.0	CD
	60T	33.8	ABC	41.3	AB	32.8	A
	50T	35.1	AB	40.2	B	26.8	B
	70R	28.0	D	34.6	D	10.6	D
	50R	31.3	CD	36.6	CD	16.4	C
Tr	CTRL	18.4	B	13.0	B	11.1	A
	80T	21.7	A	13.6	AB	5.6	C
(mmol $H_2O \cdot m^{-2} \cdot s^{-1}$)	70T	21.3	A	13.1	B	4.4	C
	60T	21.1	A	14.2	A	10.0	A
	50T	21.0	A	13.2	B	7.5	B
	70R	16.1	B	11.3	C	2.9	D
	50R	15.6	B	11.9	C	4.5	C
WUE_i	CTRL	1.8	A	3.2	A	3.4	CD
(μmol $CO_2 \cdot$ $mmol^{-1}$ H_2O)	80T	1.6	BC	3.2	A	3.6	AB
	70T	1.6	C	3.0	BC	3.6	A
	60T	1.6	C	2.9	C	3.2	D
	50T	1.7	BC	3.0	BC	3.5	BC
	70R	1.8	AB	3.1	ABC	3.6	AB
	50R	2.1	AB	3.1	AB	3.6	AB

† Mean values with the same letter group were not significantly different from each other.

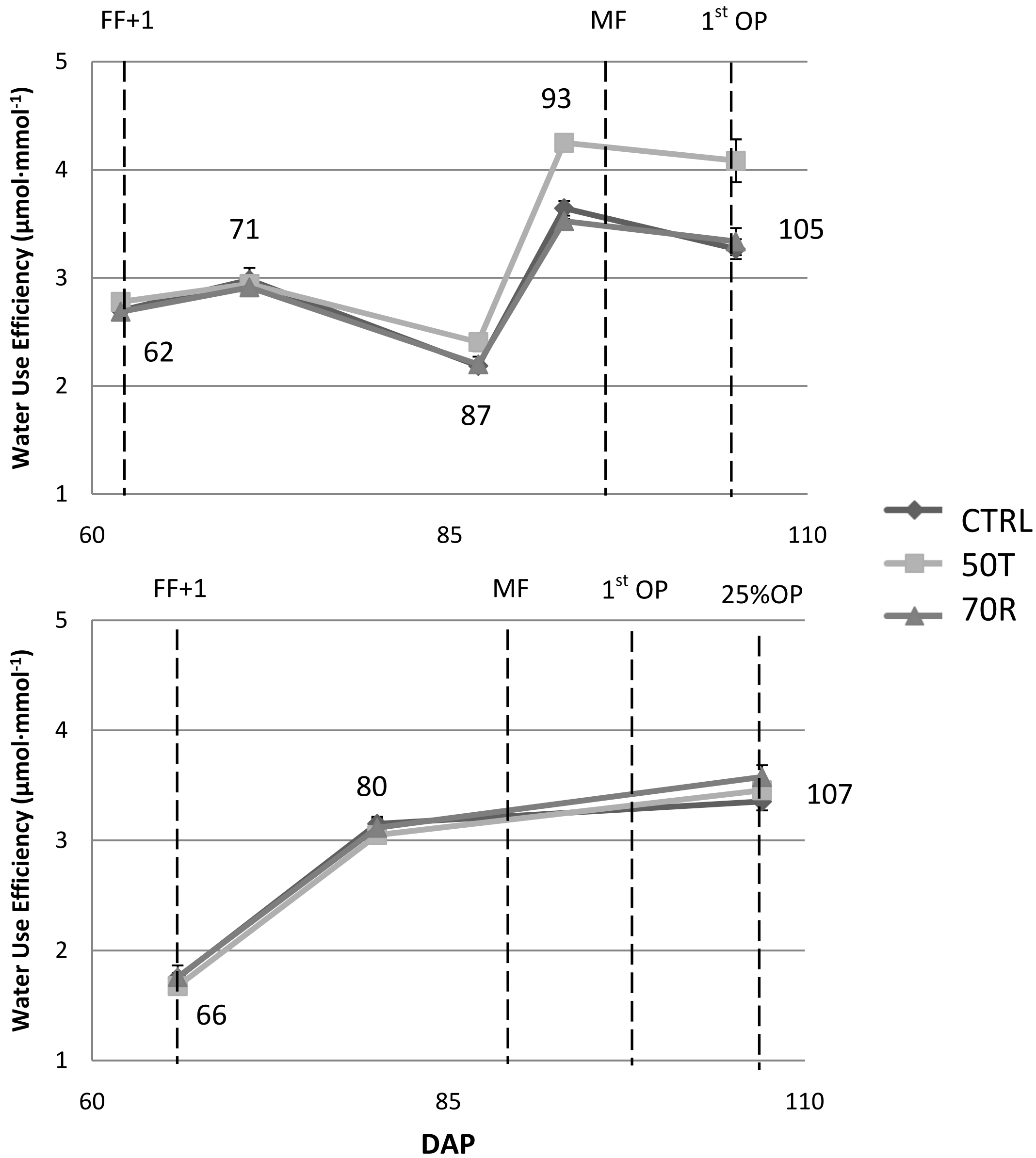

Figure 7. Instantaneous water use efficiency (µmol CO_2· $mmol^{-1}$ H_2O) over the growing seasons in 2008 (upper) and 2009 (lower). CTRL, 50T and 70R signify the full irrigation (the control), 50%ET traditional deficit irrigation, and 70%ET-initiating regulated deficit irrigation treatments. FF+1, MF, 1st OP and 25% OP signify one week after first flower, maximum flower, first open boll and 25% open boll, respectively.

The pattern of transpiration rate contrast in 2009 seems not to be consistent among varieties (Fig. 9). For example, for DP935, the transpiration rate of the CTRL was approximately three times higher than the rates of the other treatments, while for DP555, the transpiration rate was depressed in the CTRL. What was consistent across all varieties was a general lowering of transpiration rates for both RDI treatments (70R and 50R) with a 50% or more decrease from the CTRL in DP935 and DP949.

The interaction term between irrigation and variety for WUE_i was significant only in 2008 (Table 12). Looking at the WUE_i of each variety at about the first open boll stage (DAP 105), DP164 showed that the WUE_i of the 50T treatment was significantly higher than the WUE_i of the other treatments (Fig. 10). The other three varieties failed to show this significant increase compared to the CTRL. Both RDI treatments showed similar WUE_i patterns compared to the CTRL. In all four varieties almost no significance was observed, besides a significantly higher WUE_i value of the 50R treatment than the WUE_i of the CTRL for DP164.

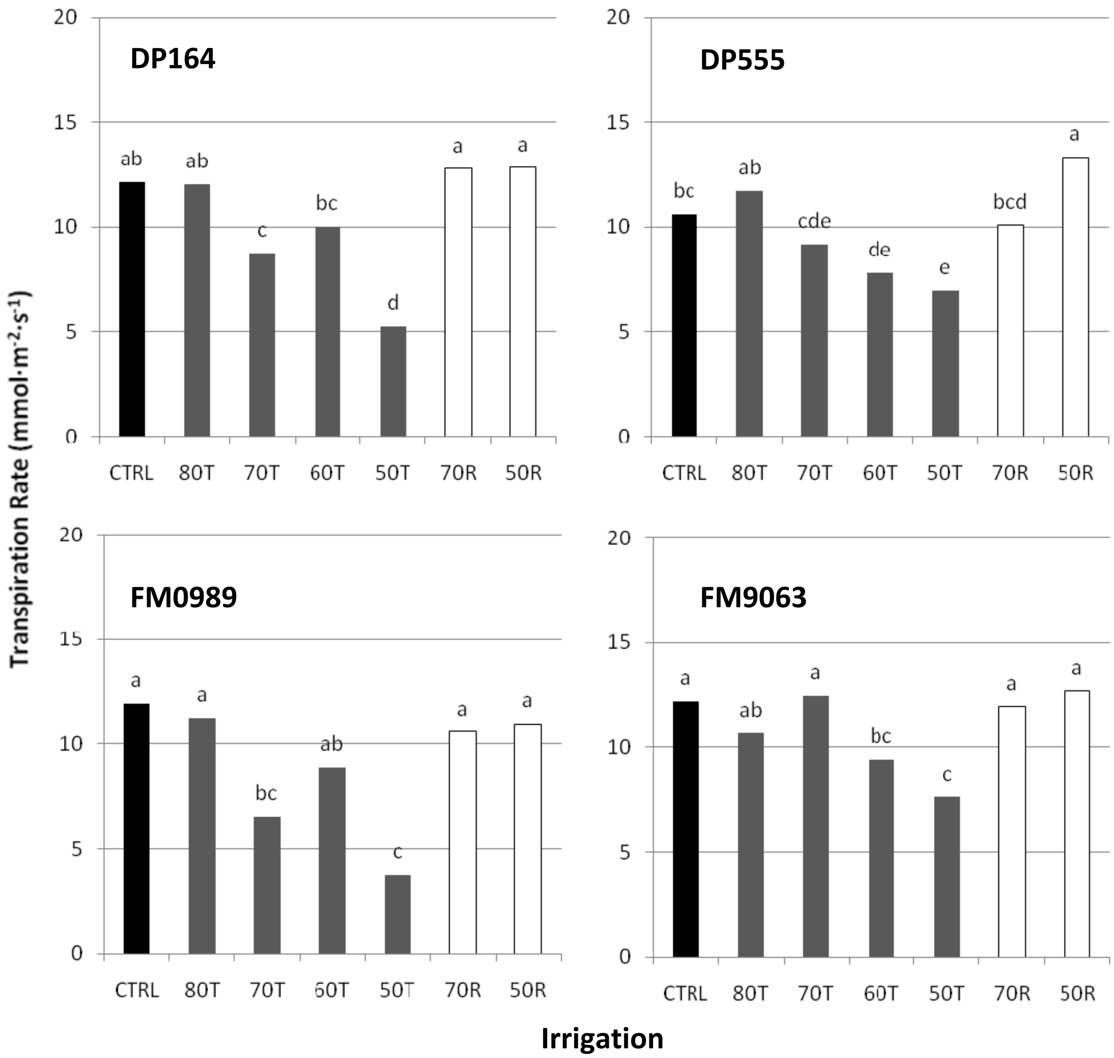

Figure 8. Transpiration rate (mmol $H_2O{\cdot}m^{-2}{\cdot}s^{-1}$) of each variety at the first open boll stage (DAP 105) in 2008. T and R signify traditional and regulated deficit irrigation treatments, respectively. Treatments with letters in common do not significantly differ.

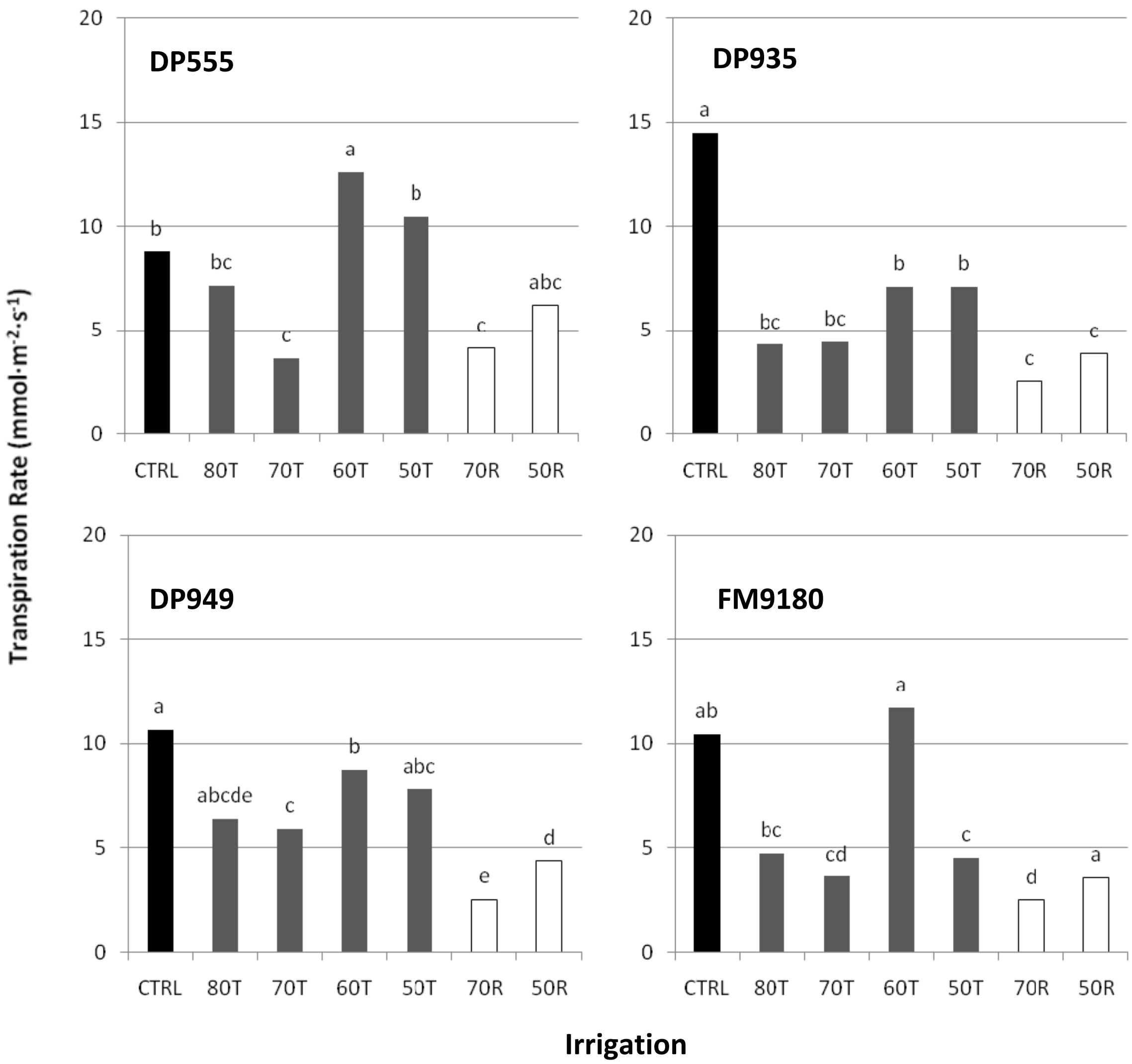

Figure 9. Transpiration rate (mmol $H_2O \cdot m^{-2} \cdot s^{-1}$) of each variety at the 25% open boll stage (DAP 107) in 2009. T and R signify traditional and regulated deficit irrigation treatments, respectively. Treatments with letters in common do not significantly differ.

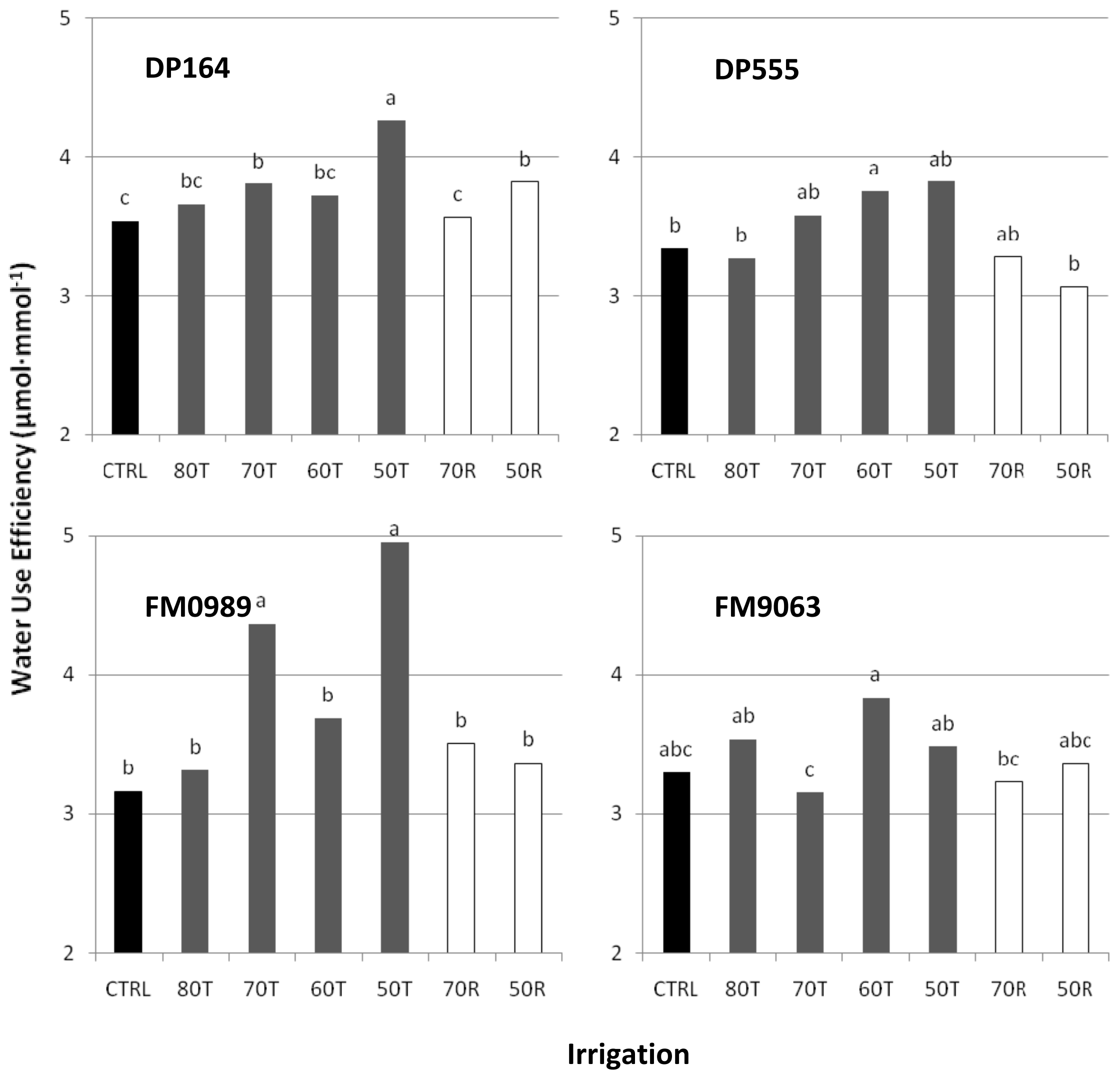

Figure 10. Water use efficiency (µmol CO2· mmol-1 H2O) of each variety at the first open boll stage (DAP 105) in 2008. T and R signify traditional and regulated deficit irrigation treatments, respectively. Treatments with letters in common do not significantly differ.

Discussion

Environmental patterns

The dramatic differences in climatic conditions between 2008 and 2009 were likely to be at least partially responsible for the different responses in lint yields and physiology between years, across irrigation treatments and varieties. The average daily maximum temperatures of the S2 (first flower until 10% open boll) in 2008 and 2009 were 35 to 36 °C and 38 to 40 °C, respectively. Considering the optimal temperature for cotton growth is 30/22 °C (Reddy et al., 1992b), the temperatures in both years may have introduced some high temperature stress that reduced lint yields (Reddy et al., 1995). Further, the climatic condition in 2009 likely caused significant crop heat stress, because the daily maximum temperature was 2 to 3 °C higher than the temperature in 2008, which was already higher than the optimal growth temperature range for cotton. In addition, approximately 17 mm of precipitation occurred during the flowering stage, which was approximately 50% less than the precipitation amount received in the same duration in 2008. Physiological responses of cotton plants to heat stress include the use of assimilates to produce defense compounds (e.g. heat shock proteins, HSPs) against heat stress (Abrol and Ingram, 1996; Vierling, 1991), thus limiting the amount available for fruit production. Also, under high temperature, less carbohydrate is accumulated due to exponentially increased photorespiration (Krieg, 1986; Perry et al., 1983) and declined photosynthetic rates caused by inhibition of rubisco activase which activates rubisco for carbon fixation in the Calvin cycle (Law and Crafts-Brandner, 1999). In consequence, the lint yields of some deficit irrigation treatments that were similar to the CTRL in 2008, were lower than the CTRL in 2009.

Lint yield and lint percentage

Within individual years, similar lint yield patterns across irrigation treatments did occur for some cotton varieties (Table 4). In 2008, both the 80T and the 70R treatments were able to maintain yield levels comparable to the CTRL treatment for most cotton 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 statistically in most of the cotton varieties, RDI may be a productive and possibly less extreme alternative to the TDI scheme for water savings. Both the 70T and the 50R treatments presented significantly reduced lint yields compared to the CTRL treatment, indicating that these treatments were not suitable for maintaining lint production.

In 2009, 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. Singh (2007) summarized several studies (Oosterhuis, 1999; Reddy et al., 1992a; Reddy et al., 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 may 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) may not respond to deficit irrigation scheme well enough under hot and dry climatic conditions (such as the 2009 summer) to maintain lint yield. Therefore, this makes the selection of cotton cultivar critical during years with extreme conditions and the decision to use TDI or RDI must be done cautiously.

The non-significant irrigation effect on lint percentage in both years indicates that lint percentage is primarily determined by variety. However, the minimum irrigation treatment in our study was 50%ET replacement; below this level of irrigation, varietal response may become significantly different. Pettigrew (2004a) 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, while no significance was detected between moderate or slightly stressed and stress-free treatments. Thus, at least for the adoptable irrigation treatments (i.e., 80T and 70R), the influence on lint percentage appears to be negligible.

Lint quality

Lint quality has a direct impact on the economic return to the producer in cotton production because these parameters determine the classification of lint, and the price 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 is about \$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 has a return of only \$1.09 kg^{-1} (\$0.06 kg^{-1} discount) even if all the other characteristics are the same. In this study, the results showed limited differences among both varieties and irrigation treatments for lint quality parameters. The numerical trend is obvious such that the less water applied, the lower the fiber quality. The most obvious 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 general, the responses of lint quality to irrigation treatment in our study were quite stable in both 2008 and 2009. In contrast, Pettigrew (2004a) reported inconsistency in the responses of fiber quality to irrigation treatments, which may be attributed to the inconsistent precipitation total among different growing seasons under dryland conditions. 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 any premiums or discounts according to the 2008 and 2009 loan rate references of upland cotton (USDA-FSA, http://www.apfo.usda.gov/FSA/webapp?area

=home&subject=prsu&topic=lor), which indicated that the economic return of lint does not differ among irrigation treatments or varieties in our case.

Plant morphology and physiology

In order to clearly show the differences between slight and severe drought stress responses on plant morphology and physiology, two deficit irrigation treatments, 70R (to represent slight drought stress) and 50T (to represent severe drought stress), were chosen for discussion. The morphological parameters of the two treatments (plant height, node number and fruit number) have clear trends that illustrate the relationship between increased stress and decreased growth and development. Generally speaking, reduced plant height, node number and fruit number were observed in the 50T than in the 70R treatment compared to the CTRL in both years (Table 8, 9 and 10). The only difference between 2008 and 2009 is that the reductions in these parameters were greater in magnitude for both the 50T and 70R treatments in 2009 than in 2008, i.e. the difference between deficit irrigation treatments and the CTRL were enhanced in 2009 compared to the difference in 2008. This phenomenon may be attributed to the heat stress introduced by high temperatures in the growing season of 2009 because high temperature can negatively affect cotton plant development (Meyer, 1969; Reddy et al., 1992b; Reddy et al., 1992c).

The gas exchange parameters show inconsistent results between 2008 and 2009. However, one consistency between the two years was the response in the 50T treatment which had significantly lower A_n and Tr than the measured values of these physiological parameters of the CTRL. In contrast, the 70R treatment did not show significant differences from the CTRL in either parameter through the flowering and boll-setting stages in 2008. However, in 2009, the 70R treatment had significantly lower A_n and Tr than the 50T treatment (and surely lower than the CTRL). The sharply decreased A_n and Tr may be attributed to different stomatal conductance and/ or osmotic adjustment of the 50T and 70R treatments to the heat stress in 2009. These significantly decreased values in A_n and Tr may also be related to differences in root architecture such as maximum root depth and root length density. Lower soil moisture in the 50T than the 70R treatments during the vegetative stage may have caused the crop root systems in the 50T treatment to be deeper and more developed than the 70R treatment. Other studies have shown that moderate soil water deficit enhances root growth and reduces shoot biomass accumulation (Malik et al., 1979; Pace et al., 1999; Tang et al., 2010). Also, considering that the plant height in the 50T treatment is shorter than the plant height of the 70R treatment, less evapotranspiration demand for the 50T treatment is expected. Thus, under heat stress during the flowering stage, deeper root systems of the 50T treatment could fulfill the ET demand, while relatively shallower root systems in the 70R treatment might not be able to support the ET requirement of taller plants, resulting in stomatal closure. However, even though the 70R treatment seems to have a significantly lower net assimilation rate, it does not necessarily mean the daily-averaged net assimilation rate of this treatment is lower than the rate of the 50T treatment. The sharply decreased A_n might be only temporary during the noon time when the air temperature is high. This was reflected by the yield of the 70R treatment, which was significantly higher than the lint yield of the 50T treatment.

The WUE_i patterns were also inconsistent between the two years. In 2008, the WUE_i of the 50T treatment was significantly higher than the CTRL and 70R treatments. This result is similar to the result reported by Liu *et al.* (2008). They conducted a pot-culture experiment on cotton to examine net assimilation rate and transpiration rate changes over soil water depletion. They also found that both A_n and Tr were decreased rapidly when soil became dry, but Tr decreased faster than A_n at the early stage of soil water depletion, which resulted in increased WUE_i. In our study in 2009, however, no significant difference of WUE_i was detected among all treatments. This inconsistency of WUE_i may again be due to high temperature stress. Zhou *et al.* (2010) studied the impacts of drought- and heat-stress conditions in poplar (*Populus euphratica*) leaves and concluded that under these conditions, the leaf surfaces were overheated; thus the stomata opened unequally at the cost of relatively low WUE_i, to dissipate the excess heat and to ensure the functionality of key enzymes for carbon and nitrogen metabolism. The osmotic adjustment process was also involved in drought resistance (Ackerson, 1981). For cotton, the physiological mechanism of the WUE_i inconsistency observed in 2009 might be attributed to a higher level of stomatal control and osmotic adjustment processes under high temperature conditions to reduce leaf damage at the cost of reduced WUE_i.

Although the slopes of the trends of morphological parameters (plant height, node number and fruit number) are slightly different in 2008 and 2009, the correlations between lint yield and morphological parameters seem to be positive. It has been well documented that cotton yields and boll number (Grimes et al., 1969; Singh and Narkhede, 2010; Wiatrak et al., 2006; Zeng and Meredith Jr, 2009) or plant height (Karademir et al., 2009) were positively correlated. These positive correlations may indicate that certain morphological parameters, such as plant height and boll number, can be used as quantitative indicators to estimate the potential lint yield before harvest.

Among all physiological parameters, net carbon assimilation rate (A_n), or net photosynthetic rate, has the potential to be directly related to crop yields because it is the carbon acquisition system for the plant. Zelitch (1982) commented that the whole-season net photosynthesis is closely related to crop yields, but the relationship between instantaneous A_n (point measurement) and yield appeared to be poor and misleading [see also Long *et al.* (2006)]. Under field conditions, many factors can contribute to the A_n variation of an individual leaf, such as irradiation, air temperature, water availability, cloud covering, and even developmental stage. Even if the first fully expanded leaf was used for A_n measurement, like in Ko and Piccinni (2009a), or our study, the ages of the leaves as well as the angles of these leaves may still have some differences, which can cause large measurement errors of A_n values within treatments (Zelitch, 1982). Another phenomenon that needs to be taken into consideration is the change of the diurnal curve of A_n. Wang et al. (2006) found in spring wheat (*Triticum aestivum*) that the daily A_n change presented a "typical two-hump curve", one in the morning and the other in the afternoon which is slightly lower than the peak shown in the morning. Pettigrew (2004b) also discussed the polarity characteristic of A_n during the daytime. He concluded that A_n

in the morning was higher than the values measured in the afternoon and this pattern may be due to the deterioration of the hydraulic status of plants caused by elevated demand of evapotranspiration in the afternoon. Pettigrew (2004a) went on to argue that the polarity characteristic may explain some inconsistency of the lint yield under irrigation in the Southeast USA. Further, the seasonal variation of the diurnal curves of A_n may differ between varieties as well, and these changes seem inconsistent (Liu et al., 2002). Due to the fact that all of our physiological parameters were measured between 1100h and 1400h on cloud-free days, the effect of diurnal variation of A_n within one variety should not be obvious. Thus, the unstable variations of A_n among different varieties could be the reason for the A_n inconsistency observed in our study in 2008 and 2009. It may also be possible that the inconsistency of the relationship between physiology and yield observed in 2009 was caused at least partially by high temperature impacts. The noon-to-afternoon depression in A_n mentioned above may be also caused by heat stress which inhibits PSII and reduces the quantum efficiency of the leaves (Correia et al., 1990). The inconsistency of the physiological responses may imply that the physiological parameters such as net assimilation rate or transpiration rate are not good direct predictors of lint yield if the measurements are conducted only on a point basis. Using seasonal cumulative net photosynthesis might be more appropriate in estimating lint yield. However, since our measurements were not operated on a continuously CO_2 exchange basis, we could not obtain the estimated cumulative net photosynthesis through the growing season and evaluate the correlation between seasonal photosynthesis and lint yield for this experiment.

Partitioning coefficients of certain plant tissues are widely used to evaluate the improvement of crop production through breeding processes (Gifford and Evans, 1981). In our study, the partitioning coefficients of boll dry weight in both years failed to show significance between deficit irrigation treatments and the CTRL, indicating that reallocation of carbohydrates may not be the major factor of maintaining lint yield for some deficit irrigation treatments such as 70R and 80T. The mechanism of lint yield maintenance may be attributed to a high retention rate of bolls under a slight stress condition (Rahman et al., 2008) rather than increasing WUE_i or A_n, or shifting allocation of assimilates.

In this study, four traditional and two regulated deficit irrigation treatments were evaluated against a full irrigation treatment (CTRL) for lint yield maintenance among several cotton varieties. The high temperature stress in the growing season of 2009 caused some inconsistency in the results compared to the results of 2008. The 80T and 70R treatments were found to be able to maintain lint yield similar to the CTRL in most of the varieties in both years. No significant lint percentage difference was detected among irrigation treatments, but there were differences observed in lint quality parameters. However, these differences did not significantly affect economic return based on price (loan rate). Morphological parameters reflected the differences in lint yield well and may be used as predictors of lint yield before harvest. On the contrary, physiological parameters failed to show a close relationship to the lint yield. The reason for the inconsistency in A_n may be attributed to the variation of its diurnal course changes over the growing season, and variety differences. Seasonal cumulative A_n

instead of instantaneous measurement of A_n may be a better parameter for predicting lint yield before harvest.

CHAPTER VI

SOIL MOISTURE: A FURTHER ANALYSIS

Introduction

Soil moisture monitoring is essential for good irrigation management. Soil water content can be used for irrigation scheduling (Garcia et al., 2009) because it can indicate the potential plant stress conditions reflected in crop yields (Ko and Piccinni, 2009). In our study, the major reason to monitor soil moisture was to ensure correct adjustment of the crop coefficient at each growth stage in the ET-based irrigation scheduling procedure. One of the widely used methods for monitoring soil moisture content in agricultural research (as well as in other fields) is that of neutron scattering through a neutron hydroprobe. This instrument allows for nondestructive and repeatable measuring characteristics (Li et al., 2003). Although satisfactory accuracy and high precision of the soil water content measurement can be obtained by this method, the radioactivity of the neutron probe limits its application in agronomic practices (Evett et al., 2009; Mwale et al., 2005). Capacitance sensors are considered as alternative instruments to measure soil water content because their use requires less regulation and training , and they provide possibilities of automatic data acquisition using data loggers (Evett et al., 2009; Evett et al., 2006). Through measuring the permittivity values (dielectric constants) of the adjacent soil layer and then converting them using equations either provided by the manufacturer or *in situ* calibration, the soil water content can be obtained (Evett et al., 2009; Evett et al., 2006; Mwale et al., 2005; Qi and Helmers, 2010). The profile probe (type PR2, Delta-T Devices, Cambridge, UK) is a multi-sensor capacitance probe that was reported to be lacking in accuracy when the default setup was used (Qi and Helmers, 2010). Calibration of the PR2 for each soil type, or over each soil depth, can significantly improve the accuracy of soil water content measurement (Qi and Helmers, 2010).

An alternative way to use the PR2 probe for irrigation scheduling is monitoring relative soil water content. Although the permittivity readings can be converted to volumetric soil water content using the manufacturer's default setup in the data logger, the changes observed in PR2 readings may not reflect the actual changes of the soil water content. In other words, the changes of PR2 readings need to be adjusted using coefficients to show the actual changes in soil water content. The adjustment coefficient describes the actual soil water content change when the soil water content measured by the PR2 probe changes by one unit. For instance, if the adjustment coefficient at the 20-cm depth is 0.5, and we observed through PR2 probe that the soil water content changes from 20% to 18%, we can calculate the actual soil water content change as $0.5 \times (20\% - 18\%) = 1\%$. With the help of this method, a relative soil moisture measurement using the PR2 probe with default setup could be used for irrigation scheduling purpose.

The objective of this analysis was to evaluate the statistical procedure of estimating adjusting coefficients for the PR2 probe of different soil depths and irrigation treatments.

Materials and Methods

The experiment was conducted on the research farm of the Texas AgriLife Research and Extension Center at Uvalde, TX in the 2009 growing season. The soil type is Uvalde silty clay loam (Fine-silty, mixed, active, hyperthermic Aridic Calciustolls) (Ko and Piccinni, 2009). The crop planted in the research field was upland cotton (*Gossypium hirsutum L.*), which included four cultivars, although only the cultivar DP555 (Monsanto Company, Chesterfield, MO) was used for the particular objectives of this study. Twelve plots were selected from the DP555 cv. that included three different irrigation treatments (full irrigation, CTRL; 70%ET replacement, 70T; and 50%ET replacement, 50T) and four replications. A neutron probe access tube and a PR2 probe access tube were installed in the center of each plot. The distance between the two access tubes was approximately one meter (40 in.). The neutron probe count readings were taken from the 20-cm, 40-cm and 60-cm depths. These counts were then divided by a standard count to compute the count ratios, which were then converted into volumetric soil water content (in %) using the site specific calibration equations obtained through field calibration (unpublished data). The PR2 readings were collected three times in each plot at several depths: 10-, 20-, 30-, 40-, 60-, and 100-cm, and the permittivity values were converted into volumetric soil water content (in %) automatically in the data logger using the manufacturer's default setup. Only the 20, 40 and 60 cm depths data were used in this analysis. Through the growing season in 2009, the soil moisture data from both methods were collected seven times (June 26 and 29; July 10, 23 and 27; August 12 and 17).

The data collected from both probes at each combination of measurement date, irrigation treatments and depths were paired. Unpaired data were removed from the data set. The statistical analysis involved two steps. First, both soil water content (PR2 and neutron probe) were used as dependent variables to fit two separated ANOVA with repeated measure (i.e., DAP) using the PROC MIXED model in SAS 9.2 (SAS Institute, Inc., Cary, NC). The significance of irrigation treatments, depth, and measurement timing (day after planting, DAP; as repeated measure) as well as all possible interactions were tested. Then, based on the ANOVA results, data were grouped by factors or factor-combinations (if one or more interaction terms were statistically significant) to fit simple linear regression models separately. The regression model can be described as:

$$\theta_{NP} = b_0 + b_1 \cdot \theta_{PR2}$$

where θ_{NP} and θ_{PR2} are volumetric soil water content measured by the neutron probe and PR2 probe at a certain depth, respectively. The slope, b_1, is the adjustment coefficient for PR2 probe readings.

Results and Discussion

The ANOVA result (Table 15) indicated that the data need to be grouped by each combination of depth, irrigation treatment and measurement time (DAP) because all three two-way interactions for neutron probe measurements were statistically significant. Table 16 showed the slope of each linear model, the R^2, and model significance.

Table 15. The ANOVA table of all possible impact factors to soil moisture measurements and their interactions. PR2 and Neutron signify the soil water content of the PR2 and neutron probes, respectively. TRT, DEPTH and DAP signify irrigation treatment, depth of measurement, and day after planting (when the soil moisture data were measured), respectively.

		PR2		Neutron	
	DF	P-value		P-value	
TRT (T)	2	<0.0001	**	<0.0001	**
DEPTH (D)	2	0.0083	**	<0.0001	**
T × D	4	0.3270	NS	<0.0001	**
DAP	6	<0.0001	**	<0.0001	**
DAP × T	12	0.0004	**	0.0316	*
DAP × D	12	0.5063	NS	<0.0001	**
DAP × T × D	24	0.6132	NS	0.4458	NS

**: significant at $p < 0.01$;.*: significant at $p < 0.05$; NS: not significant.
DF: degree of freedom.

Table 16. Adjustment coefficients (the slope of the regression function for neutron probe/ PR2 probe measurement) of volumetric soil water content measured by PR2 probe under different soil depths, irrigation treatments, and measurement time. Cells highlighted in gray show the useable adjustment coefficients for PR2.

IRRIGATION	DAP†																				
	67	R^2		70	R^2		81	R^2		94	R^2		98	R^2		114	R^2		119	R^2	
20cm‡																					
CTRL	-	-	-	-0.52	0.562	*	-0.36	0.444	*	0.71	0.479	*	-0.27	0.410	*	-0.28	0.933	**	-0.14	0.514	**
70T	-0.27	0.255	+	0.12	0.059	NS	0.98	0.289	+	0.34	0.145	NS	-0.03	0.001	NS	-0.11	0.188	NS	-1.51	0.793	**
50T	-1.11	0.673	**	-0.01	0.012	NS	-1.04	0.489	*	-0.42	0.439	+	-0.80	0.685	**	-0.45	0.721	**	-0.35	0.685	**
40cm																					
CTRL	-	-	-	0.05	0.037	NS	0.09	0.041	NS	***0.32***	***0.949***	**	0.01	0.001	NS	-0.09	0.554	NS	-0.10	0.790	**
70T	-0.11	0.607	**	0.18	0.614	*	0.25	0.417	*	***0.25***	***0.751***	**	0.06	0.023	NS	0.02	0.056	NS	0.22	0.323	+
50T	0.04	0.022	NS	-0.08	0.100	NS	0.4	0.372	+	0.25	0.169	NS	-0.10	0.018	NS	0.17	0.310	+	0.23	0.283	+
60cm																					
CTRL	-	-	-	0.12	0.108	NS	0.07	0.104	NS	***0.08***	***0.903***	**	-0.04	0.093	NS	0.07	0.192	NS	-0.15	0.611	**
70T	-0.23	0.596	**	***0.13***	***0.964***	**	0.07	0.429	*	***0.12***	***0.678***	**	***0.12***	***0.923***	**	0.02	0.211	NS	0.05	0.057	NS
50T	-0.06	0.134	NS	-0.24	0.322	NS	-0.33	0.395	*	***0.57***	***0.822***	**	0.09	0.021	NS	-0.05	0.019	NS	-0.13	0.109	NS

† DAP: day after planting. ‡ 20/40/60 cm are the depths soil moisture were measured.
**: p < 0.01; *: p < 0.05; +: p < 0.10; NS: not significant.

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In general, the adjustment coefficient, or the slope of the regression function, is expected to be non-negative, since the soil moisture measurements of both probes are presumed to be positively correlated. However, many negative "coefficients" were demonstrated in Table B, which are not useable adjustment coefficients for the PR2 probe. If the model significance exhibits a "not significant (NS)" value, the coefficient is not significantly different from zero; thus, the coefficients would not be a useable adjustment coefficient for PR2 either. With the exclusion of these two types of coefficients, a few groups were selected where the adjustment coefficients were "potentially useable" (cells marked in gray; see Table 16). These selected cells show some patterns. First, the timing of measuring soil water content had a significant influence on the correlations between the readings of the two types of probes. The best adjustment coefficients in each soil depth were all found at DAP 94 (approximately maximum flower stage). Secondly, the 70T irrigation treatment had the strongest correlation of soil moisture measured by the two probes than the other irrigation treatments. Third, better correlation between the neutron probe and PR2 probe measurements were found in deeper soil layers (60 cm). These results may imply that the measurements of the two types of probes correlate best in medium-wet soil rather than in dry or wet conditions. It was reported that capacitance probes perform better for soil moisture measurement under wet rather than dry conditions (Evett et al., 2009; Hignett and Evett, 2008). However, this was not confirmed under the wettest treatment (CTRL) in our study. Also, the temperature differences may explain the significant effect of measurement timing. This agrees with the results reported by Hignett and Evett (2008) that capacitive sensors (including PR1/6 and PR2) are sensitive to salt, electrical conductivity of soil (including water content) and temperature.

Evett et al. (2009) examined the accuracies and variabilities of a neutron probe and several electromagnetic devices including PR1/6 against the direct sampling measurements at Bushland, TX from 2003 to 2005. The experimental field had relatively uniform soil moisture as confirmed by both the neutron probe and gravimetric measurements that showed the variance of soil water content was small. Ten accessing tubes for each device were installed in an alley (transect) at 10-m intervals within a single treatment to evaluate the mean soil water content of the profile, and the standard deviation of these measurements. The gravimetric soil samples were taken multiple times between these alleys. All EM sensors as well as the neutron probe were calibrated specifically for the Pullman soil. They reported the means and standard deviations of soil water content for each device under dry and wet conditions, and calculated the minimum amount of measurements of each probe that was needed to reach a given precision and significance level. Their results showed much higher SDs in EM sensors than for neutron probes in all cases. The authors argued that EM sensors may be influenced by “the smaller scale structure of soil electrical properties” and/ or temperature, and concluded that EM sensors poorly reproduced the tempo-spatial variation demonstrated by neutron probe measurement and gravimetric sampling. Another published work described specifically how the PR2 sensor was calibrated (Qi and Helmers, 2010). They suggested that equations calibrated by data from a longer period (2-year in their case) performed better than data from a shorter period. They also reported the parameters of the calibration equations in different land covers, and the results showed the significance of the calibration results were influenced by soil depth and land use types. Another potential source of variance is the shrinking/ expanding characteristics of clay soil, which may cause loose contact between accessing tubes and the adjacent soil under dry conditions (Evett et al., 2009).

To summarize, in order for us to accomplish an acceptable comparison between two probes, the following conditions need to be fulfilled:

- Good laboratory or field calibration of both probes.
- Uniformity of the soil.
- Sufficient number of installed access tubes (ten in Evett et al., 2009) for variance estimation.
- Multiple gravimetric soil sample collections between two sets of tubes, and known soil bulk density (for volumetric soil water content conversion).
- Measurement under both dry and wet conditions (treatments).
- Repeated measurements over a certain period.
- Repeat of the experiment for at least one more year.

The data we collected during the 2009 growing season are lacking in several of the conditions mentioned above, especially the probe calibration. The soil in our field is not as uniform, and the sample number was only four for each irrigation treatment. As temperature influences the EM readings, timing of measurement would be another potential source of variance. The shrinking/ expanding characteristics of clay soil may also contribute some variation in the measurement. These factors may explain the poor correlations between the two types of probes in general. For clay soil at least, with the default conversion equation, the PR2 probe seems to be unable to adequately monitor soil moisture changes for irrigation scheduling over the whole growing season.

CHAPTER V

ECONOMIC ANALYSIS OF DEFICIT IRRIGATION SCHEMES

Profit Analysis under TDI and RDI Schemes: An ANOVA Approach

Although lint yield is the major concern in cotton production, the maximum profit may not be guaranteed when lint yield reaches the maximum. From this perspective, the profit rather than the lint yields should be used to decide which irrigation scheme (full irrigation, TDI or RDI) to adopt. Implementing an optimal irrigation scheme may not necessarily produce the same lint yield as the full irrigation scheme; however, the loss in lint production can be compensated by the reduced cost of irrigation application, including both the cost of water and other fees such as electricity cost for pumping and running the irrigation system.

A general financial budget model for cotton production can be described as follows (based on one hectare):

(1) The profit (PF) is the difference between the revenue (REV) and the total cost (TC), i.e., PF = REV – TC.

(2) The gross income is the production of the current lint price (p_L) and the lint yield (LY), i.e., REV = $p_L \cdot LY$.

(3) The total cost includes two portions, which are 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 we have TC = FC + VC = FC + $p_W \cdot$WI.

(4) According to (1) – (3), the whole model can be rewritten as:

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

The lint price is set to \$1.44/ kg, and the water price is \$0.15/ m^3, as reported by Dagdelen et al.(2009). The FC is arbitrarily set to \$750/ha, but since FC is not a function of WI, the value has no impact on the selection of irrigation regime. Using Eq. [3] and inserting the values stated above, we calculated the PF of each plot on a one-hectare basis and analyzed the PF values using PROC GLIMMIX in SAS 9.2.

The results of mean comparisons by variety, and across variety and irrigation treatment in both growing seasons (Table 17) show that in 2008, the 80T treatment produced the highest profit (\$574.96/ha). Compared to the profit of the CTRL treatment (\$460.63/ha), the profit obtained from the 70R and 50R treatments (\$414.77/ha and \$321.26/ha, respectively) are not significantly different. The 70T treatment shows a significantly lower profit (\$135.08/ha) than the profit of the CTRL. In 2009, the CTRL showed a significantly higher profit (\$1423.23/ha) than all the other treatments. The profit of the 70T treatment (\$699.96/ha) was not significantly different from the profit of the 80T treatment (\$838.02/ha). Comparing the 80T treatment to the profit of both RDI treatments (\$800.86/ha and \$708.92/ha, respectively) showed no significant difference. Most of the economic results obtained through the ANOVA approach support those of the lint yield mean comparison that 80T and 70R are adoptable deficit irrigation treatments under normal-year conditions. The 50R treatment, from an economic perspective, is adoptable under normal-year conditions, which is not an option based on the lint yield comparisons. Under the conditions of a hot-and-dry year such as 2009, the optimal irrigation treatment was the full replacement (CTRL), which was demonstrated in both lint yield and profit comparisons. In general, using the profit approach seems to be a better method to evaluate the performance of deficit irrigation regimes due to its intuitive characteristic, assuming the prices of lint and water are known.

Profit Analysis under TDI Scheme: Further Analysis through an Economic Modeling Approach

The ultimate goal of economic analysis is to find the optimal parameters that maximize profit and/or minimize loss. For an analysis in agriculture, the profit is determined partially by agronomic production, which is a function of some agronomic factors such as crop water consumption, fertilize application, temperature, sunshine hours, etc. This function describing the relationship between crop yield and agronomic factors is known as a production function. In this study, in order to simplify the discussion, only crop water use is considered as the variable agronomic factor. Thus, the production function can be described as $Y = f(W)$. A quadratic form of crop yield model has been widely accepted for practical use (Ali, 2011). The following discussions were based on a quadratic production function with respect to a total water consumption (WT). All calculations, unless specified, were based on one hectare (ha) of farmland. Due to different characteristics of TDI and RDI schemes, and different responses of crop

Table 17. 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 due to mis-operation of this treatment and are not present in the table.

	Lint Yield															
	2008								**2009**							
	$ ha^{-1}								$ ha^{-1}							
BY VAR	DP555		DP164		FM0989		FM9063		DP935		DP555		FM9180		DP949	
CTRL	1382.40	A†	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
MEAN																
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. † Mean values with the same letter group were not significantly different from each other.

varieties to water use, this model is limited to the condition of a single variety under TDI scheme. Assuming the irrigation water supply is unlimited (current situation), the objectives of the analysis in this section are to determine the optimal irrigation water amount to maximize the profit, and estimate the optimal water price to support adoption of deficit irrigation of a certain ratio.

The cotton lint yield (LY) is a quadratic function of total water consumption (WT) with maximum extreme value:

$$LY = b_0 + b_1 \cdot WT + b_2 \cdot WT^2 \quad [4]$$

where $b_2 < 0$.

The effective precipitation (P_e) was defined as the total amount of rainfall that was used by the crop. As such, the total water consumption (WT) is composed of two terms: irrigation water (WI), and effective precipitation (P_e). Taking the irrigation efficiency (r_i) into consideration,

$$WT = r_i \cdot WI + P_e \,.$$

In other words, the irrigation water can be calculated as

$$WI = \frac{WT - P_e}{r_i} \quad [5]$$

The revenue is the gross income obtained from the cotton lint, which is the product of the current cotton lint price (p_L) and lint yield:

$$REV = p_L \cdot LY \quad [6]$$

And the total cost (TC) of producing the cotton lint is

$$TC = VC + FC \Rightarrow TC = p_W \cdot WI + FC \quad [7]$$

The profit (PF) is the difference between revenue and total cost:

$$PF = REV - TC\ .$$

Substituting the components on the right-hand side of the equation using Eqs. [4] - [7] yields

$$PF = p_L b_2 \cdot WT^2 + \left(p_L b_1 - \frac{p_W}{r_i} \right) WT + (p_L b_0 + \frac{p_W P_e}{r_i} - FC) \quad [8]$$

which is also a quadratic function of total water consumption (WT).

The extreme value of PF is reached when the first derivate equals to zero, i.e.,

$$\frac{d(PF)}{d(WI)} = 2 p_L b_2 \cdot WT + (p_L b_1 - \frac{p_W}{r_i}) = 0\,.$$

Solve the above equation:

$$WT_{(\max)} = \frac{p_L b_1 - \dfrac{p_W}{r_i}}{-2 p_L b_2} \quad [9]$$

Check the second derivative of the PF function to ensure that the maximum value can be reached at this level of WT:

$$\frac{d^2(PF)}{d(WT)^2} = 2 p_L b_2 < 0\ .$$

Thus, the maximum profit [$PF_{(max)}$] is achieved when total water consumption reaches $WT_{(max)}$ given above. The maximum profit is given by

$$PF_{(\max)} = \frac{(p_L b_1 - \frac{p_W}{r_i})^2}{-4 p_L b_2} + (p_L b_0 + \frac{p_W P_e}{r_i} - FC) \qquad [10]$$

In this case, the optimal irrigation water can be computed using the optimal total water consumption:

$$WI_{(\max)} = \frac{WT_{(\max)} - P_e}{r_i}.$$

We would like to present a real case for further discussion. Taking our study as an example, a lint production function was built with respect to total water consumption (WT) based on the lint yield data of one cotton variety DP555 which was the only variety being planted in both the 2008 and 2009 growing seasons. As mentioned before, only the lint yield (averaged across the four replications) of the full irrigation and the four TDI treatments were used to establish this production function. The production function follows the same form as Eq. [4]:

$LY(DP555) = -1434.36 + 9.75 \times WT - 0.0068 \times WT^2$. (adj. $R^2 = 0.83$, RMSE = 177.2)

From the discussion of the previous section in this chapter, the lint price (p_L) is \$1.44/kg, and the water price (p_W) is \$0.15/m^3, which is equal to \$1.50/mm per hectare. The irrigation efficiency (r_i) is 95% for a LEPA system. The effective precipitation (P_e) was 141.5 mm and 50.4 mm for 2008 and 2009 growing seasons, respectively. With these parameters, the optimal total water consumption would be

$$WT_{(\max)} = \frac{1.44 \times 9.75 - \frac{1.50}{0.95}}{-2 \times 1.44 \times (-0.0068)} = 636.3\ mm.$$

In 2008, this optimal amount was 636.3/593.9 = 107.1% of the water consumption in the CTRL. In 2009, it was 636.3/542.7 = 117.2% of the water consumption in the CTRL. Neither case seems to support adopting deficit irrigation practices. Further studies on irrigation practice, especially the risk assessment for the deficit irrigation scheme, are needed to evaluate the adoptability of deficit irrigation.

A more interesting consideration is to know how much the water price would have to be to expect farmers to adopt deficit irrigation instead of full irrigation. Using this model, we can also estimate the water price at a chosen optimal deficit ratio and a given lint price. For a chosen deficit ratio, r_d, the total water use can be calculated as $r_d \cdot ET_c$. Assuming total water use amount to be the optimal total water consumption [i.e., $WT_{(max)}$] in Eq. [9], we can obtain the water price at this $WT_{(max)}$:

$$p_W = r_i(p_L b_1 + 2 p_L b_2 r_d ET_c)\,. \qquad [11]$$

Then, the profit under this irrigation regime can be computed using Eq.[10]. With Eqs.[10] and [11], the water prices and the related profit values of the CTRL and each TDI treatment for both 2008 and 2009 growing seasons were calculated at the lint price of \$1.44/kg, \$1.80/kg (+25%) and \$1.08/kg (-25%), shown in Tables 18 and 19. The profit values can be used to roughly estimate the breakeven water price in each case (at a given lint price in a certain year). Based on the model used in this study, it seems that the 80T regime may be applied (profit > 0) when lint price is relatively high (\$1.44/kg, \$1.80/kg) in 2008, but should not be adopted since the profits are negative in all three lint prices in 2009. If the water authorities increase the water price to force the farmers to adopt deficit irrigation, the consequences might vary from year to year. To incentivize local farmers to adopt deficit irrigation, an insurance product that can help farmers hedge the potential risks of deficit irrigation under extreme environmental conditions such as drought and heat may be necessary.

Although the water prices mentioned in the economic model are fixed in different cases (i.e. the same fee applies to each unit of water use), these prices can be treated as weighted average water prices if a multi-level water price policy is used. For example, in a two-level water price system, a lower price is charged up to the quota, and a much higher price is applied to the portion that exceeds the quota. This may also be a measure to incentivize the farmers to use less water.

In this chapter we conducted two types of economic analyses and discussed some major issues related to farmers' profit. The ANOVA approach showed that the profit values obtained under three deficit irrigation regimes (80T, 70R and 50R) did not significantly differ from the CTRL in a normal year. Through the economic modeling approach based on the TDI data collected from the DP555 variety in both years, however, we failed to confirm the results of the ANOVA approach. Since this model was built using only two years of yield data, it may have its limitation in estimating the production function. A possible way to improve the economic model is to use multiple-year data to build the production function, and take risk into account in the model. Still, this model suggests that at current water prices, it is not optimal to adopt deficit irrigation. If adopting deficit irrigation is expected in the future, water prices would be increased. However, the consequence depends on the weather conditions, especially that of (effective) precipitation. Also, lint price fluctuation will impact the adoptability of deficit

Table 18. The water prices and profits of the control and four traditional deficit irrigation regimes in 2008.

(a) lint price = $1.44/kg

Regime	Fixed Cost	Water Price	Optimal Total Water Use	Effective Rainfall	Irrigation Water	Variable Cost	Total Cost	Lint Price	Lint Yield	Revenue	Profit
	$	$/mm	mm	mm	mm	$	$	$/kg	kg	$	$
optimal	750.00	1.50	636.3	141.5	494.8	742.18	1492.18	1.44	2016.4	2903.59	1411.41
CTRL	750.00	2.29	593.9	141.5	452.4	1035.37	1785.37	1.44	1957.7	2819.07	1033.70
80T	750.00	4.50	475.1	141.5	333.6	1500.79	2250.79	1.44	1663.0	2394.77	143.98
70T	750.00	5.60	415.7	141.5	274.2	1536.63	2286.63	1.44	1443.8	2079.01	-207.62
60T	750.00	6.71	356.3	141.5	214.8	1441.23	2191.23	1.44	1176.5	1694.16	-497.06
50T	750.00	7.81	297.0	141.5	155.5	1214.58	1964.58	1.44	861.3	1240.25	-724.33

(b) lint price = $1.80/kg (increases by 25%)

Regime	Fixed Cost	Water Price	Optimal Total Water Use	Effective Rainfall	Irrigation Water	Variable Cost	Total Cost	Lint Price	Lint Yield	Revenue	Profit
	$	$/mm	mm	mm	mm	$	$	$/kg	kg	$	$
optimal	750.00	1.50	652.4	141.5	510.9	766.37	1516.37	1.80	2032.3	3658.13	2141.76
CTRL	750.00	2.86	593.9	141.5	452.4	1294.21	2044.21	1.80	1957.7	3523.84	1479.63
80T	750.00	5.62	475.1	141.5	333.6	1875.98	2625.98	1.80	1663.0	2993.46	367.48
70T	750.00	7.00	415.7	141.5	274.2	1920.78	2670.78	1.80	1443.8	2598.76	-72.03
60T	750.00	8.39	356.3	141.5	214.8	1801.53	2551.53	1.80	1176.5	2117.71	-433.83
50T	750.00	9.77	297.0	141.5	155.5	1518.22	2268.22	1.80	861.3	1550.31	-717.91

(c) lint price = $1.08/kg (decreases by 25%)

Regime	Fixed Cost	Water Price	Optimal Total Water Use	Effective Rainfall	Irrigation Water	Variable Cost	Total Cost	Lint Price	Lint Yield	Revenue	Profit
	$	$/mm	mm	mm	mm	$	$	$/kg	kg	$	$
optimal	750.00	1.50	609.4	141.5	467.9	701.87	1451.87	1.08	1982.0	2140.56	688.69
CTRL	750.00	1.72	593.9	141.5	452.4	776.53	1526.53	1.08	1957.7	2114.30	587.78
80T	750.00	3.37	475.1	141.5	333.6	1125.59	1875.59	1.08	1663.0	1796.08	-79.51
70T	750.00	4.20	415.7	141.5	274.2	1152.47	1902.47	1.08	1443.8	1559.25	-343.22
60T	750.00	5.03	356.3	141.5	214.8	1080.92	1830.92	1.08	1176.5	1270.62	-560.30
50T	750.00	5.86	297.0	141.5	155.5	910.93	1660.93	1.08	861.3	930.19	-730.75

Table 19. The water prices and profits of the control and four traditional deficit irrigation regimes in 2009.

(a) lint price = $1.44/kg

Regime	Fixed Cost	Water Price	Optimal Total Water Use	Effective Rainfall	Irrigation Water	Variable Cost	Total Cost	Lint Price	Lint Yield	Revenue	Profit
	$	$/mm	mm	mm	mm	$	$	$/kg	kg	$	$
optimal	750.00	1.50	636.3	50.4	585.9	878.83	1628.83	1.44	2016.4	2903.59	1274.76
CTRL	750.00	3.24	542.7	50.4	492.3	1595.63	2345.63	1.44	1854.2	2670.06	324.43
80T	750.00	5.26	434.2	50.4	383.8	2018.78	2768.78	1.44	1516.9	2184.39	-584.40
70T	750.00	6.27	379.9	50.4	329.5	2065.98	2815.98	1.44	1288.2	1855.03	-960.94
60T	750.00	7.28	325.6	50.4	275.2	2003.58	2753.58	1.44	1019.4	1468.00	-1285.58
50T	750.00	8.29	271.4	50.4	221.0	1831.58	2581.58	1.44	710.6	1023.28	-1558.30

(b) lint price = $1.80/kg (increases by 25%)

Regime	Fixed Cost	Water Price	Optimal Total Water Use	Effective Rainfall	Irrigation Water	Variable Cost	Total Cost	Lint Price	Lint Yield	Revenue	Profit
	$	$/mm	mm	mm	mm	$	$	$/kg	kg	$	$
optimal	750.00	1.50	652.4	50.4	602.0	903.02	1653.02	1.80	2032.3	3658.13	2005.11
CTRL	750.00	4.05	542.7	50.4	492.3	1994.54	2744.54	1.80	1854.2	3337.57	593.03
80T	750.00	6.58	434.2	50.4	383.8	2523.48	3273.48	1.80	1516.9	2730.48	-543.00
70T	750.00	7.84	379.9	50.4	329.5	2582.47	3332.47	1.80	1288.2	2318.79	-1013.68
60T	750.00	9.10	325.6	50.4	275.2	2504.47	3254.47	1.80	1019.4	1835.00	-1419.47
50T	750.00	10.36	271.4	50.4	221.0	2289.48	3039.48	1.80	710.6	1279.10	-1760.38

(c) lint price = $1.08/kg (decreases by 25%)

Regime	Fixed Cost	Water Price	Optimal Total Water Use	Effective Rainfall	Irrigation Water	Variable Cost	Total Cost	Lint Price	Lint Yield	Revenue	Profit
	$	$/mm	mm	mm	mm	$	$	$/kg	kg	$	$
optimal	750.00	1.50	609.4	50.4	559.0	838.52	1588.52	1.08	1982.0	2140.56	552.04
CTRL	750.00	2.43	542.7	50.4	492.3	1196.72	1946.72	1.08	1854.2	2002.54	55.82
80T	750.00	3.95	434.2	50.4	383.8	1514.09	2264.09	1.08	1516.9	1638.29	-625.80
70T	750.00	4.70	379.9	50.4	329.5	1549.48	2299.48	1.08	1288.2	1391.27	-908.21
60T	750.00	5.46	325.6	50.4	275.2	1502.68	2252.68	1.08	1019.4	1101.00	-1151.68
50T	750.00	6.22	271.4	50.4	221.0	1373.69	2123.69	1.08	710.6	767.46	-1356.23

irrigation. All these uncertainties need to be covered by agricultural insurance programs to incentivize the farmers to save water through deficit irrigation.

CHAPTER VI

CALCULATION OF ACTUAL WATER SAVING RATIOS

The actual water saved in an irrigation scenario in a given year is not constant. The savings through a TDI scheme depends on the total amount of precipitation during the growing season. For an RDI scheme, the precipitation total is not the only impact factor; the amount of precipitation at different crop growth stages, i.e. the precipitation distribution over the growing season, has to be taken into consideration as well. In this case, the effective precipitation (P_e) is equal to the sum of the effective portion of each rainfall event across the irrigation stages (S1-S3). In each rainfall event, if the precipitation received exceeds the cumulative water loss of the control, only the portion that replaced the water loss is recorded, as effective; otherwise, all received rainfall is effective.

The water balance of the CTRL is described as follows:

$$ET = P_e + r_i \cdot I_o \quad [12]$$

where ET is the total evapotranspiration of the irrigation period, r_i is the irrigation efficiency (0.95 for a LEPA system), and I_o is the total irrigation amount of the CTRL.

In a TDI regime, the ET is partially replaced (in a ratio of r_d); thus, the water balance is:

$$r_d \cdot ET = P_e + r_i \cdot I_t \quad [13]$$

where I_t is the total irrigation amount of the TDI treatment.

Using Eqs. [12] and [13], the actual water saved from the TDI treatment (φ_t) is calculated as:

$$\varphi_t = 1 - \frac{I_t}{I_o} = 1 - \frac{r_d \cdot ET - P_e}{ET - P_e}$$

$$\Rightarrow \varphi_t = 1 - r_d + \frac{(1 - r_d)P_e}{ET - P_e} \quad [14]$$

According to the definition of the effective precipitation, $P_e < ET$, and $r_d < 1$; thus

$$\varphi_t > (1 - r_d),$$

which implies that the actual water saving ratio is higher than the difference between 1 and the selected deficit ratio. When the 80T regime is used, the actual water saved is more than 1 – 80% = 20% as long as precipitation events occur.

The RDI scheme involves several deficit ratios through the growing season; thus, the water balance equation includes more terms:

$$\sum (r_{d(i)} \cdot ET_{(i)}) = P_e + r_i \cdot I_r, \quad [15]$$

where $ET_{(i)}$ represents the evapotranspiration at stage i, $r_{d\,(i)}$ is the deficit ratio of stage i, and I_r is the total irrigation amount of the RDI treatment. Using Eqs. [12] and [15], the actual water saved from an RDI treatment (φ_r) can be computed as

$$\varphi_r = 1 - \frac{\sum (r_{d(i)} \cdot ET_{(i)}) - P_e}{ET - P_e} \quad [16]$$

The average deficit ratio ($\bar{r}_d$) is defined as

$$\bar{r}_d = \frac{\sum (r_{d(i)} \cdot ET_{(i)})}{ET} \quad [17]$$

Then Eq. [16] can be rewritten as

$$\varphi_r = 1 - \overline{r}_d - \frac{(1-\overline{r}_d)P_e}{ET - P_e} \qquad [18]$$

which follows the same form as the actual water saving ratio of the TDI scheme. Again, the actual water saving ratio is less than the theoretical one.

In Chapter II, we defined three irrigation stages based on the plant phenological stages and assigned different deficit ratios for each stage (see Table 1). According to Eq. [17], the average deficit ratio in our study can be calculated as:

$$\overline{r}_d = \frac{r_{d(1)} \cdot ET_{(1)} + r_{d(2)} \cdot ET_{(2)} + r_{d(3)} \cdot ET_{(3)}}{ET} \qquad [19]$$

which is an ET-weighted average of the deficit ratio in each irrigation stage. As $r_{d(2)}$ and $r_{d(3)}$ were set to 1.0 and 0.1, respectively, the RDI scheme was determined only on $r_{d(1)}$, which was the deficit ratio of the pre-flowering stage (S1).

Assuming a deficit ratio, r_d, is chosen as the ratio of S1. If we wish the average deficit ratio to be no larger than r_d, according to Eq. [19] we have:

$$\overline{r}_d = \frac{r_d \cdot ET_{(1)} + ET_{(2)} + 0.1 \cdot ET_{(3)}}{ET} \leq r_d \, ,$$

and

$$ET = ET_{(1)} + ET_{(2)} + ET_{(3)} \, .$$

Thus,

$$ET_{(2)} + 0.1 \cdot ET_{(3)} \leq r_d \cdot ET_{(2)} + r_d \cdot ET_{(3)}$$

$$\Rightarrow \frac{ET_{(2)}}{ET_{(3)}} \leq \frac{r_d - 0.1}{1 - r_d} \qquad [20]$$

The threshold ET ratio of S2 and S3 (η) is defined as

$$\eta = \frac{r_d - 0.1}{1 - r_d} \qquad [21]$$

Then,

$$\frac{ET_{(2)}}{ET_{(3)}} \le \eta .$$

The actual water saving ratio of each irrigation treatment calculated using Eqs. [14] and [18] is shown in Table 20.

Table 20. The actual water saving ratios (φ) of the TDI and RDI treatments in 2008 and 2009.

	Irrigation	Effective Precipitation	Total Water Used	φ
	mm	mm	mm	
2008				
CTRL	452.4	141.5	593.9	-
80T	329.6	141.5	471.1	27.14%
70T	266.2	141.5	407.7	41.16%
60T	253.0	141.5	394.5	44.08%
50T	159.6	141.5	301.1	64.72%
70R	328.9	141.5	470.4	27.30%
50R	283.2	141.5	424.7	37.40%
2009				
CTRL	493.2	50.4	543.6	-
80T	389.7	50.4	440.1	20.99%
70T	315.0	50.4	365.4	36.13%
60T	266.3	50.4	316.7	46.01%
50T	222.5	50.4	272.9	54.89%
70R	361.0	50.4	411.4	26.80%
50R	334.1	50.4	384.5	32.26%

In the 70R treatment, if we expect that $\bar{r}_d = r_d = 0.7$, the threshold $\eta_{70R} = 2$, which implies that the ET of S2 should not exceed twice as much as the ET of S3. Similarly, $\eta_{50R} = 0.8$. In 2008 and 2009, the calculated ET(2) to ET(3) ratios were both approximately 5.7 (Table 21). Given such a higher rate, the RDI scheme needs to be further adjusted to fulfill the expectation that the average deficit ratio is equal to the deficit ratio of the first stage at the minimum.

Table 21. The evapotranspiration in each growing stage in 2008 and 2009.

Year	S1	S2	S3	Total
2008	171.2	376.9	66.3	614.4
2009	202.2	312.4	55.1	569.7

CHAPTER VII

CONCLUSIONS

Two types of deficit irrigation schemes, traditional and regulated deficit irrigation, were evaluated through on-farm experiments in Uvalde, TX in the summers of 2008 and 2009. Based on the results and discussions, the following conclusions were drawn:

1) 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. The 70%ET-initial RDI scheme (70R) performed well in maintaining lint yield in most cotton varieties tested. The significant changes detected in lint quality failed to introduce premiums or discounts in cotton price.

2) The morphological parameters of the two treatments (plant height, node number and fruit number) showed clear trends that illustrate the relationship between increased stress and decreased growth and development. Since the correlations between lint yield and morphological parameters seem to be positive, these morphological parameters can be used as quantitative indicators to estimate the potential lint yield before harvest.

3) The high temperature stress in the growing season of 2009 caused some inconsistency in the results of physiological responses compared to the results of 2008. Although net carbon assimilation rate (A_n), or net photosynthetic rate, has the potential to be directly related to crop yields because it is the carbon acquisition system for the plant, the observed inconsistency of the physiological responses, especially on net

carbon assimilation rate, may imply that the physiological parameters such as net assimilation rate or transpiration rate are not good direct predictors of lint yield if the measurements are conducted only on a point basis.

4) The partitioning coefficients of boll dry weight in both years failed to show significance between deficit irrigation treatments and the control, indicating that reallocation of carbohydrates do not seem to be the major factor in maintaining lint yield for some deficit irrigation treatments such as 70R and 80T. The mechanism of lint yield maintenance may be attributed to a high retention rate of bolls under a slight stress condition rather than increasing WUE_i or A_n, or shifting allocation of assimilates.

5) The results of the ANOVA approach still support those of the lint yield mean comparison that 80T and 70R are adoptable deficit irrigation treatments under normal-year (such as 2008) conditions. The 50R treatment, from an economic perspective, is adoptable under normal-year conditions, which is not an option based on the lint yield comparisons. Thus, using the ANOVA approach to analyze profit seems to be a better method to evaluate the performance of deficit irrigation regimes due to its intuitive characteristic, assuming the prices of lint and water are known.

6) The economic modeling approach based on the TDI data collected from the DP555 variety in both years failed to confirm the results of the ANOVA approach. Since this model was built using only two years of yield data, it may have its limitation in estimating the production function. This model suggests that at current water prices, it is not optimal to adopt deficit irrigation. If adopting deficit irrigation is expected in the future, water prices would be increased, but the consequence depends on the weather

conditions, especially (effective) precipitation. Also, lint price fluctuation will affect the adoptability of deficit irrigation.

7) The actual water saved in an irrigation scenario in a given year is not constant. The savings through a TDI scheme depend on the total amount of precipitation during the growing season. For an RDI scheme, the precipitation total is not the only impact factor; the amount of precipitation at different crop growth stages, i.e. the precipitation distribution over the growing season, has to be taken into consideration as well.

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