MODELING COTTON AND WINTER WHEAT GROWTH AND YIELD RESPONSES TO IRRIGATION MANAGEMENT IN THE TEXAS HIGH PLAINS AND ROLLING PLAINS

A Dissertation

by

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ABSTRACT

A significant portion of the intensively cultivated agricultural areas in the U.S. is located in the Texas High Plains and Rolling Plains. In recent years, decreasing ground water supplies and precipitation variability are presenting challenges for profitable cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.) production in these regions. A field study was conducted in 2012 and 2013 at Chillicothe, TX, to investigate the growth, yield, and water use efficiency (WUE) responses of cotton cultivars under different irrigation and tillage treatments. Results revealed that deficit irrigation of 45% of cotton evapotranspiration (ET) increased the dryland yield and WUE by 260% and 39%, respectively. The irrigation-by-variety interaction showed that the 90% ET replacement treatment involving PHY375 produced the greatest lint yield and WUE. Tillage did not significantly affect lint yield, WUE, and fiber quality. Increasing irrigation resulted in a linear increase in fiber length and strength, and a linear decrease in fiber micronaire. Two vegetation indices, Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) were calculated using spectral reflectance dat. During the peak growing season, NDWI performed better compared to NDVI as no saturation problems were observed. The Crop Water Stress Index (CWSI) calculated using canopy and air temperature measurements showed significant differences among irrigation treatments. It was also observed that the CWSI and NDWI were negatively correlated. A modeling study was performed using the cotton growth simulation model, Cotton2K, to investigate the lint yield, WUE, and economic return responses using 31 years weather records (1980 – 2010) from the Texas Rolling Plains. Results revealed that replacing 112% ET maximized the yield while economic return was maximized at 108% ET. When water resources are limited, deficit irrigation at 80% ET replacement can be used to improve cotton WUE without significant yield and economic reductions in the semi-arid Texas Rolling Plains. A third study was performed on winter wheat using the DSSAT-CERES-Wheat model to investigate winter wheat growth and yield responses to irrigation management in the Texas High Plains using long-term weather datasets available for the Texas High Plains region (1980-2012). Results of winter wheat response to irrigation indicated that deficit irrigation between jointing and anthesis could significantly increase winter wheat grain yield and WUE. Application of 100 mm of irrigation at jointing and 120 mm at anthesis was found to produce a grain and biomass yields and WUE similar to full irrigation with significant amount of water saving.

DEDICATION

I dedicate this dissertation to the soul of my father, Dr. Mohamed Attia, who was the inspiration for me to hang on to my dreams. I also dedicate this dissertation to my mother, Amal Ibrahim, for her affection, help, and encouragement throughout my life.

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CHAPTER I

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.) are two major field crops grown in Texas. The majority of cotton and wheat producing areas of Texas is located in the semi-arid Texas High Plains and Rolling Plains. Twenty seven counties in the Texas High Plains account for approximately 64% of cotton production and 34% of wheat production in Texas (USDA-NASS, 2010 and 2012). Twenty two counties in the Texas Rolling Plains account for approximately 15-20% of the total cotton production and 21% of wheat production in the state (USDA-NASS, 2010). Of the 5 million acres of land planted to cotton each year in Texas, about 64% is irrigated. Approximately 75% of total acreage in the Texas High Plains and 17% of total acreage in the Texas Rolling Plains are irrigated (Colaizzi et al., 2008; USDA-NASS, 2010).

The Ogallala aquifer is the main source of irrigation water in the Texas High Plains (Rajan, 2010). Ogallala is a vast underground aquifer spanning across the High Plains of Texas, New Mexico, Oklahoma, Kansas, Colorado, and Nebraska. This aquifer was discovered in the early 20th century by the early settlers in the region (Allen et al., 2007). By the mid-20th century, the use of improved irrigation systems transformed this region into one of most intensively cultivated agricultural regions in the U.S. More than 90% of the water pumped from the Ogallala aquifer is currently used for supporting irrigated crop production in the region (TWDB, 2011; Nair et al., 2013). In many areas of the Texas High Plains, the withdrawal rate of water from the aquifer exceeds the recharge rate and the ground water levels are declining rapidly (TWDB, 2012). The growing concern for the depletion of the Ogallala aquifer has resulted in several proposals to conserve the aquifer water. Recently, regulations have been enacted by the High Plains Underground Water Conservation District (HPUWCD) in portions of the Texas High Plains for restricting the annual amount of water that can be pumped from the Ogallala aquifer for irrigation (Nair et al., 2013; Wang and Nair, 2013). This new restriction on pumping water from the Ogallala aquifer is popularly known as the "50/50" rule. The goal of this "50/50" rule is to have a minimum of 50% saturated thickness of Ogallala aquifer still available after 50 years. Pumping limits have been proposed to limit the allowable annual water extraction to provide a total irrigation of 21, 18, and 15 inches per contiguously owned acre of land for the periods of 2012–2013, 2014–2015, and 2016 and beyond, respectively (HPUWCD, 2012).

The Seymour Aquifer is the major source of irrigation water in the Texas Rolling Plains. The shallow Seymour Aquifer is highly permeable and sensitive to seasonal changes in rainfall. It recharges at a rate of 25 to 63.5 mm per year (Scanlon et al., 2003). Expanding acreage using the current furrow and pivot irrigation systems in the Texas Rolling Plains region is challenging because the ground water resources of the Seymour Aquifer are nearly fully utilized (Sij et al., 2010). Thus, expanding irrigated acreage requires efficient management of ground water resources and installation of efficient irrigation systems, such as sub-surface drip irrigation (SDI). Many research studies have found that SDI is more efficient than center-pivot and furrow irrigation (Camp et al., 1998; Colaizzi et al., 2004; Grismer, 2002; Dagdelen et. al., 2009). In addition to choosing the irrigation system, efficient management of ground water resources is possible through crop and variety section, irrigation management, and conservation tillage, to name a few (Rajan, 2007).

Irrigation of crops to meet the maximum daily water demand or evapotranspiration (ET) is often challenging due to declining aquifer water levels and increasing pumping costs (Nair et al., 2013). Studies have shown that some deficit irrigation strategies will not significantly reduce crop yield. For example, Falkenberg et al. (2007) reported that irrigation at 75% of maximum ET produced lint yield on par with fully irrigated cotton in Southwest Texas. Basal et al. (2009) reported that deficit irrigation at 75% of maximum ET decreased the yield by only 8% as compared to full irrigation. Musick et al. (1984) and Oweis et al. (2000) reported that deficit irrigation significantly increased winter wheat grain yield, ET, and WUE compared to dryland wheat. Xue et al. (2006) reported that deficit irrigation in wheat between jointing and anthesis significantly increased grain yield and WUE. Sun et al. (2006) reported that excessive irrigation increased seasonal ET without significant increase in grain yield or WUE of winter wheat (S).

The ability of field studies to indentify irrigation water management strategies depends on the number of treatments that we can include in these studies. Including a large number of treatments to study various factors and their interactions may not be feasible due to lack of facilities. In such situations, plant growth simulation models can be used to answer such questions. Under field conditions, a number of factors including climate, soils, and management strategies affect plant growth and development. After calibration and validation using field data, crop models can integrate the effects of dynamic soil, management, and weather factors to simulate plant growth. Models can also be used to study plant growth and development under current and future climate conditions. Crop growth models can also be combined with remotely sensed data for better yield predictions.

The research presented in this dissertation includes results from a field study conducted in the Texas Rolling Plains for investigating the effect of irrigation on cotton growth, and yield, and fiber quality (Chapters II and III). The data from this study was used for calibrating and validating a cotton plant growth simulation model, Cotton 2K. After calibration and validation, the cotton 2K model was used for simulating cotton lint yield and water use efficiency (WUE) responses to irrigation management practices in the Texas Rolling Plains using historical weather data set (Chapter IV). Winter wheat grain yield responses to irrigation water management strategies were investigated using the DSSAT-CSM-CERES wheat model. Data from published studies conducted in the Texas High Plains was used to calibrate and validate the DSSAT-CSM-CERES wheat model. The calibrated model was used to simulate winter wheat grain yield response to irrigation practices using historical weather data from the Texas High Plains. This is presented as Chapter V. The final chapter (Chapter VI) is a summary of the major findings from this dissertation research.

CHAPTER II

COTTON YIELD, FIBER QUALITY, AND WATER USE EFFICIENCY RESPONSES TO IRRIGATION AND TILLAGE MANAGEMENT IN THE TEXAS ROLLING PLAINS

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is a major field crop grown in the Texas Rolling Plains accounting for approximately 13% of cotton production in Texas (USDA-NASS, 2010). In this semi-arid region, the growth and yield of cotton is mainly determined by the amount of water available from precipitation and/or irrigation. The Seymour Aquifer is the major source of irrigation water in the Texas Rolling Plains. The shallow Seymour Aquifer is highly permeable and sensitive to seasonal changes in rainfall. It recharges at a rate of 25 to 63.5 mm per year (Scanlon et al., 2003). Expanding acreage using the current furrow and pivot irrigation systems in the Texas Rolling Plains region is challenging because the ground water resources of the Seymour Aquifer are nearly fully utilized (Sij et al., 2010). Thus, expanding irrigated acreage requires efficient management of ground water resources and installation of efficient irrigation systems, such as sub-surface drip irrigation (SDI). Many research studies have found that SDI is more efficient than center-pivot and furrow irrigation (Camp et al., 1998; Colaizzi et al., 2004; Grismer, 2002; Dagdelen et. al., 2009). In addition to choosing the irrigation system, efficient management of ground water resources is possible through crop and variety section, irrigation scheduling, and conservation tillage, to name a few (Rajan, 2007).

Yield of irrigated cotton is usually two to four times greater than dryland cotton, but depends on the amount of irrigation and the type of irrigation system (TAWC, 2012; Wanjura et al., 2002; Basal et al., 2009; Rajan et al., 2014). In addition to yield, fiber quality is also a function of growing season conditions, genetic background, and management practices including irrigation. Irrigation of crops to meet the maximum daily water demand or ET is often challenging due to declining aquifer water levels and increasing pumping costs (Nair et al., 2013). Studies have shown that some deficit irrigation strategies will not significantly reduce lint yield in cotton. Falkenberg et al. (2007) reported that irrigation at 75% of maximum ET produced lint yield on par with fully irrigated cotton in Southwest Texas. Basal et al. (2009) reported that deficit irrigation at 75% of maximum ET decreased the yield by only 8% as compared to full irrigation.

ET-based irrigation scheduling is the most popular method because of its simplicity in calculating daily irrigation needs. In recent years, methods of estimating crop water demand evaluated on a field-by-field basis that can account for non-standard conditions are also becoming popular in irrigation management (Rajan and Maas, 2014). Such field-specific irrigation scheduling would be beneficial when water for irrigation is limited. Brodovsky et al. (1992) reported that deficit irrigation enhanced cotton lint yield and conserved water resources in the Southern Texas High Plains. Benefits of deficit irrigation include increasing the WUE. Previous research reported higher irrigation

WUE of deficit irrigation compared to full irrigation (Dagdelen et al., 2009; Brodovsky et al., 2011; DeLaune et al., 2012). Deficit irrigation can prevent plants from being too stressed in critical growth stages like flowering. Imposing water deficit during peak flowering reduced the lint yield more than imposing water deficit either at earlier or later stages (Mauney and Stewart, 1986). Others reported that the period from squaring to first flower is the most critical period in terms of water supply effect on yield components and fiber quality. Water stress usually results in decreasing fiber quality especially fiber length and strength (Ritchie et al., 2004; Dagdelen et al., 2009; Feng et al., 2014).

Very few studies in the Texas Rolling Plains have investigated lint yield, WUE, and fiber quality responses of cotton cultivars under different irrigation conditions. Therefore, the objectives of this study are (1) to investigate growth and spectral reflectance response of cotton under different irrigation levels in the semi-arid Texas Rolling Plains, and (2) to compare lint yield, WUE, and fiber quality of four cotton varieties under different irrigation and tillage management practices.

MATERIALS AND METHODS

Site Description and Cultural Practices

The study was conducted in 2012 and 2013 at the Chillicothe Research Station of Texas A&M AgriLife Research near Vernon, TX (34º15'N and 99º30'W; 431 m above mean sea level). Cotton was planted on 23 May in both growing seasons at a seeding rate of 10 seeds per m of row. Row spacing was 1 m. The field was irrigated using subsurface drip irrigation installed at a depth of 30 cm. The emitter spacing was 50 cm. The crop rows were oriented east-west. The soil in the field was an Abilene clay loam (fine, mixed, superactive, thermic Pachic Agriustolls) with 0 to 1% slope (Soil survey staff, 2004). The climate of the study region is semiarid with a mean long-term annual precipitation of 560 mm. About two-thirds of the precipitation is normally received during the growing season (Table 2.1). The nitrogen fertilizer rate was determined based on a yield goal of 1680 kg lint ha^{-1} which is about 168 kg N ha^{-1}. Soil samples were collected in late spring to determine the residual N content in the top 60 cm of soil. After considering the residual soil N, remaining N was applied as urea ammonium nitrate (28-0-0) in two split applications which included planting and first-square stage. In 2012, 0.876 L ha^{-1} Lorsban-4E [O-O-diethyl-O-(3,5,6-trichloro-2-pyridinyl)-phosphorothioate] and 4.67 L ha^{-1} Karate [3-phenoxyphenyl- methyl-3-(2-choloro-3,3,3-trufuoro-1-propenyl)-2,2-dimethyl-cyclopropane-carboxylate] were applied for insect control. Pre-emergence Ignite 280 SL (Glufosinate-ammonium) was applied at 2.892 L ha^{-1} and post-emergence Honcho [Glyphosate-N-(phosponomethyl)-glycine] was applied at 2.318 L ha^{-1} for weed control. In 2013, Roundup [Glyphosate-N-(phosphonomethyl)-glycine] at 3.5 L ha^{-1} and Staple LX [Sodium-2-chloro-6-(4,6-dimethoxypyrimidin-2-yl)-thio-benzoate] at 0.175 L ha^{-1} were applied for weed control. Pix Plus (N,N-dimethylpiperdinim choloride) was applied in both years at 1.182 L ha^{-1} to manage cotton growth. Cotton was defoliated using Folex 6 EC (S,S,S-Tributyl phosporotrithioate) at a rate of 1.182 L ha^{-1} in October.

Table 2.1. Monthly average minimum (Min.) temperature (temp.), maximum (Max.) temperature, growing degree days (GDD), relative humidity (RH), and total precipitation (P) in 2012 and 2013 and 30 yr monthly averages of minimum temperature, maximum temperature, and total precipitation.

	2012					**2013**					**30-yr average†**		
Month	**Min. temp.**	**Max temp.**	**GDD$_{15.6}$‡**	**RH**	**P**	**Min. temp.**	**Max temp.**	**GDD$_{15.6}$**	**RH**	**P**	**Min temp.**	**Max temp.**	**P**
	-----------°C-----------			--%--	--mm--	-----------°C----------			--%--	--mm--	------°C-----		--mm--
May	17.0§	32.7	288	51.5	20.3	14.1	31.4	238	55.8	24.4	14.8	29.3	77.5
June	20.5	35.7	376	54.3	79.0	19.8	34.8	358	49.6	76.7	19.5	33.4	91.3
July	23.2	38.1	465	43.9	36.3	21.5	34.6	381	53.2	112.5	22.1	36.2	42.1
August	21.1	36.2	406	48.5	82.3	22.6	35.8	417	54.1	34.3	21.7	36.1	54
September	17.0	31.2	257	58.7	116.0	17.9	33.4	296	54.8	26.2	17.3	31.8	66.3
October	9.5	24.1	105	57.6	8.6	10.5	26.7	109	59.1	18.6	10.5	25.8	60.8

Experimental Design

The experimental design was a split-split plot design with three replications. Each main plot was 16 m wide (sixteen 1 m rows) and 42 m long, sub plot was 16 m wide (sixteen 1 m rows) and 21 m long, and sub-sub plot was 4 m wide (four 1 m row) and 21 m long. There was 1 m alley between sub plots. Main plots consisted of four irrigation treatments, subplots consisted of two tillage systems, and sub-subplots consisted of four cotton varieties. Irrigation treatments included dryland, 45% ET, 90% ET, and irrigation based on a remote sensing method following Rajan et al. (2010) and Rajan and Maas (2014). ET-based irrigation treatments were determined according to the crop coefficient approach (Allen et al., 1998).

The daily crop water demand was calculated as follows;

$ET_c = k_c \times ET_0$ [Eq. 1] (Allen et al., 1998)

where ET_c is the crop evapotranspiration (mm day^{-1}), k_c is the crop coefficient recommended for the Southern High Plains region, and ET_0 is the reference evapotranspiration (mm day^{-1}). Daily values of ET_0 were obtained from the Texas High Plains PET network (https://txhighplainset.tamu.edu). In this procedure, irrigation was applied at 2-3 days intervals based on the previous days cumulative ET after considering the effective precipitation. In the remote sensing-based irrigation, also known as the spectral crop coefficient approach, the value of the crop coefficient on any day during the growing season was considered numerically equivalent to the average crop ground cover. In this procedure, crop water demand was calculated by multiplying potential ET calculated using weather data and average ground cover. The average amounts of irrigation applied using the 90% ET, 45% ET, and remote sensing-based irrigation treatments were 392 mm, 187 mm, and 365 mm, respectively. Irrigation was terminated at three nodes above white flower stage which occurred on 15 August in 2012 and 20 August in 2013. Tillage treatments included minimum tillage and conventional tillage. All conventional tillage plots were cultivated using a disk plow in early spring and before planting. Cotton varieties planted included ‘FiberMAX 9170’ (FM9170), ‘Deltapine 1044’ (DP1044), ‘Phytogen 375’ (PHY375), and ‘Phytogen 499’ (PHY499).

Data Collection and Statistical Analysis

At physiological maturity, the two center rows were machine harvested using a cotton stripper and subsamples were collected for obtaining ginning and fiber quality data. Fiber quality analysis was performed at the Fiber and Biopolymer Research Institute in Lubbock, TX. Water use efficiency (WUE) was calculated as a ratio of lint yield to total water (Irrigation + Precipitation).

Analysis of variance was performed using the PROC GLIMMIX (SAS version 9.3, Institute Inc, Cary, NC). Irrigation, tillage, variety, and their interaction were considered as fixed effects. Year, replication, and all interactions among these effects were considered as random effects. Considering year as random source of error allows the conclusion of treatment effects to be broadened over a range of environments (Carmer et al., 1989). Treatment means were averaged over years and were separated by the protected least significant difference (LSD) at $P \leq 0.05$ significance level. The Pdiff calculations were made to compare varieties within each irrigation treatment or irrigation treatments within each variety. Lint yield and fiber quality response to irrigation by variety significant interactions were analyzed by linear and quadratic regression analysis utilizing the *drc* statistical addition package (Ritz and Strebig, 2010) in R statistical software (R Development Core Team, Vienna, Austria).

RESULTS AND DISCUSSION

Weather

The monthly average data on minimum air temperature, maximum air temperature, growing degree days (GDD), relative humidity, and precipitation during the growing seasons of 2012 and 2013 are presented in Table 2.1. The cumulative precipitation was noticeably different between 2012 and 2013 (Table 2.1). The precipitation received during the 2012 growing season (May–September) was 333.9 mm which was similar to the 30 yr average precipitation of 331.2 mm. The precipitation received during the 2013 growing season was 274.1 mm which was less than the 30 yrs average precipitation (Table 2.1). In addition to cumulative precipitation, the seasonal distribution of precipitation was also different in 2012 and 2013. In 2012, the highest amount of precipitation was received in September (116 mm). In 2013, the highest amount of precipitation was received in June (91.3 mm). The minimum air temperatures in both growing seasons were similar to the long-term average temperature except for May 2012. In May 2012, the average minimum air temperature was approximately 3^{o}C higher than the average minimum temperature during the corresponding period in 2013 and the 30 yr period (1980-2010). In general, during the early month of 2012, the average monthly maximum air temperature and average air temperature was higher compared to 2013. As a result, the accumulated GDD calculated using a base temperature of 15.6^{o}C was higher in 2012 than in 2013.

Lint Yield

Lint yield as affected by irrigation, tillage, variety, and irrigation by variety interaction is shown in Table 2.2. Irrigation treatments significantly affected cotton lint yield in the current study (Table 2.2). Lint yield increased linearly as the amount of irrigation increased (Fig. 2.1). The highest lint yield (1764 kg lint ha^{-1}) was obtained with the 90% ET replacement treatment. The lowest lint yield (490 kg lint ha^{-1}) was obtained from the dryland treatment. The regression analysis showed that a supplemental irrigation of 160 mm resulted in a 100% yield increase compared to the dryland treatment. The 45% ET replacement treatment resulted in a yield increase of 130% and the 90% ET replacement treatment resulted in a yield increase of 260% compared to the dryland lint yield. Lint yield was increased by 200% for the remote sensing-based irrigation treatment. A number of studies reported a positive response of lint yield to irrigation for cotton grown in other semi-arid regions (Wanjura et al., 2002; Bordovsky et al., 2011; DeLaune et al., 2012; Snowden et al., 2013). In a long-term field study conducted in the Texas High Plains, Wanjura et al. (2002) found that applying 200 mm of irrigation produced 1185 kg lint ha^{-1}. DeLaune et al. (2012) reported a 66% increase in lint yield in the Texas Rolling Plains with a 33% ET replacement irrigation treatment compared to dryland.

The minimum tillage system at our study site is in the early stages of transitioning from conventional tillage to minimum tillage. Therefore, it might be too early to recognize any significant effect of tillage on lint yield in the current study.

Bordovsky et al. (1994) reported a 6.9% increase in dryland lint yield compared to conventionally tilled dryland cotton in the Southern High Plains of Texas. They also reported a 5.5% increase in lint yield of no-till irrigated cotton compared to conventionally tilled irrigated cotton. Several other studies reported beneficial effects of reduced tillage and no-tillage on soil health with no significant impact on cotton lint yield compared to conventional tillage (Keeling et al., 1989; Bronson et al., 2001; Buman et al., 2005; Pettigrew et al., 2009; DeLaune et al., 2012).

Comparisons of varieties under dryland conditions showed no significant differences in lint yield. However, significant variety differences were observed within the other irrigation treatments (Table 2.2). At the low irrigation level of 45% ET, PHY499 and FM9170 performed better, but as irrigation level increased PHY375 and DP1044 produced higher yield. Lint yield response of varieties to total water is presented in Figure 2.2. Increasing the total water linearly increased lint yield of all varieties. However, PHY375 had the greatest lint yield increases as the water amounts increased but showed lower yield at low irrigation amounts. PHY499 had the lowest increases in lint yield as the water amounts increased. However, it showed higher yield at low irrigation amounts. These results suggest that PHY375 performed better at higher irrigation conditions and PHY499 performed better at lower irrigation conditions compared to the other varieties.

Table 2.2. Lint yield and water use efficiency of four cotton varieties as affected by irrigation level and tillage systems over 2012 and 2013 growing seasons.

		Lint yield	WUE
Irrigation	Variety	kg ha^{-1}	Kg ha^{-1} mm^{-1}
Dryland	PHY499	485	1.65
	DP1044	511	1.73
	PHY375	479	1.65
	FM9170	485	1.64
45% ET	PHY499	1168a†	2.36a
	DP1044	1146ab	2.31ab
	PHY375	1090b	2.22b
	FM9170	1189a	2.40a
RS‡	PHY499	1411b	2.11
	DP1044	1490a	2.22
	PHY375	1498a	2.25
	FM9170	1446ab	2.16
90% ET	PHY499	1652c	2.37c
	DP1044	1741b	2.50bc
	PHY375	1865a	2.68a
	FM9170	1796ab	2.60ab
Irrigation			
	Dryland	490D§	1.67B
	45% ET	1148C	2.32A
	RS	1462B	2.19AB
	90% ET	1764A	2.54A
Tillage			
	No till	1219	2.19
	Conv. till	1213	2.17
Variety			
	PHY499	1179B	2.12
	DP1044	1223A	2.19
	PHY375	1233A	2.20
	FM9170	1229A	2.20
ANOVA			
	Irrigation (I)	<0.0001	0.018
	Tillage	0.799	0.570
	Variety (V)	0.053	0.173
	I × V	0.001	0.008

† The same lowercase letter within a column indicates no significant difference among varieties means within irrigation level at $P \leq 0.05$. Columns that do not contain letters indicate no significance difference between treatments.

‡ RS, remote sensing–based irrigation treatment.

§The same uppercase letter within a column indicates no significant difference among treatments means at $P \leq 0.05$. Columns that do not contain letters indicate no significance difference between treatments.

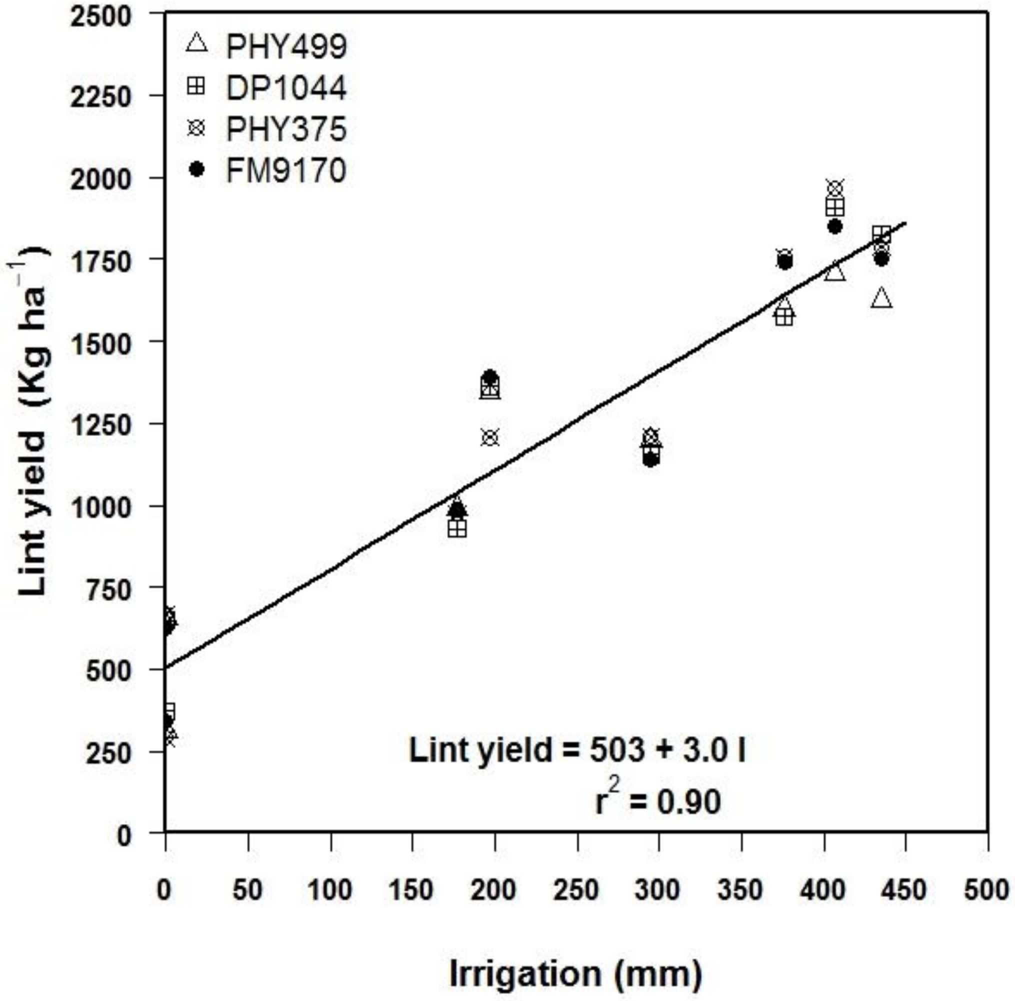

Figure 2.1. Lint yield of four cotton varieties in response to irrigation water described by ordinary least squares regression in 2012 and 2013 growing seasons.

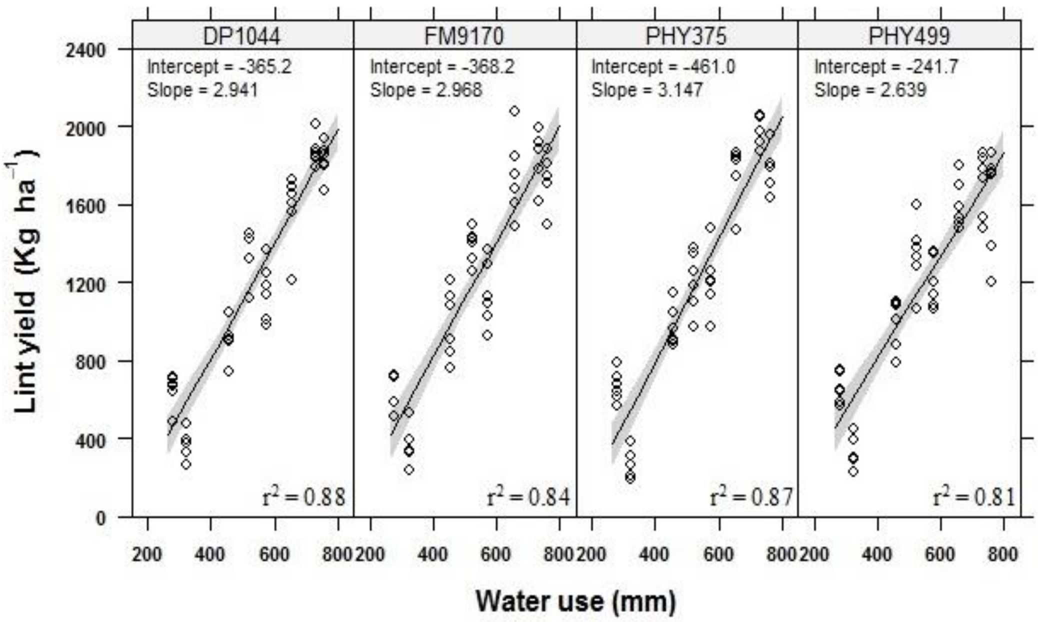

Figure 2.2. Relationship between lint yield and water use (irrigation + precipitation) for four cotton varieties described by ordinary least squares regression in 2012 and 2013 growing seasons. Shaded areas are 95% of confidence intervals.

Water Use Efficiency

Attaining high WUE is a priority in the semi-arid Texas Rolling Plains to optimize the use of the limited water resources available for irrigation. Table 2.2 shows the WUE of cotton grown under different treatments. The average WUE at the 90% ET irrigation level was 2.54 kg of lint ha^{-1} for every mm of water used. WUE decreased to 2.32 kg of lint ha^{-1} mm^{-1} and 2.19 kg of lint ha^{-1} mm^{-1} for the 45% ET and remote sensing-based irrigation treatments, respectively. The average WUE of dryland was 1.67 kg of lint ha^{-1} mm^{-1}. There was a significant irrigation by variety interaction on WUE (Table 2.2). At 45% ET, PHY499 had the highest WUE of 2.36 kg lint ha^{-1} mm^{-1} while PHY375 had the lowest WUE of 2.22 kg lint ha^{-1} mm^{-1}. However, at the high irrigation level, PHY375 had the highest WUE of 2.68 kg lint ha^{-1} mm^{-1} while PHY499 had the lowest WUE of 2.37 kg ha^{-1} mm^{-1}. There is limited information available about WUE values of SDI cotton in the Texas Rolling Plains. The reported values of WUE for cotton in the neighboring Texas High Plains were slightly higher than the average values estimated in the current study. In a demonstration project conducted in the Texas High Plains, the average WUE of SDI-irrigated producer fields for 22 site-years was 2.99 kg of lint per mm of total water (TAWC, 2013). In another recent study conducted by Whitaker et al. (2008) at Lubbock, TX, the average WUE of SDI cotton was 2.91 kg ha^{-1} mm^{-1} and the average total water applied was 592 mm. A similar trend of WUE response to irrigation rates in cotton was reported in a long-term field study conducted in the Texas High Plains where a high irrigation rate of 3.4 mm d^{-1} produced the highest WUE of 0.263 kg lint m^{-3} of total water (Bordovsky et al., 2011).

Fiber Quality

Advances in textile processing have increased the need for improved cotton fiber quality. Fiber quality measurements from the Uster High Volume Instrument (HVI) systems include fiber length, uniformity, strength, elongation, micronaire, and color (USDA-AMS, 2005). In the current study, varying irrigation levels significantly affected fiber length, strength, micronaire, and uniformity (Table 2.3). In general, fiber length, strength, and uniformity were increased as irrigation increased. Compared to dryland cotton, 90% ET irrigation increased fiber length, strength, and uniformity by 8.9, 6.7, and 7.1%, respectively. Previous researchers also reported similar results for fiber length, strength, and uniformity responses to irrigation (Basal et al., 2009; Dagdelen et al., 2009). Hearn et al. (1994) attributed the reduction in fiber length by severe water deficit conditions to the negative impacts on mechanical and physiological processes of cell expansion. Pettigrew (2004a) and Booker et al. (2006) reported no effect of soil moisture on fiber strength. They found that this parameter was more related to the genotype background rather than production factors. Fiber micronaire was found to decrease as irrigation level increased (Table 2.3). There was no significant difference in fiber micronaire among the dryland, 45% ET, and remote sensing-based irrigation. However, the 90% ET treatment had 21% lower fiber micronaire compared with dryland or 45% ET. Water stress usually causes increase in micronaire or fiber fineness because the carbohydrate supply is limited to a smaller number of bolls. Some researchers found seasonal variations in the fiber micronaire response to irrigation (Pettigrew 2004; Snowden et al., 2013). This was due to variations in growing season temperature and rainfall, which affected fiber maturation. Several studied reported a decrease in fiber micronaire as irrigation rate increased (Bauer and Frederick, 2005; Basal et al., 2009; Dagdelen et al., 2009; Feng et al., 2014).

Varieties (main effect) showed significant differences in fiber length, strength, uniformity, and elongation (Table 2.3). Differences in fiber micronaire were significant at the 0.1 probability level. FM9170 and DP1044 produced lint with the highest fiber length. PHY499 produced lint with significantly higher fiber strength while PHY375 had the lowest fiber strength. PHY499 also showed significant advantages for fiber micronaire, uniformity, and elongation. Lint with the lowest fiber micronaire and elongation were produced by FM9170, while PHY375 had the lowest fiber uniformity (Table 2.3). Differences among varieties main effect on fiber quality demonstrate the influence of genetic traits on fiber quality.

Figure 2.3a-c illustrates fiber length, strength, and micronaire response to irrigation. Increasing total water linearly increased fiber length and strength for all varieties (Fig. 2a and b). For fiber length, FM9170 had the highest increases while DP1044 had the lowest increases in response to increasing irrigation water application (Fig. 2.3a). FM9170 showed the greatest fiber strength increase as a result of increased water level (Fig. 2.3b). At low water amounts, PHY499 and DP1044 had higher fiber strength while PHY375 produced the lowest fiber strength (Fig. 2.3b). For fiber micronaire, all varieties showed a linear decrease as water application increased (Fig. 2.3c). These results demonstrate that fiber quality parameters for cotton varieties respond differently to irrigation amounts.

Table 2.3. Fiber quality parameters of four cotton varieties as affected by different irrigation levels averaged over 2012 and 2013 growing seasons.

Variety	Irrigation	Fiber length	Fiber strength	Micronaire	Uniformity	Elongation
		--mm--	--g/tex--	---Mic---	---------%---------	
PHY499	Dryland	26.7b†	31.3b	4.2a	80.1b	10.1a
	45% ET	27.1b	31.8a	4.4a	81.7a	10.1a
	RS‡	28.2a	32.9a	3.9a	82.2a	9.9ab
	90% ET	28.6a	31.9a	3.4b	81.0ab	9.5b
DP1044	Dryland	27.0c	30.0b	4.3a	79.4b	9.7
	45% ET	27.8bc	30.6ab	4.2a	81.0a	9.9
	RS	28.4ab	31.4a	4.0a	81.8a	10.1
	90% ET	29.1a	31.7a	3.1b	81.3a	10.0
PHY375	Dryland	26.2c	27.6b	4.1a	79.1b	8.6
	45% ET	26.4bc	28.4ab	4.1a	80.2ab	8.8
	RS	27.6b	29.2a	4.0a	81.0a	8.7
	90% ET	29.7a	29.9a	3.4b	80.6a	8.6
FM9170	Dryland	26.8c	29.8b	4.2a	78.7b	8.2
	45% ET	28.3b	30.9b	4.1a	81.1a	7.9
	RS	28.8b	31.2ab	3.8a	81.2a	7.9
	90% ET	29.9a	32.6a	3.1b	81.3a	8.2
Irrigation						
	Dryland	26.7C§	29.7B	4.2A	79.3B	9.1
	45% ET	27.6BC	30.5AB	4.2A	81.0A	9.2
	RS	28.2AB	31.2A	3.9A	81.6A	9.2
	90% ET	29.1A	31.5A	3.3B	81.2A	9.1
Variety						
	PHY499	27.7B	32.0A	4.0A	81.2A	9.9A
	DP1044	28.1A	30.9B	3.9AB	81.0AB	9.9A
	PHY375	27.4B	28.8C	3.9AB	80.2C	8.7B
	FM9170	28.5A	31.1B	3.8B	80.6BC	8.0C
ANOVA		------------------------------$P > F$--------------------------				
	Irrigation (I)	0.0006	0.034	0.005	0.0007	0.767
	Tillage	0.417	0.693	0.904	0.176	0.121
	Variety (V)	<.0001	<.0001	0.055	<.0001	<.0001
	I × V	0.406	0.248	0.436	0.150	0.011

† The same lowercase letter within a column indicates no significance difference among irrigation levels means within variety @ $P \le 0.05$. Columns that do not contain letters indicate no significance difference between treatments.

‡ RS, Remote sensing-based irrigation treatment.

§ The same uppercase letter within a column indicates no significant difference among treatments means @ $P \le 0.05$. Columns that do not contain letters indicate no significance difference between treatments.

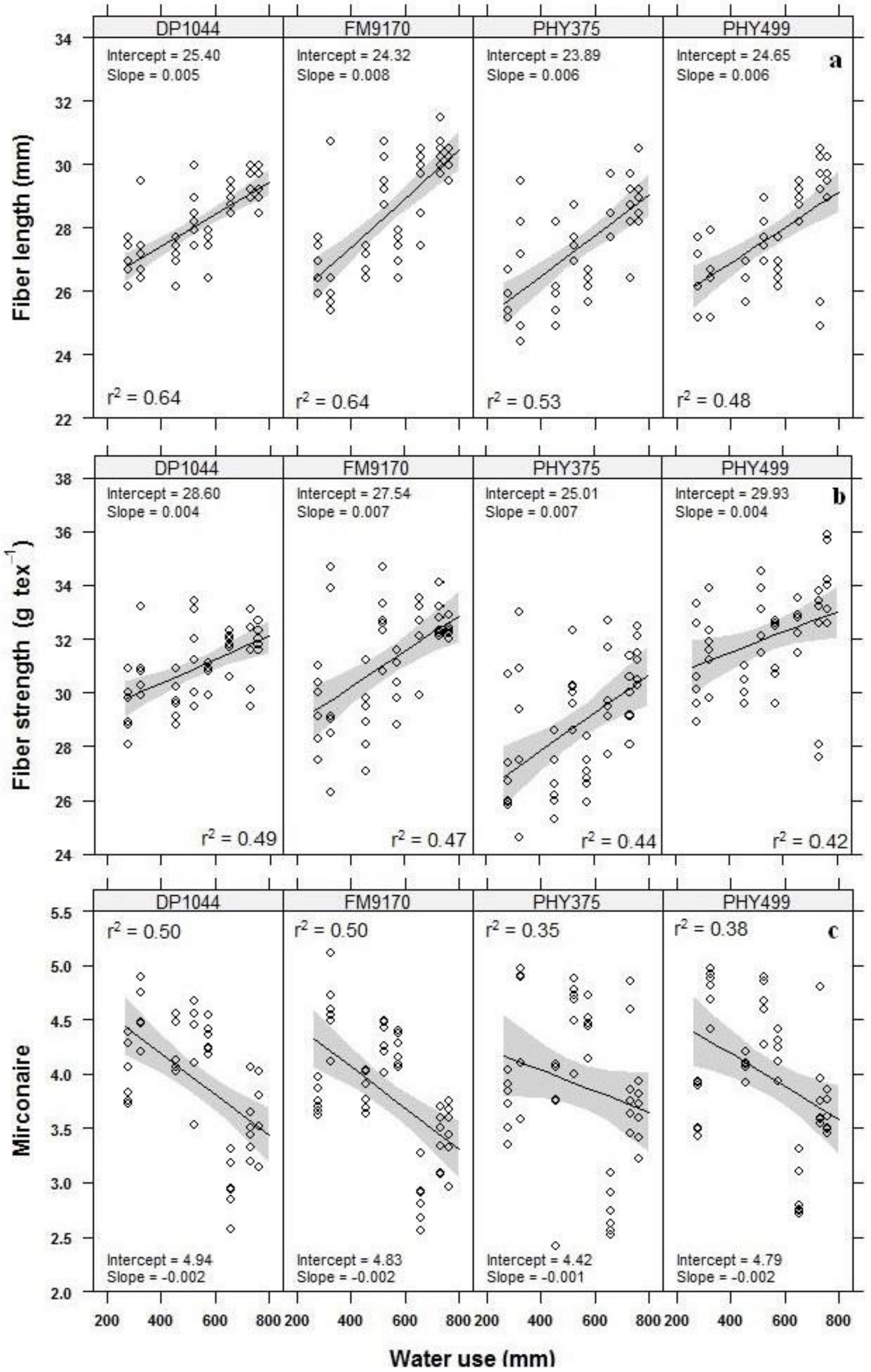

Figure. 2.3. Fiber length (a), strength (b), and micronaire (c) of four cotton varieties in response to water use (irrigation + precipitation) described by ordinary least squares regression in 2012 and 2013 growing seasons. Shaded areas are 95% of confidence intervals.

CONCLUSIONS

Results from this field study showed that lint yield, fiber quality, and WUE were affected by irrigation amounts and variety characteristics in the semi-arid Texas Rolling Plains. The highest lint yield (1764 kg ha^{-1}) and WUE (2.54 kg lint ha^{-1} mm^{-1}) was obtained for the 90% ET irrigation treatment. Increasing irrigation level resulted in a linear increase in lint yield and WUE. Among the varieties, PHY375 performed better at higher irrigation levels while PHY499 performed better at low irrigation levels. The irrigation-by-variety interaction showed that the 90% ET replacement treatment involving PHY375 produced the greatest lint yield and WUE. Tillage did not significantly affect lint yield, WUE, and fiber quality. Fiber quality was significantly affected by irrigation and variety characteristics. Increasing irrigation resulted in a linear increase in fiber length and strength, and a linear decrease in fiber micronaire. The 90% ET irrigation treatment significantly increased fiber length, strength, and uniformity, and decreased fiber micronaire.

CHAPTER III

WITHIN SEASON GROWTH, CANOPY TEMPERATURE, AND SPECTRAL REFLECTANCE RESPONSES OF FOUR COTTON VARIETIES TO IRRIGATION AND TILLAGE MANAGEMENT IN THE TEXAS ROLLING PLAINS

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is a major cash crop in the United States. The estimated value of U.S. cotton production in 2013 is approximately $5.2 billion. A major portion of U.S. cotton is produced in the Texas High Plains and Rolling Plains regions. In these semi-arid regions, cotton growth and development are strongly influenced by the availability of water for irrigation and precipitation. Cotton is a drought tolerant crop. However, water stress during flowering can result in a significant reduction in lint yield. Several studies have documented the effect of water stress on cotton growth and development (Pittegrew, 2004a; Silva and Rao, 2005; Snowden et al., 2014). Rajan et al. (2010) reported that the average ground cover of dryland and irrigated cotton during the peak growing season in the Texas High Plains was 82 % and 35 %, respectively. Soil moisture deficit conditions can reduce lint yield by adversely affecting initiation of squares and development of bolls (Hake and Grimes, 2010). It also has detrimental impacts on leaf expansion, node production, and boll retention and distribution (Hake and Grimes, 2010; Snowden et al., 2013). Pettigrew (2004a) reported that severe moisture deficit conditions resulted in 19% reduction in number of bolls for cotton grown in Mississippi. When cotton plants undergo water stress, they sacrifice their vegetation growth for maximum fruit production. Snowden et al. (2014) reported that withholding irrigation from squaring to flowering period resulted in a 23% reduction in plant height compared to fully irrigated cotton grown in the Texas High Plains. Pettigrew (2004b) reported that for cotton grown in Misisssippi, water stress reduced leaf area index (LAI) by 35% compared to well-watered plants.

Soils in the Texas Rolling Plains are characteristically low in organic matter. One of the main management practices that reduce soil organic matter content is tillage. In the long-term, absence of tillage may help improve soil organic matter content, structural aggregation, and micropore spacing (Griffith et al., 1992). Studies have found that tillage practices can significantly affect the water and nutrient availability for crops (Rhoads and Bennett, 1990). Tillage management can alter cotton growth by affecting soil temperature and soil water storage. In a five-year study conducted by Boquet et al. (1994), cotton grown in conventional tillage plots were found to be 10% taller than cotton grown in no-tillage plots (Boquet et al., 1994). Kennedy and Hutchinson (2001) found that no-tillage management increased cotton LAI compared with conventional tillage in a three-year study conducted in Louisiana. The impact of tillage on within-season growth characteristics for cotton has not been previously investigated for the Texas Rolling Plains.

Varieties with different genetic background respond differently to management practices, including irrigation and tillage. Indices based on canopy temperature and spectral reflectance can be used to quantify the response of cotton varieties to water deficit conditions and management practices (Idso et al., 1977; Jackson et al., 1977; Idso et al., 1981; Jackson et al., 1981; Mauget and Upchurch, 2000; Gwathmey et al., 2010). For example, the crop water stress index (CWSI), calculated based on canopy temperature, could be used for identifying and quantifying water stress conditions (Li et al., 2010). Several studies have addressed the use of vegetation and water indices to detect cotton growth and water status (Wiegand et al., 1994; Plant et al., 2000; Ritchie, 2003; Rajan et al., 2010). Many such methods use vegetation indices calculated using spectral reflectance data in the red and near-infrared (NIR) wavelengths, such as the NDVI because it is related to crop growth and development (Bausch and Neale, 1987; Gwathmey et al., 2010; Raper et al., 2013; Rajan et al., 2014). Vegetation indices such as the NDWI are popular in estimating the water content of vegetation (Gao, 1996; Clay et al., 2005; Hatfield et al., 2008). NDWI is calculated using the NIR and short-wave infrared (SWIR) bands. Leaf pigments absorb electromagnetic radiation in the visible wavelengths. In the infrared wavelengths, leaf optical properties are dominated by the water status of vegetation and cellular structure. When a crop is water-stressed, dehydration of leaves increases their reflectance due to shrinkage of cells and overall increases in the number and sizes of intercellular spaces. Similarly, prolonged water stress will cause less canopy development and causes reduced absorption of electromagnetic radiation in the visible wavelengths. No studies have been carried out in the Texas Rolling Plains investigating the effect of irrigation and tillage on within-season growth, spectral reflectance, and canopy temperature of cotton varieties. Such data are critical in indentifying cotton varieties that are adapted to the management and environmental conditions in the Texas Rolling Plains. The objective of this study was to determine the within-season growth, normalized difference vegetation index, normalized difference water index, and crop water stress index responses of four cotton varieties to irrigation and tillage management in the Texas Rolling Plains

MATERIALS AND METHODS

Site Description and Cultural Practices

The study was conducted in 2012 and 2013 at the Chillicothe Research Station of Texas A&M AgriLife Research near Vernon, TX (34º15'N and 99º30'W; 431 m above mean sea level). Cotton was planted on 23 May in both growing seasons at a seeding rate of 10 seeds per m of row at 1 m row spacing. The field was irrigated using subsurface drip irrigation (SDI) installed at a depth of 30 cm. The emitter spacing of the SDI system was 50 cm. The crop rows were oriented east-west. The soil in the field was an Abilene clay loam (fine, mixed, superactive, thermic Pachic Agriustolls) with 0 to 1% slope (Soil survey staff, 2004). The climate of the study region is semiarid with a mean long-term annual precipitation of 560 mm. About two-thirds of the precipitation is normally received during the growing season (Table 2.1).

Soil samples were collected in late spring to determine the residual N content in the top 60 cm of soil. The nitrogen fertilizer rate was determined based on a yield goal of 1680 kg lint ha^{-1} which is about 168 kg N ha^{-1}. After considering the residual soil N, remaining N was applied as urea ammonium nitrate (28-0-0) in two split applications which included planting and first-square stage. In 2012, 0.876 L ha^{-1} Lorsban-4E [O-O-diethyl-O-(3,5,6-trichloro-2-pyridinyl)-phosphorothioate] and 4.67 L ha^{-1} Karate [3-phenoxyphenyl- methyl-3-(2-choloro-3,3,3-trufuoro-1-propenyl)-2,2-dimethyl-cyclopropane-carboxylate] were applied for insect control. Pre-emergence Ignite 280 SL (Glufosinate-ammonium) was applied at 2.892 L ha^{-1} and post-emergence Honcho [Glyphosate-N-(phosponomethyl)-glycine] was applied at 2.318 L ha^{-1} for weed control. In 2013, Roundup [Glyphosate-N-(phosphonomethyl)-glycine] at 3.5 L ha^{-1} and Staple LX [Sodium-2-chloro-6-(4,6-dimethoxypyrimidin-2-yl)-thio-benzoate] at 0.175 L ha^{-1} were applied for weed control. Pix Plus (N,N-dimethylpiperdinim choloride) was applied in both years at 1.182 L ha^{-1} to manage cotton growth. Cotton was defoliated using Folex 6 EC (S,S,S-Tributyl phosporotrithioate) at a rate of 1.182 L ha^{-1} in October.

Experimental Design

The experimental design was a split-split plot design with three replications. Each main plot was 16 m wide (sixteen 1 m rows) and 42 m long, sub plot was 16 m wide (sixteen 1 m rows) and 21 m long, and sub-sub plot was 4 m long (four 1 m row) and 21 m long. There was 1 m alley between sub plots. Main plots consisted of four irrigation treatments, subplots consisted of two tillage systems, and sub-subplots consisted of four cotton varieties. Irrigation treatments included dryland, 45% ET, 90% ET, and irrigation based on a remote sensing method following Rajan et al. (2010) and Rajan and Maas (2014). ET-based irrigation treatments were determined according to the crop coefficient approach (Allen et al., 1998).

The daily crop water demand was calculated as follows;

$ET_c = k_c \times ET_0$

where ET_c is the crop evapotranspiration (mm day^{-1}), k_c is the crop coefficient recommended for the Southern High Plains region, and ET_0 is the reference evapotranspiration (mm day^{-1}). Daily values of ET_0 were obtained from the Texas High Plains PET network (https://txhighplainset.tamu.edu). In this procedure, irrigation was applied at 2-3 days intervals based on the previous days cumulative ET after considering the effective precipitation. In the remote sensing-based irrigation, also known as the spectral crop coefficient approach, the value of the crop coefficient on any day during the growing season was considered numerically equivalent to the average crop ground cover. In this procedure, crop water demand was calculated by multiplying potential ET calculated using weather data and average ground cover. The average amounts of irrigation applied using the 90% ET, 45% ET, and remote sensing-based irrigation treatments were 392 mm, 187 mm, and 365 mm, respectively. Irrigation was terminated at three nodes above white flower stage which occurred on 15 August in 2012 and 20 August in 2013. Tillage treatments included minimum tillage and conventional tillage. All conventional tillage plots were cultivated using a disk plow in early spring and before planting. Cotton varieties planted included ‘FiberMAX 9170’ (FM9170), ‘Deltapine 1044’ (DP1044), ‘Phytogen 375’ (PHY375), and ‘Phytogen 499’ (PHY499).

Data Collection and Statistical Analysis

Each year, data collected included plant height, spectral reflectance, and canopy temperature. A total of 30 plant height measurements were collected at sub-sub plots and averaged. The LAI measurements were collected in the 2013 growing season using an LAI-2200 plant canopy analyzer (LI-COR, Inc, NE, USA). Multispectral scene reflectance was recorded using a portable 16 channel spectroradiometer (CropScan, Rochester, MN) at 2 m above the surface. Reflectance measurements were taken on cloud-free days within 2 hours around local solar noon time on harvest rows throughout the growing season. Each reflectance value was an average of four measurements. Two vegetation indices were calculated using the reflectance data. The normalized difference vegetation index (NDVI; Jackson, 1984) was calculated as:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}) \qquad \text{[Eq. 2]}$$

The normalized difference water index (NDWI; Gao, 1996) was calculated as:

$$\mathrm{NDWI} = (\mathrm{NIR} - \mathrm{SWIR})/(\mathrm{NIR}+\mathrm{SWIR}) \qquad \text{[Eq. 3]}$$

NIR is the reflectance at the wavelength of 810 nm, RED is the reflectance at the wavelength of 665 nm, and SWIR is the reflectance of shortwave infrared at wavelength of 1160 nm.

Canopy temperature was measured using a hand-held infrared thermometer (IRtec MicroRAY HVAC, Langhorne, PA) under clear skies at around solar noon on day of the year (DOY) 193 and DOY 227 in 2012 and on DOY 193, DOY 214, and DOY 232 in 2013. Each value was an average of 30 readings. The CWSI was calculated as a function of canopy temperature and air temperature as follows;

$$\mathrm{CWSI} = \frac{(\mathrm{T_C}-\mathrm{T_a})-(\mathrm{T_c}-\mathrm{T_a})\mathrm{ll}}{(\mathrm{T_C}-\mathrm{T_a})\mathrm{ul}-(\mathrm{T_c}-\mathrm{T_a})\mathrm{ll}} \qquad \text{[Eq. 4]} \qquad \text{(Idso et al., 1981)}$$

where Tc is the canopy temperature (°C) and Ta is the air temperature (°C). The subscripts ll and ul refer to the lower (well watered plants) and upper (water stressed plants) limit between canopy and air temperatures, respectively. The air temperature at the time of filed-based measurements was obtained from the West Texas Mesonet website (http://www.mesonet.ttu.edu/tech/1-output/climate.html).

Analysis of variance was performed using the PROC GLIMMIX (SAS version 9.3, Institute Inc, Cary, NC). Within each year, irrigation, tillage, variety, and their interaction were considered as fixed effects. Replicate and replicate by irrigation were considered as random effects. Treatment means were averaged over years and were separated by the protected LSD at the $P \leq 0.05$ probability level. Within the GLIMMIX procedure, Pdiff calculations were made to compare varieties within each irrigation level or irrigation levels within each variety. Variables response to irrigation by variety interaction was described by linear and quadratic regression analysis and equation and graphs were made utilizing the *drc* statistical addition package (Ritz and Strebig, 2010) in R programming (R Development Core Team, Vienna, Austria).

RESULTS AND DISCUSSION

Plant Height

In 2012, irrigation and variety significantly affected plant height at all growth stages (Table 3.1). Replacing 90% of the ET produced the tallest plants throughout the 2012 growing season (Table 3.2). Early in the season (DOY 178), there was no significant difference between 45% ET or remote sensing-based irrigation treatments and dryland treatment (Table 3.2). However, later in the season, dryland treatment significantly varied from other irrigation treatments. At DOY 205, there was no significant difference between 45% ET and remote sensing-based irrigation treatments.

The last plant height reading at DOY 232 showed a gradual plant height increase as irrigation level increased. Replacing 90 % ET produced the tallest plants with an average height of 113 cm. These plants were 73% taller than dryland plants.

In 2013, there was no significant difference among irrigation treatments early in the season (DOY 178) (Table 3.1). However, later in the season, dryland had significantly shorter plants compared to other irrigation treatments. At flowering and boll filling stages (DOYs 205 and 232), 90% ET produced the tallest plants whereas dryland produced the shortest plants with 45% ET and remote sensing-based irrigation in-between (Table 3.3). The effect of irrigation amount on plant height agrees with the findings of numerous other studies (Stockton et al., 1961; Guinn et al., 1981; Snowden et al., 2014). Supplemental irrigation reduces plant water stress and increases the vegetative growth of plants (Bednarz and Nichols, 2005; Basal et al., 2009).

Tillage did not significantly affect plant height in both growing seasons (Table 3.1). The minimum tillage system at our study site is in the early stages of transitioning from conventional tillage to minimum tillage. Therefore, it might be too early to recognize any significant effect of tillage on plant height in the current study. Plant height of varieties significantly varied at all measuring dates in both growing seasons (Table 3.1). The average plant height in both growing seasons indicated that PHY499 is a tall variety whereas DP1044 and FM9170 are short varieties (Tables 3.2 and 3.3). At the end of the 2012 season, PHY499 had the greatest plant height of 98 cm whereas DP1044 and FM9170 had an average plant height of 87 cm (Table 3.2). Similar observations were recorded at the end of 2013 season. PHY499 had the greatest plant height of 93 cm whereas DP1044 and FM9170 had an average plant height of 82 cm (Table 3.3).

Table 3.1. Analysis of variance of plant height at different growth stages as affected by irrigation (I), tillage (T), and variety (V) in 2012 and 2013.

		Plant height$_a$†	Plant height$_b$	Plant height$_c$	Plant height$_d$
		2012			
SV	df	-------------------------*P* > *F*-------------------------			
I	3	0.015	0.0009	0.0006	0.0007
T	1	0.516	0.610	0.421	0.555
I × T	3	0.112	0.488	0.724	0.797
V	3	<0.0001	<0.0001	0.0002	<0.0001
I × V	9	0.081	0.012	0.545	0.002
T × V	3	0.364	0.338	0.962	0.389
I × T × V	9	0.553	0.253	0.788	0.386
		2013			
		-------------------------*P* > *F*-------------------------			
I	3	0.419	0.005	0.0003	0.0006
T	1	0.151	0.092	0.189	0.318
I × T	3	0.668	0.898	0.920	0.600
V	3	0.0009	<0.0001	<0.0001	<0.0001
I × V	9	0.331	0.908	0.824	0.434
T × V	3	0.036	0.483	0.674	0.206
I × T × V	9	0.814	0.527	0.206	0.874

† a through d stand for plant height at emergence (DOY 178), Squaring (DOY 190), flowering (DOY 205), and boll filling (DOY 232) growth stages, respectively.

Table 3.2. Plant height of four cotton varieties as affected by irrigation levels in 2012.

Variety/Irrigation	Dryland	45% ET	RS†	90% ET	Average$_{var}$
	Plant height$_a$‡ (cm)				
PHY499	34a	34a	32a§	40a	35a
DP1044	31b	31b	31b	32c	31b
PHY375	33a	36a	32a	36b	34a
FM9170	30b	31b	30b	36b	31b
Average$_{Irri}$	32B¶	33B	31B	36A	
	Plant height$_b$ (cm)				
PHY499	51a	63a	66a	70a	63a
DP1044	47b	55c	60c	60c	56c
PHY375	52a	60b	63b	64b	60b
FM9170	46b	55c	56d	60c	54c
Average$_{Irri}$	49C	58B	61AB	64A	
	Plant height$_c$ (cm)				
PHY499	67a	88a	91a	103a	88a
DP1044	54b	82b	83b	89b	78b
PHY375	65a	84ab	89ab	95b	84a
FM9170	55b	78b	85b	96ab	79b
Average$_{Irri}$	61C	84B	87B	96A	
	Plant height$_d$ (cm)				
PHY499	70a	89a	104a	127a	98a
DP1044	59b	86ab	96b	102c	86c
PHY375	66ab	86b	99ab	112b	91b
FM9170	63b	83b	95b	109b	88c
Average$_{Irri}$	65D	87C	99B	113A	

† RS, Remote sensing-based irrigation scheduling.

‡ a through d stand for plant height at emergence (DOY 178), Squaring (DOY 190), flowering (DOY 205), and boll filling (DOY 232) growth stages, respectively.

§ Vertical means (lowercase letters) followed by the same letter within a column are not significantly different at 0.05 probability level. Columns that do not contain letters indicate no significant difference among treatments.

¶ Horizontal means (uppercase letters) followed by the same letter within a row are not significantly different at 0.05 probability level.

Table 3.3. Plant height of four cotton varieties as affected by irrigation levels in 2013.

Variety/Irrigation	Dryland	45% ET	RS†	90% ET	Average$_{var}$
	Plant height$_{a}$‡ (cm)				
PHY499	25bc§	28ab	26ab	29a	27a
DP1044	24c	25b	25b	26b	25b
PHY375	29a	29a	27a	28ab	28a
FM9170	27ab	31a	29a	28ab	28a
Average$_{Irri}$	26ns¶	28	27	27	
	Plant height$_{b}$ (cm)				
PHY499	43ab	54b	53b	55a	51a
DP1044	40b	51b	49b	52b	48b
PHY375	45a	56ab	54a	56a	53a
FM9170	43b	57a	54a	57a	53a
Average$_{Irri}$	43B#	44A	52A	55A	
	Plant height$_{c}$ (cm)				
PHY499	64a	80a	78a	85a	77a
DP1044	56b	72b	72b	77c	69c
PHY375	59b	79a	75ab	84ab	74b
FM9170	57b	75b	72b	80bc	71c
Average$_{Irri}$	59C	76B	74B	82A	
	Plant height$_{d}$ (cm)				
PHY499	76a	94a	95a	109a	93a
DP1044	68bc	84bc	83bc	96bc	83c
PHY375	71b	88b	84b	100b	86b
FM9170	63c	83c	82c	92c	80d
Average$_{Irri}$	69C	87B	86B	99A	

† RS, Remote sensing-based irrigation treatment.

‡ a through d stand for plant height at emergence (DOY 178), Squaring (DOY 190), flowering (DOY 205), and boll filling (DOY 232) growth stages, respectively.

§ Vertical means (lowercase letters) followed by the same letter within a column are not significantly different at 0.05 probability level. Columns that do not contain letters indicate no significant difference among treatments.

¶ ns, not significant.

Horizontal means (uppercase letters) followed by the same letter within a row are not significantly different at 0.05 probability level.

Canopy Temperature

Canopy temperature was recorded around solar noon time during the growing season to evaluate the effects of irrigation and tillage on plants. Results indicated that canopy temperature readings recorded on DOYs 193 and 227 in 2012 were significantly affected by irrigation. On both days, irrigated plants had significantly lower canopy temperature than dryland (Table 3.5). On DOY 227, there were no significant differences in canopy temperature among the irrigated plants (Table 3.5). In 2013, canopy temperature was significantly affected by irrigation only on DOY 214 (Table 3.4). The 90% ET had significantly lower canopy temperature than other irrigation treatments (Table 3.5). Higher canopy temperature indicates that plants have reduced transpiration compared to plants with lower canopy temperature. Previous research documented the canopy temperature obtained by infrared thermometry as an efficient indicator of crop water status (Idso et al., 1977; Jackson et al., 1981; Pinter and Reginato, 1982). Varieties showed significant canopy temperature differences recorded on DOY 193 in 2012 and DOY 214 in 2013 (Table 3.4). On DOY 193 in 2012, PHY375 had approximately 4% higher canopy temperature than other varieties. On DOY 214 in 2013, FM9170 had lower canopy temperature compared with other varieties (Table 3.5). There was no significant irrigation by variety interaction on canopy temperature in both years, indicative of similar response of varieties within each irrigation level (Table 3.4).

Table 3.4. Analysis of variance of canopy temperature (CT) and crop water stress index (CWSI) at different growth stages as affected by irrigation (I), tillage (T), and variety (V) in 2012 and 2013.

		$\mathrm{CT}_{a\dagger}$	CWSI_{a}	CT_{b}	CWSI_{b}	CT_{c}	CWSI_{c}
SV	df	2012					
I	3	0.009	0.002	-	-	0.006	0.005
T	1	0.290	0.569	-	-	0.382	0.353
I × T	3	0.418	0.610	-	-	0.320	0.557
V	3	0.020	0.002	-	-	0.792	0.394
I × V	9	0.484	0.227	-	-	0.652	0.668
T × V	3	0.840	0.919	-	-	0.536	0.840
I × T × V	9	0.750	0.585	-	-	0.681	0.767
		2013					
I	3	0.115	0.108	0.032	0.032	0.143	0.145
T	1	0.288	0.285	0.270	0.270	0.352	0.185
I × T	3	0.969	0.962	0.783	0.780	0.629	0.834
V	3	0.495	0.366	0.017	0.014	0.111	0.620
I × V	9	0.968	0.947	0.383	0.369	0.206	0.575
T × V	3	0.818	0.862	0.945	0.945	0.220	0.823
I × T × V	9	0.956	0.903	0.429	0.421	0.467	0.812

† a through c stand for canopy temperature or crop water stress index at DOYs 193 and 227 in 2012 and at DOYs 193, 214, and 232 in 2013.

Table 3.5. Canopy temperature recorded at noon h at DOYs 193 and 227 in 2012 and at DOYs 193, 214, and 232 in 2013.

Variety/Irrigation	Dryland	45% ET	RS†	90% ET	Average variety
	2012				
	Canopy temperature (DOY‡ 193) (°C)				
PHY499	41.8	35.5	29.8b‡	26.4b	33.4b
DP1044	42.4	35.2	30.3b	26.2b	33.5b
PHY375	42.1	36.9	32.3a	28.4a	34.9a
FM9170	41.0	34.9	31.7ab	26.3b	33.5b
Average Irrigation	41.8A§	35.6B	31.0BC	26.8C	
	Canopy temperature (DOY 227) (°C)				
PHY499	34.7	27.5	25.3	25.3	28.2
DP1044	35.1	28.2	25.8	25.4	28.6
PHY375	34.3	27.9	25.8	25.4	28.4
FM9170	34.7	27.6	25.3	25.7	28.3
Average Irrigation	34.7A	27.8B	25.5B	25.4B	
	2013				
	Canopy temperature (DOY 193) (°C)				
PHY499	32.2	27.2	29.0	25.7	28.5
DP1044	33.5	28.0	29.2	25.5	29.0
PHY375	32.2	26.5	28.5	25.7	28.2
FM9170	32.2	27.7	29.0	25.7	28.6
Average Irrigation	32.5A	27.3AB	28.9AB	25.6B	
	Canopy temperature (DOY 214) (°C)				
PHY499	32.9	32.4	32.0	29.6a	31.7a
DP1044	32.8	32.4	32.1	29.1a	31.6a
PHY375	32.7	32.2	31.7	29.9a	31.6a
FM9170	32.4	32.0	31.4	28.0b	30.9b
Average Irrigation	32.7A	32.2A	31.8A	29.2B	
	Canopy temperature (DOY 232) (°C)				
PHY499	32.9	31.7b	32.8ab	27.8	31.3ab
DP1044	32.7	31.7b	32.3b	27.6	31.1b
PHY375	32.8	33.2ab	34.0ab	27.9	32.0a
FM9170	32.8	33.6a	34.3a	26.8	31.9ab
Average Irrigation	32.8	32.6	33.4	27.5	

† RS; Remote sensing-based irrigation scheduling.

‡ Vertical means (lowercase letters) followed by the same letter within a column are not significantly different at 0.05 probability level. Columns that do not contain letters indicate no significant difference among treatments. .

§ Horizontal means (uppercase letters) followed by the same letter within a row are not significantly different at 0.05 probability level.

The results showed that the CWSI calculated based on canopy temperature recorded on DOY 193 in 2012 indicated significant irrigation and variety effects (Table 3.4). On DOY 193 in 2012, 90% ET had significantly lower CWSI than other irrigation treatments. Dryland had the highest CWSI of 0.89 on that day (Fig. 3.1a). Among varieties, PHY375 had significantly higher CWSI (0.55) compared with other varieties (0.46). On DOY 227 in 2012, the CWSI was only affected by irrigation level showing the highest CWSI of 0.98 for the dryland and the lowest CWSI of 0.13 for the 90% ET irrigation (Table 3.4 and Fig 3.1b).

In 2013, irrigation and variety characteristics significantly affected the CWSI recorded on DOY 214 (Table 3.4). Averaged across varieties, significantly lower CWSI was produced by the 90% ET treatment (0.46) compared with other irrigation treatments (Fig 3.2b). The absence of significant irrigation effect on CWSI recorded on DOYs 193 and 232 in 2013 could be attributed to the precipitation received during the growing season. In addition, dryland and 45% ET had a wide range of CWSI (Fig. 3.2a and b). This demonstrates that plants with less water availability have reduced transpiration earlier than those with more available water which increased the likelihood of having a wider range of canopy temperature. Similar observation was reported by Silva and Rao (2005) in a study where variations of CWSI were more intense for stressed plants than non-stressed plants. The only significant effect of variety on CWSI was observed on DOY 214 where FM9170 had lower (0.66 vs. 0.74) CWSI than other varieties.

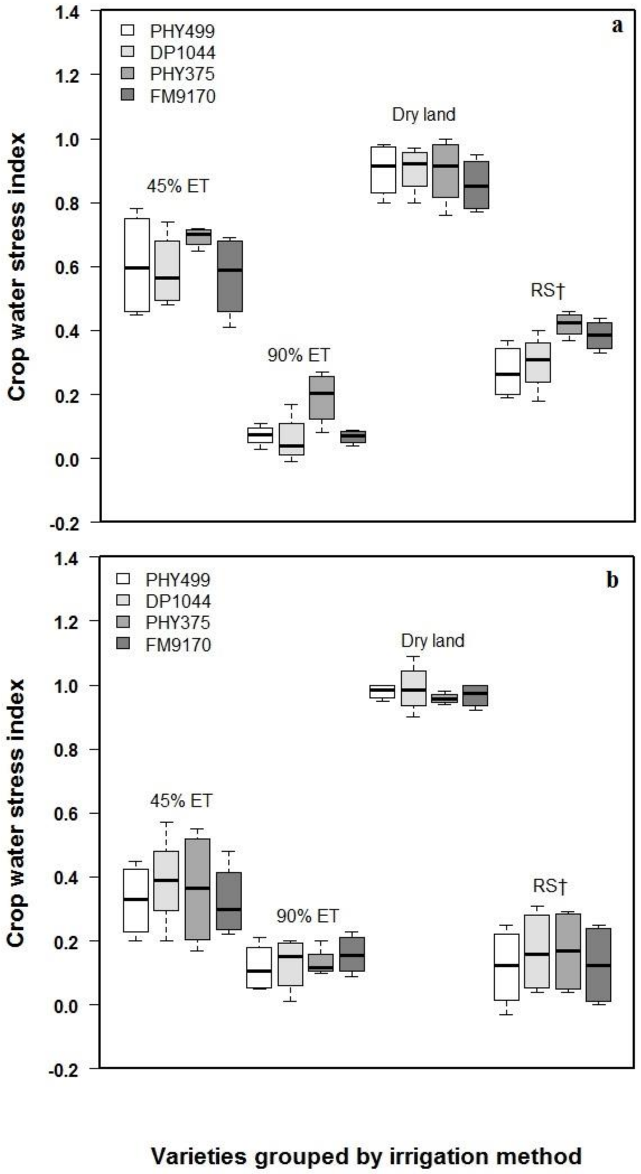

Figure 3.1. The Crop Water Stress Index calculated based on canopy temperature recorded on DOY 193 (a) and DOY 227 (b) as affected by irrigation and variety in 2012.

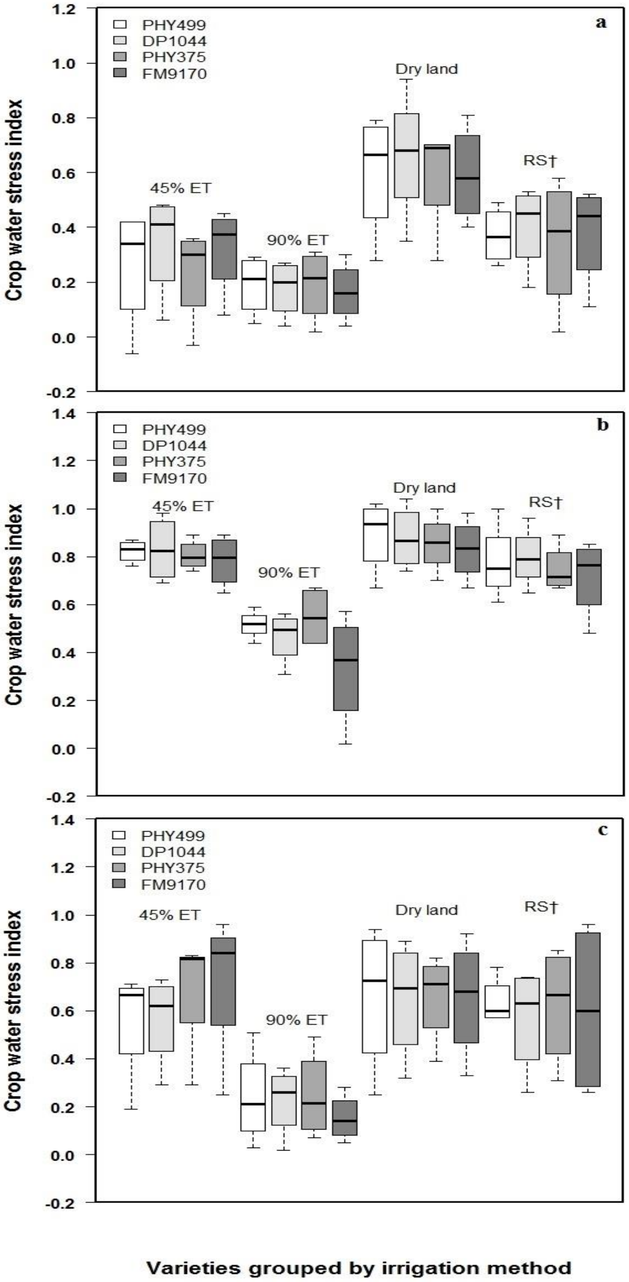

Figure 3.2. The Crop Water Stress Index calculated based on canopy temperature recorded on DOY 193 (a), 214 (b), and 232 (c) as affected by irrigation and variety in 2013.

Previous research reported that cotton shows a great reduction in ET when experiencing water stress (Rajan et al., 2010). Reduction in ET increases the canopy temperature of cotton plants (Grimes and Yamada, 1982; Baumhardt et al., 2009). Data from this study shows that when averaged across years and sampling dates, well watered plants had the minimum CWSI (< 0.2) indicating maximum transpiration, while dryland plants had the maximum CWSI (> 0.80) indicating minimum transpiration. The remote sensing-based irrigation had an average CWSI of 0.36 whereas 45% ET had an average CWSI of 0.47. Silva and Rao (2005) investigated the potential of CWSI to determine water status for cotton in arid environment. They concluded that cotton was experiencing water stress when the CWSI is > 0.3 a. Some researchers found that cotton lint yield was negatively correlated with mean seasonal CWSI and concluded that canopy-air temperature difference used in the computation of CWSI is a useful tool for quantifying crop water status (Jackson et al., 1977; Howell et al., 1984; Wanjura and Upchurch, 2000).

Leaf Area Index

Irrigation treatments significantly affected LAI development at the 0.1 probability level for measurements recorded on DOYs 184, 212, and 221 (Table 3.6). Results of the contrast analysis showed significant difference between 90% ET and dryland at all growth stages (Table 3.6). Throughout the growing season, there was no significant difference between LAI of 45% ET and remote sensing-based irrigation treatments (Table 3.7). Rapid LAI development was observed at the squaring and flowering stages. The maximum LAI of dryland was 2.42 which was attained at the boll filling stage (Table 3.7). At the boll filling stage (DOY 241), 90% ET irrigation produced the maximum LAI (4.99). Maximum LAI for 45% ET and remote sensing-based irrigation occurred three weeks earlier than 90% ET irrigation (Table 3.7). Varieties showed significant differences in LAI at all growth stages except the boll filling stage (Table 3.7). At the end of the season, no significant differences in LAI were observed among varieties (Table 3.6). Averaged across irrigation treatments, the highest LAI of 3.72 was reported for PHY499 on DOY 221. There was significant irrigation by variety interaction on LAI at squaring and flowering stages (DOYs 212 and 221) (Table 3.6). Among the varieties, PHY499 consistently produced higher LAI at all irrigation levels (Table 3.7). The maximum and minimum LAI reported in this study for dryland, deficit irrigated, and fully irrigated cotton is similar to the LAI values reported in other studies in similar regions (Orgaz and Fereres, 1992; Karam et al., 2006; Dagdelen et al., 2009). Pettigrew (2004) reported 35% reduction in LAI due to drought stress in cotton, which caused an overall vegetation growth reduction by 32% compared with irrigated plants.

Table 3.6. Analysis of variance of leaf area index (LAI) at different growth stages as affected by irrigation (I), tillage (T), and variety (V) in 2013.

		$LAI_{a†}$	LAI_b	LAI_c	LAI_d
SV	df	------------------------*P* > *F*------------------------			
I	3	0.081	0.097	0.080	0.031
T	1	0.246	0.263	0.827	0.431
I × T	3	0.151	0.748	0.726	0.881
V	3	0.003	0.015	<.0001	0.384
I × V	9	0.095	0.017	0.005	0.633
T × V	3	0.645	0.693	0.003	0.280
I × T × V	9	0.069	0.007	0.256	0.874
Contrasts					
90% ET vs. 45% ET	1	0.110	0.457	0.107	0.041
RS‡ vs. 45% ET	1	0.555	0.982	0.933	0.887
90% ET vs. Dryland	1	0.020	0.043	0.027	0.010
45% ET vs. Dryland	1	0.108	0.085	0.131	0.063

† a through d stand for leaf area index at emergence (DOY 184), squaring (DOY 212), flowering (221), and boll filling (DOY 241) growth stages, respectively.

‡ RS; Remote sensing-based irrigation scheduling.

Table 3.7. Leaf area index of four cotton varieties as affected by irrigation levels in 2013.

Variety/Irrigation	Dryland	45% ET	RS†	90% ET	Average$_{var}$
			Leaf area index$_a$‡		
PHY499	0.48	0.72a§	0.58b	0.83b	0.65c
DP1044	0.40	0.73a	0.86a	1.01ab	0.75cb
PHY375	0.50	0.61b	0.87a	1.04a	0.75b
FM9170	0.50	0.88a	0.94a	1.10a	0.85a
Average $_{Irrigation}$	0.47B¶	0.73AB	0.81AB	0.99A	
			Leaf area index$_b$		
PHY499	2.18b	3.16b	3.37ab	3.43b	3.04c
DP1044	2.52a	3.49a	3.10c	3.71a	3.21ab
PHY375	2.47a	3.20b	3.13bc	3.58a	3.09bc
FM9170	2.57a	3.29ab	3.51a	3.56ab	3.23a
Average $_{Irrigation}$	2.43B	3.28AB	3.28AB	3.57A	
			Leaf area index$_c$		
PHY499	2.30	3.85a	3.93a	4.78a	3.72a
DP1044	2.45	3.07b	3.11bc	3.99c	3.15c
PHY375	2.34	3.26b	2.83c	4.37b	3.20c
FM9170	2.56	3.30b	3.45b	4.66ab	3.49b
Average $_{Irrigation}$	2.41B	3.37AB	3.33AB	4.45A	
			Leaf area index$_d$		
PHY499	2.28	3.62	3.34	5.06	3.57
DP1044	2.17	3.28	3.72	4.67	3.46
PHY375	1.84	3.18	2.99	4.97	3.24
FM9170	1.95	3.33	3.12	5.24	3.41
Average $_{Irrigation}$	2.06B	3.35B	3.29B	4.99A	

† RS, Remote sensing based irrigation schedule.

‡ a through d stand for leaf area index at emergence (DOY 184), squaring (DOY 212), flowering (221), and boll filling (DOY 241) growth stages, respectively.

§ Vertical means (lowercase letters) followed by the same letter within a column are not significantly different at 0.05 probability level. Columns that do not contain letters indicate no significant difference among treatments.

¶ Horizontal means (uppercase letters) followed by the same letter within a row are not significantly different at 0.05 probability level.

Within Season Changes in NDVI and NDWI

The rate at which NDVI increased was affected by irrigation during the growing season (Fig. 3.3a). NDVI was highest for the 90% ET irrigation treatment and lowest for dryland. There was no significant difference between NDVI of 45% ET and the remote sensing-based irrigation treatments. For all irrigation treatments, NDVI peaked around 79 days after planting (DOY 222). No significant changes in NDVI were observed later in the growing season (DOY 232). Because the plant height still increased after DOY 222, we assume that this lack of increase in NDVI was primarily due to saturation of the reflectance signal. This is a major limitation in using NDVI for assessing crop development (Bouman, 1992; Casanova et al., 1998; Haboudane, et al., 2004).

Unlike NDVI, NDWI increased during the growing season until DOY 232 (Fig. 3.3b). Within irrigation treatments, there were no significant differences in NDWI early in the growing season (Fig. 3.3b). However, approaching mid-August, the 90% ET treatment had higher NDWI than the other irrigation treatments. For all irrigation treatments, the NDWI peaked at the end of August (DOY 232). No saturation problems were observed with NDWI during the peak growing season. Jackson et al. (2004) found that NDWI was superior to NDVI in estimating vegetation water content. Yi et al. (2007) also reported superior performance of NDWI in estimating vegetation water content of winter wheat. They also reported strong positive correlations between NDWI and dry matter and between NDWI and soil moisture contents. In the current study, NDWI performed better than NDVI.

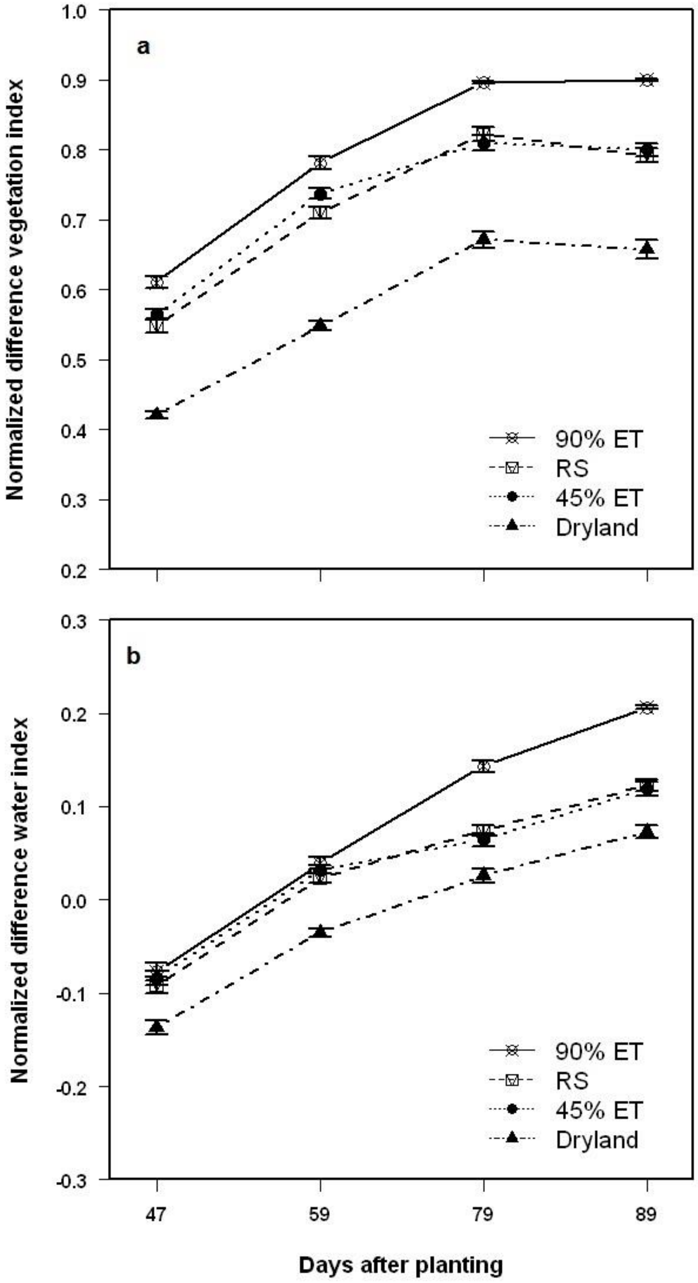

Figure 3.3. Normalized Difference Vegetation Index (a) and Normalized Difference Water Index (b) measured during the growing season. Error bars represent the standard error of the mean. RS is the remote sensing-based irrigation treatment.

In this study, NDVI was positively correlated with NDWI (Fig. 3.4). Since NDVI is an indicator of green leaf area, we can conclude that this correlation was due to more water content in vegetation as green leaf area increased. The CWSI calculated based on canopy temperature recorded on DOY 232 was found to be negatively correlated (r^2 = 0.69) with NDWI calculated based on crop reflectance measured on the same day (Fig. 3.5). The dryland plants had the highest CWSI values (~ 1) and the lowest NDWI values (~ 0). The well watered plants had lower CWSI (~ 0.2) and higher NDWI (~ 0.25). A relationship between LAI and NDVI was estimated using the linear plus plateau model (Fig. 3.6). The NDVI had a positive linear relationship with LAI that reached a plateau value of 0.89 when LAI was 4.66 (Fig. 3.6). This lack of response of NDVI at higher LAI was primarily due to saturation of the reflectance signal. The linear regression model, NDVI = 0.371 + 0.11(LAI), explained 71% of variation in LAI when the LAI was below 4.66.

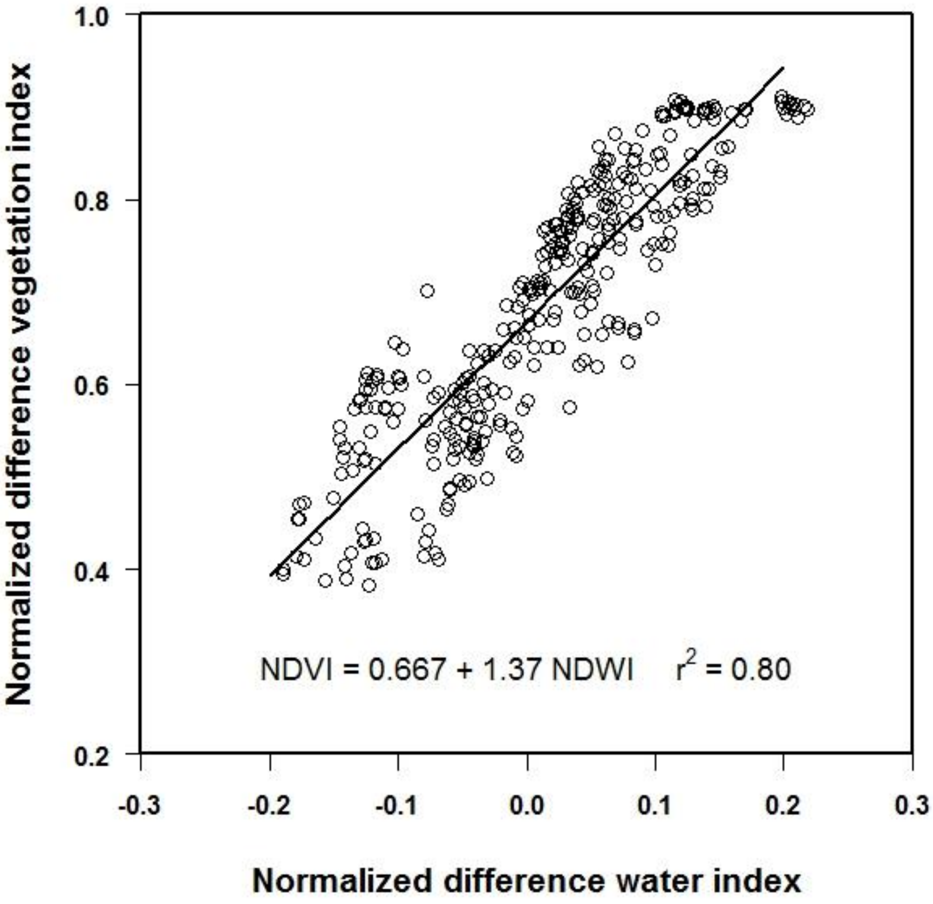

Figure 3.4. Relationship between normalized difference vegetation index and normalized difference water index for canopy reflectance recorded throughout 2013 growing season.

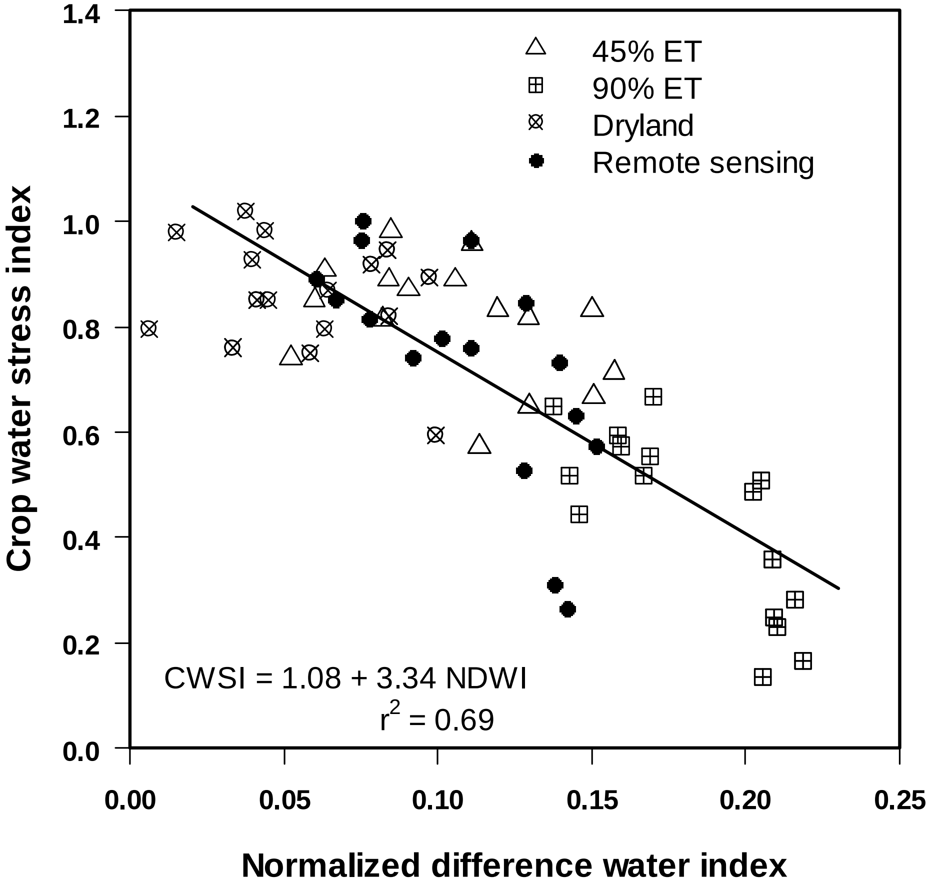

Figure 3.5. Relationship between crop water stress index and normalized difference water index based on canopy temperature and spectral reflectance recorded on DOY 232 in 2013.

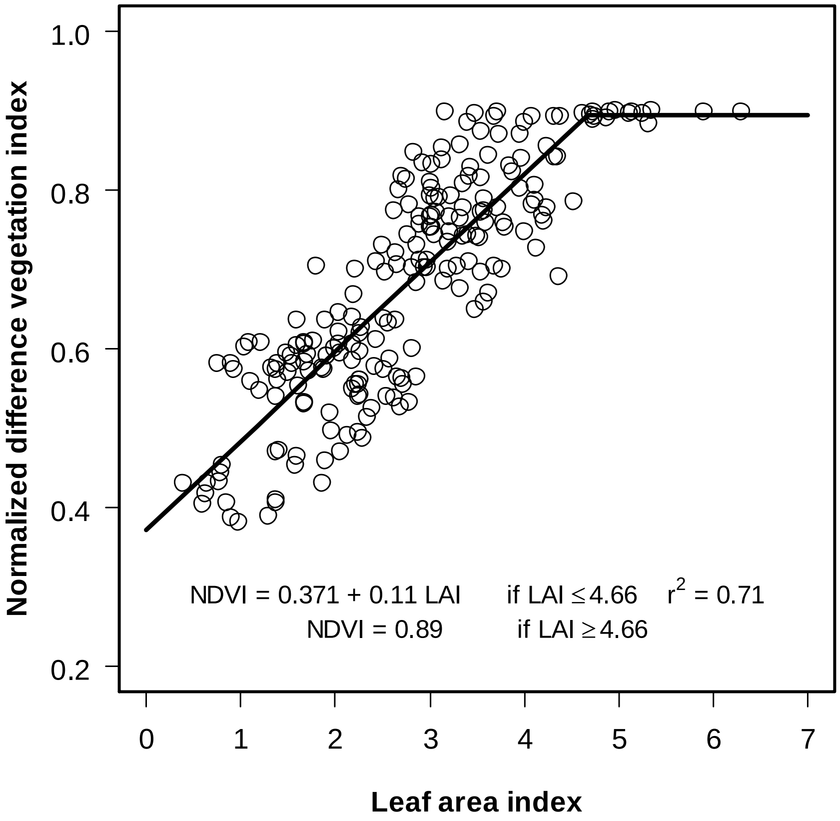

Figure 3.6. Normalized difference vegetation index plotted against leaf area index measured during the 2013 growing season.

CONCLUSIONS

Results of this study indicated within-season changes in leaf area index and plant height of cotton were significantly affected by irrigation and variety characteristics in the semi-arid Texas Rolling Plains. The higher irrigation of 90% ET replacement resulted in the highest average plant height of 113 cm in 2012 and 99 cm in 2013. Varieties tested in this study (FM9170, DP1044, PHY375, and PHY499) showed significant differences in plant height. PHY499 was the tallest variety compared to other varieties. The maximum and minimum LAI measured during the peak growth period was 4.99 for the 90% ET replacement treatment and 2.28 for the dryland treatment, respectively. Tillage did not result in significant differences in plant height or LAI. The CWSI calculated based on canopy-air temperature difference indicated that for deficit irrigation treatments, the average CWSI was > 0.50. Comparison of NDVI and NDWI indicated that NDWI performed better compared to NDVI as no saturation problems were observed in NDWI values during the peak growing season. It was also observed that the CWSI and NDWI were negatively correlated.

CHAPTER IV

OPTIMIZATION OF COTTON IRRIGATION REQUIREMENTS IN THE TEXAS ROLLING PLAINS USING THE COTTON2K CROP SIMULATION MODEL

INTRODUCTION

Over 20% of the world's cotton (*Gossypium hirsutum* L.) is produced in 17 southern states in the United States collectively known as the Cotton Belt. Geographically, it is divided into four regions: the West, South, Southwest, and Southeast regions. Among these four regions, the major concentration of cotton production is found in the southwest region, especially the High Plains and Rolling Plains of Texas. The availability of water for irrigation from the Ogallala aquifer has made cotton a major field crop in the Texas High Plains region. This region alone accounts for almost 30% of the total cotton acreage and production in the U.S in 2007 (USDA-NASS, 2007). Much of the previous research with regard to cotton production and water management in Texas has been concentrated in the Texas High Plains region (Colaizzi et al., 2004; Howell et al., 2004; Rajan, 2007; Baumhardts et al., 2009; Rajan et al., 2010; Nair et al., 2013a; Snowden et al., 2013; Feng et al., 1014).

The Texas Rolling Plains is the gently rolling region that falls below the plateau of the Texas High Plains. The elevation of this region ranges from 275 m in the east to 1,250 m in the west. Cotton and winter wheat (*Triticum aestivum* L.) are the major field crops grown in the Texas Rolling Plains (USDA-NASS, 2014). Twenty-seven counties in this region account for approximately 13% of cotton production in Texas. Only 16% of the planted acreage in the Texas Rolling Plains is irrigated, but the irrigated areas account for 41% of harvested yield (DeLaune et al., 2012). The Seymour Aquifer is the major source of irrigation water in the Texas Rolling Plains. This shallow aquifer has less than 30 m of saturated thickness. Unlike the Ogallala aquifer, the Seymour aquifer is highly permeable and is sensitive to seasonal changes in rainfall. It recharges at a rate of 25 to 63.5 mm per year (Scanlon et al., 2003).

Expanding acreage using the current irrigation systems in the Texas Rolling Plains region (furrow and pivot) is challenging because the ground water resources of the Seymour aquifer are nearly fully utilized (Sij et al., 2010). Thus, expanding irrigated acreage requires efficient management of ground water resources and installation of efficient irrigation systems, such as sub-surface drip irrigation (SDI). Many research studies have found that SDI is more efficient than center-pivot and furrow irrigation systems (Camp et al., 1998; Colaizzi et al., 2004; Grismer, 2002; Dagdelen et. al., 2009). In addition to choosing the irrigation system, efficient management of ground water resources is possible through crop and variety section, irrigation scheduling, and conservation tillage, to name a few.

Cotton has several traits that enhance its adaptation to water-limited environments (Pettigrew, 2004b). However, moisture stress at critical growth stages can reduce plant height, leaf area expansion, and leaf photosynthesis, and reduces lint yield and quality (Pettigrew, 2004b; Hatfield, 2011). Water stress at the reproductive stage can cause shedding of blooms and fruiting structures (Guinn and Mauney 1984; Ball et al., 1994; Gerik et al., 1996). These negative effects associated with water stress have increased the need for supplemental irrigation to improve the performance of cotton in semi-arid regions.

Yield of irrigated cotton is usually two to four times greater than dryland cotton, depending on the absolute amount of irrigation and the type of irrigation system (TAWC, 2012; Wanjura et al., 2002; Basal et al., 2009). However, irrigating to meet the maximum daily crop water demand or crop evapotranspiration (ET) is often challenging due to declining aquifer water levels and increasing pumping costs. Studies have shown that some deficit irrigation strategies will not significantly reduce lint yield in cotton. For example, Falkenberg et al. (2007) reported that deficit irrigation at 75% of crop ET rate has produced lint yield on par with full irrigation in southwest Texas. Basal et al. (2009) reported that deficit irrigation at 75% of crop ET decreased the yield by only 8% as compared to irrigating at 50% of crop ET, which reduced the yield by 20 to 30%.

Crop growth simulation models, after calibration and validation, offer an opportunity to test the responses of crops to management factors. The outcome of simulation scenarios can be used to identify optimal management strategies. Several studies in the past have demonstrated the potential of crop growth models to help optimize irrigation management strategies (Timsina et al., 2008; Thorp et al., 2009; Ko et al., 2009; Qi et al., 2013; Nair et al., 2013a; Thorp et al., 2014). Clouse (2006) compared three cotton simulation models (GOSSYM, COTONS, and Cotton2k) for their ability to simulate water movement in the soil-plant-air continuum in the Texas High

Plains region. He concluded that the Cotton2K model performed better than the other two crop models in predicting applied water-yield relations due to better empirical relations associated with water stress in the Cotton2K model. Using the Cotton2k model, Nair et al. (2013a) investigated how lint yield and profit would be affected by only irrigating certain portions of a field. They found that irrigating 30 to 70 % of a field produced the most yield and profit, depending on the amount of irrigation water available. Very few studies in the Texas Rolling Plains have investigated the optimal irrigation strategies for cotton. Therefore, the main objectives of this research were (1) to calibrate and validate the Cotton2K crop growth simulation model using soil, hydrology, and lint yield data from field studies in the Texas Rolling Plains region, and (2) to determine the best irrigation management strategy that optimizes the yield and economic returns for cotton in the Texas Rolling Plains.

MATERIALS AND METHODS

Cotton2K Model

The cotton2K model is a process-based cotton simulation model developed by A. Marani (Marani, 2000). This is a modified version of the GOSSYM-COMAX model intended for simulating cotton growth and production for arid and semi-arid conditions (Nair et al., 2013a; Thorp et al., 2014). The model simulates the interaction between processes occurring in the plant, soil, and the microenvironment, and management inputs applied to the field. Most procedures in the model are computed on a daily time step. Some processes such as the effects of temperature on growth rates and phenology are simulated at an hourly time step. In addition, water and nutrient stresses also have a strong effect on simulated processes of growth and development.

Potential evapotranspiration (PET) is computed in the model at an hourly time step. A procedure for computing hourly values of weather parameters from daily values for calculating PET had been implemented in the latest version of the model. The root sub model had been modified to simulate the responses of root growth and activity to different soil moisture conditions. The actual crop ET is computed using PET and soil water potential which is computed as an average for the whole root zone weighted by root activity in each soil layer (Clouse, 2006). Water movement in the soil is computed at an hourly time step. Average soil water potential, plant resistance to water transport, and potential transpiration are used for computing the leaf water potential. Water-stress related empirical coefficients are then derived using the leaf water potential. Water-stress affects the growth rates of plant parts, aging rates of leaves and bolls, photosynthesis, and abscission rates of leaves, squares and bolls.

Model Calibration and Evaluation

Data from two field experiments conducted from 2009 to 2012 at the Texas A&M AgriLife Research Station near Chillicothe, TX (34˚15' N, 99˚ 30' W, and 433 m elevation) were used for model validation. The field studies were investigating the effect of different ET-based irrigation rates on cotton lint yield and quality. The experiments were conducted in fields installed with sub-surface drip irrigation (SDI). Drip tapes were installed at 0.30 m depth at 1 m spacing. The spacing between emitters was 0.40 m. Unlike other cotton models, the Cotton2K model has the option to input drip irrigation in simulation experiments. Each irrigation plot was 45 m long and 16 m wide. Irrigation was cut-off at 3 nodes above white flower stage (mid-late August or early September). The seeding rate was 10-13 plants/m of row. Cotton was planted at 1 m row spacing in May and machine harvested in November. At harvest, sub-samples were collected for yield and fiber quality analysis. Details of these experiments can be found in DeLaune et al (2012) and Rajan et al (2013).

The climate data required for simulations from 2009 to 2012 were obtained from the Texas High Plains ET Network weather station at the Chillicothe Research Station (https://txhighplainset.tamu.edu/login.jsp). Details of management practices recorded in the field studies were used for creating agricultural input files for the model. These files included information on planting, herbicide, pesticide, and fertilizer applications, irrigation, and harvesting. The ground water used for irrigation at the Chillicothe Research Station contained 19.9 NO_3-N mg L^{-1}. Corresponding amounts of nitrate in irrigation water was added in the fertilizer input file. The soil type at this location is an Abilene clay loam (fine, mixed, superactive, thermic pachic Agriustolls) with 0 to 1% slope. The climate of this region is semi-arid with an average long-term precipitation of 290 mm during the cotton growing season from May to September (Fig. 4.1).

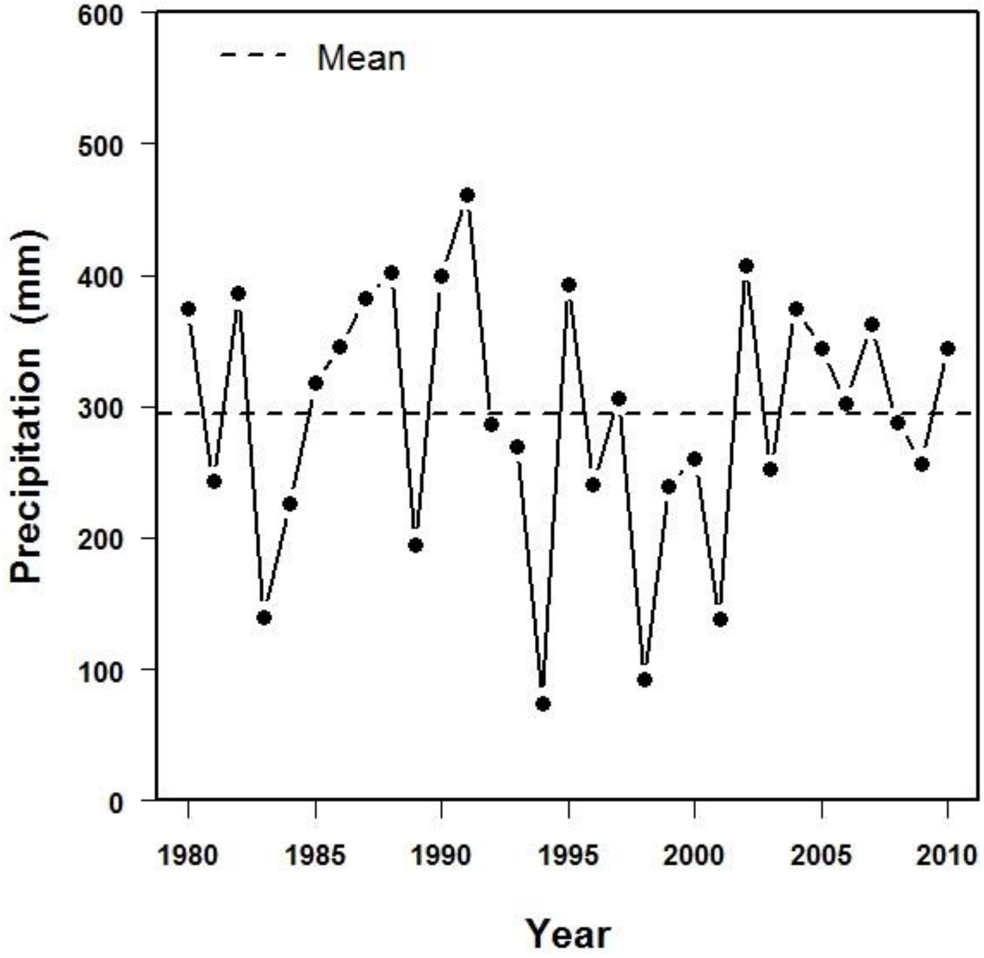

Figure 4.1. Average precipitation from 1980 to 2010 during the cotton growing season (May-September) in the Texas Rolling Plains (Data obtained from the Texas High Plains ET Network weather station at the Chillicothe Research Station).

The current version of the Cotton2K model is calibrated for several modern varieties. In this study, Deltapine 61 was used in simulation experiments. Providing accurate parameters for the soil type in the model improves the precision of model simulations. Soil chemical (NO_3-N, NH_4-N, and soil organic matter content) characteristics up to 45 cm depth were obtained from soil analysis data collected during field experiments. Details of these parameters are provided in Table 4.1. Soil NO_3-N, NH_4-N, and soil organic matter were assumed to gradually decrease to reach 6 kg ha^{-1}, 2 kg ha^{-1}, and 4 g kg^{-1}, respectively at 105 - 120 cm soil depth (Table 4.1). Details of the soil textural and hydrologic characteristics used in this study are provided in Table 4. 2. Initial soil water content of the soil profile was set at 75% field capacity (5 days prior to planting). The residual and saturated water contents were computed using hierarchical pedotransfer function package in the Rosetta model (Schaap et al., 2001) utilizing the soil texture and bulk density data from the field. The saturated hydraulic conductivity was taken from the default values published for Abilene clay loam soil (Soil survey staff, 2004).

Table 4.1. Calibrated soil chemical properties used in the simulation study.

Soil depth	NH_4-N content	NO_3-N content	SOM†
----cm----	-----------Kg ha^{-1}-----------		----g kg^{-1}----
0 – 15	12	12.6	12.0
15 – 30	12	9.6	10.0
30 – 45	12	12.4	8.0
45 – 60	10	9	6.0
75 – 90	8	8	6.0
90 - 105	5	7	4.0
105 – 120	2	6	4.0

†SOM; Soil organic matter.

Table 4.2. Calibrated soil hydrology parameters used in the simulation study.

	Soil depth, cm	
Parameters	0 – 30	30 – 200
Soil water potential at field capacity, kPa	-30	-30
Soil water potential at permanent wilting point, kPa	-1500	-1500
Residual volumetric water content, m^3 m^{-3}	0.22	0.15
Saturated volumetric water content, m^3 m^{-3}	0.41	0.36
Alpha coefficient	0.055	0.033
Beta coefficient	1.478	1.153
Saturated hydraulic conductivity, cm day^{-1}	20.0	6.0
Bulk density, g cm^{-3}	1.50	1.30
Clay, %	38.0	42.0
Sand, %	31.0	28.0

After calibrating for soil and hydrology parameters, the Cotton2K model was used to simulate lint yield for each irrigation treatment from the field studies. The simulated lint yields were then compared with the corresponding observed lint yields. The overall accuracy of the model simulations was determined using ordinary least squares regression analysis between the simulated and observed yields. The slope and intercept of the regression line through the data were tested using the Student's t-test. This was done to determine whether the regression line was significantly different from the slope and intercept of the 1:1 line. No significant difference would indicate a satisfactory performance of the Cotton2K model for simulating cotton yield in the Texas Rolling Plains.

Simulations Using Historic Weather Data

After validation, the Cotton2K model was used for simulating cotton lint yield response to six ET replacement treatments according to the FAO-56 method (Allen et al., 1998). We used the crop coefficient values recommended by the Texas High Plains ET Network for the Rolling Plains region in the simulation experiment. The weather dataset including daily minimum and maximum air temperatures, daily precipitation, dew point temperature, wind speed, and solar radiation from 2000 to 2010 was obtained from the Texas High Plains ET Network weather station at Chillicothe. For the period from 1980 to 1999, the weather dataset was obtained from the Integrated Agricultural Information and Management System (iAIMS) website (https://beaumont.tamu.edu/CLIMATICDATA/WorldMap.aspx) which has current and historic data available from various data services including the National Climate Data

Center's (NCDC) Climatic Data Online service. Simulation profiles were created starting from 1 May to 15 November for all years in the study. Planting date was set as 15 May. Input files were created similar to those in the validation study as it represents common agricultural practices followed in the region. Nitrogen was applied at planting and at first square stage at a rate of 67 kg ha^{-1} as urea. Irrigation treatments included dryland, 40, 60, 80, 100, 120, and 140% ET_c replacements. In total, 217 simulation scenarios were created using 7 irrigation treatments and 31 years of weather dataset. The ET_c was calculated as follows;

$$ET_c = k_c \times ET_o \qquad \text{[Eq. 5]} \quad \text{(Allen et al., 1998)}$$

where ET_c is the crop evapotranspiration (mm day^{-1}), k_c is the crop coefficient, and ET_o is the reference evapotranspiration (mm day^{-1}). The ET_o was calculated as follows;

$$ET_o = \frac{\mathbf{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right) u_2\,(e_s - e_a)}}{\mathbf{\Delta + \gamma(1 + 0.34u_2)}} \qquad \text{[Eq. 6]}$$

where Δ is the slope vapor pressure curve (kPa $°C^{-1}$), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $(e_s – e_a)$ is the saturation vapor pressure deficit (kPa), and γ is the psychrometric constant (kPa $°C^{-1}$). The slope vapor pressure curve (kPa $°C^{-1}$) was calculated as follows;

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \qquad \text{[Eq. 7]}$$

where Δ is te slope vapor pressure curve (kPa °C^{-1}) and T is the mean daily air temperature at 2 m height (°C). The net radiation at the crop surface (MJ m^{-2} day^{-1}) was calculated as follows;

$R_n = R_{ns} - R_{nl}$ [Eq. 8]

where R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), Rns is the net solar radiation (MJ m^{-2} day^{-1}), and R_{nl} is the net outgoing longwave radiation (MJ m^{-2} day^{-1}). Measured solar radiation was obtained from the weather dataset and used for the R_{ns} and R_{nl} calculations while the soil heat flux was ignored (G).

The saturation vapor pressure was calculated as follows;

$e_s = 0.6108 \exp\left[\frac{17.27T}{T+237.3}\right]$ [Eq. 9]

where e_s is the saturation vapor pressure (kPa) and T is the mean daily air temperature at 2 m height (°C). The actual vapor pressure (kPa) was calculated as follows;

$e_a = 0.6108 \exp\left[\frac{17.27Tdew}{Tdew+237.3}\right]$ [Eq. 10]

where e_a is the actual vapor pressure and T_{dew} is the dew point temperature (°C).

Calculation of Water Use Efficiency

Water use efficiency (WUE) is defined as a ratio of biomass accumulation expressed as total crop biomass, carbon dioxide assimilation, or yield to consumed water expressed as ET, transpiration, or total water input (Nair et al., 2013b). In this study, we calculated three WUE parameters to assess irrigation treatments.

WUE (kg m^{-3}) was calculated as:

$\text{WUE} = \frac{(\text{Lint yield}_x)}{\text{Irrigation}_x + \text{Precipittaion}}$ [Eq. 11] where lint yield$_x$ is the lint yield (g m^{-2}) at x level of irrigation and irrigation$_x$ is the amount of irrigation water (mm) applied at x level of irrigation..

Irrigation water use efficiency (IWUE, kg m^{-3}) was calculated as:

$$\mathrm{IWUE} \quad = \frac{(\text{Lint yield}_{\mathrm{x}} - \text{Dryland lint yield})}{\text{Irrigation}_{\mathrm{x}}} \qquad \text{[Eq. 12]}$$

Benchmark water use efficiency (B$_{\mathrm{WUE}}$) is calculated as:

$$\mathrm{BWUE} \quad = \frac{\text{Lint yield}_{\mathrm{x}}}{(\text{Irrigation}_{\mathrm{x}} + \text{Precipitation} + \Delta \mathrm{SM})} \qquad \text{[Eq. 13]}$$

where Δ SM is the change in soil moisture content in the root zone during the growing season (mm). Soil moisture content in the root zone was obtained from the model simulated soil moisture results.

Calculation of Effective Yield and Profit

The Texas A&M AgriLife crop and livestock budget for irrigated (Texas A&M AgriLife Extension) and dryland (Texas A&M AgriLife Extension) cotton for the Rolling Plains Region (District 3) were used to derive the cost of production for economic analysis. The total direct expenses at each level of irrigation was calculated by adjusting the cost of harvesting based on the simulated yield and irrigation labor cost, electricity cost, and repair and maintenance cost of irrigation equipment based on the amount of irrigation water applied. The price of cotton lint was held constant at 1.57 dollars kg^{-1}., which is the average of the monthly price received by farmers from March 2008 to March 2014 (National Cotton Council, 2014). The price of cotton seed was held constant at \$0.325 kg^{-1} and the seed to lint ratio was assumed to be 1.5. These values were obtained from the published reports of the Texas A&M AgriLife crop and livestock budget. The total income for each treatment was calculated from the simulated cotton lint yield, assumed cotton seed to lint ratio, and the prices of cotton lint and seed. The return over direct expenses for each treatment was calculated from the income and expenditure data.

RESULTS AND DISCUSSION

Model Evaluation

Figure 4.2 presents simulated lint yield plotted against observed lint yield from 2009 to 2012. The OLS linear regression equation fit to these points explained 94.0% of the total variance indicating good agreement between the observed and simulated data. Two separate Student's t tests were performed to test whether the OLS regression line was significantly different from the 1:1 line. The results showed that the slope of the regression was not significantly different from 1 ($p > t = 0.648$) and the intercept was not significantly different from 0 ($p > t = 0.216$). This indicated that the OLS regression line was not significantly different from the 1:1 line. Additional test of the accuracy of the simulations was performed by calculating the Root Mean Square of Error (RMSE). The RMSE was 116 kg ha^{-1} or 10% of the average observed lint yield. The t-test and the low RMSE demonstrated that the model was simulating lint yield with reasonable accuracy and can be used to simulate cotton lint yield response to irrigation in the Texas Rolling Plains with acceptable accuracy.

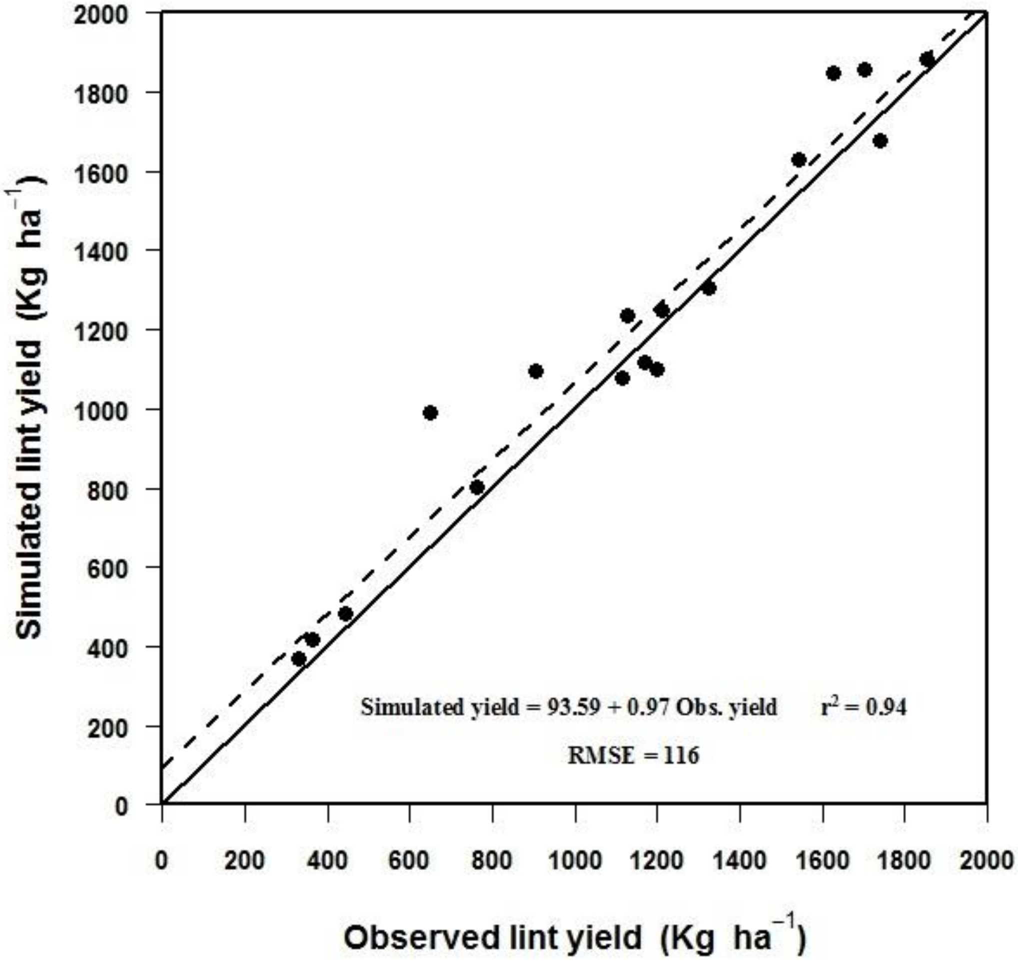

Figure 4.2. Simulated lint yield regressed against observed lint yield recorded for field experiments conducted from 2009 to 2012 in the Texas Rolling Plains. The solid line is the 1:1 line and the dashed line is the ordinary least-squares linear regression line.

Lint Yield Response to Irrigation

Figure 4.3 presents the simulated lint yield plotted against the corresponding amount of irrigation water applied for six ET treatments (excluding dryland treatment) for 31 growing seasons from 1980 to 2010. Irrigation water applied during the study period ranged from 43 mm to 839 mm depending on the ET treatment. At the same level of irrigation, yield varied among growing seasons. This was mainly due to yearly variations in the amount and distribution of precipitation (Fig. 4.1). Despite yield variations, a quadratic function provided a reasonable fit to the data with an r^2 of 0.52. The quadratic polynomial equation indicated that applying 515 mm of irrigation water maximized lint yield at 1461.7 kg ha^{-1} (Fig. 4.3). The yield increments between 43 mm and 300 mm of irrigation was 2.125 kg ha^{-1} mm^{-1}. The yield increments declined to 0.66 kg ha^{-1} mm^{-1} between 300 mm and 515 mm of irrigation and then showed a negative response to increased irrigation. In order to predict lint yield at various ET based irrigation levels, we plotted average lint yield against ET replacement treatments (Fig. 4.4). Irrigation at 112% ET produced the highest lint yield of 1405.9 kg ha^{-1} (Fig. 4.4). Lint yield increment between 40% ET and 80% ET was 11.77 kg ha^{-1} per unit of ET, which was declined to2.76 kg ha^{-1} per unit of ET between 80% and 120% ET (Fig. 4.4).

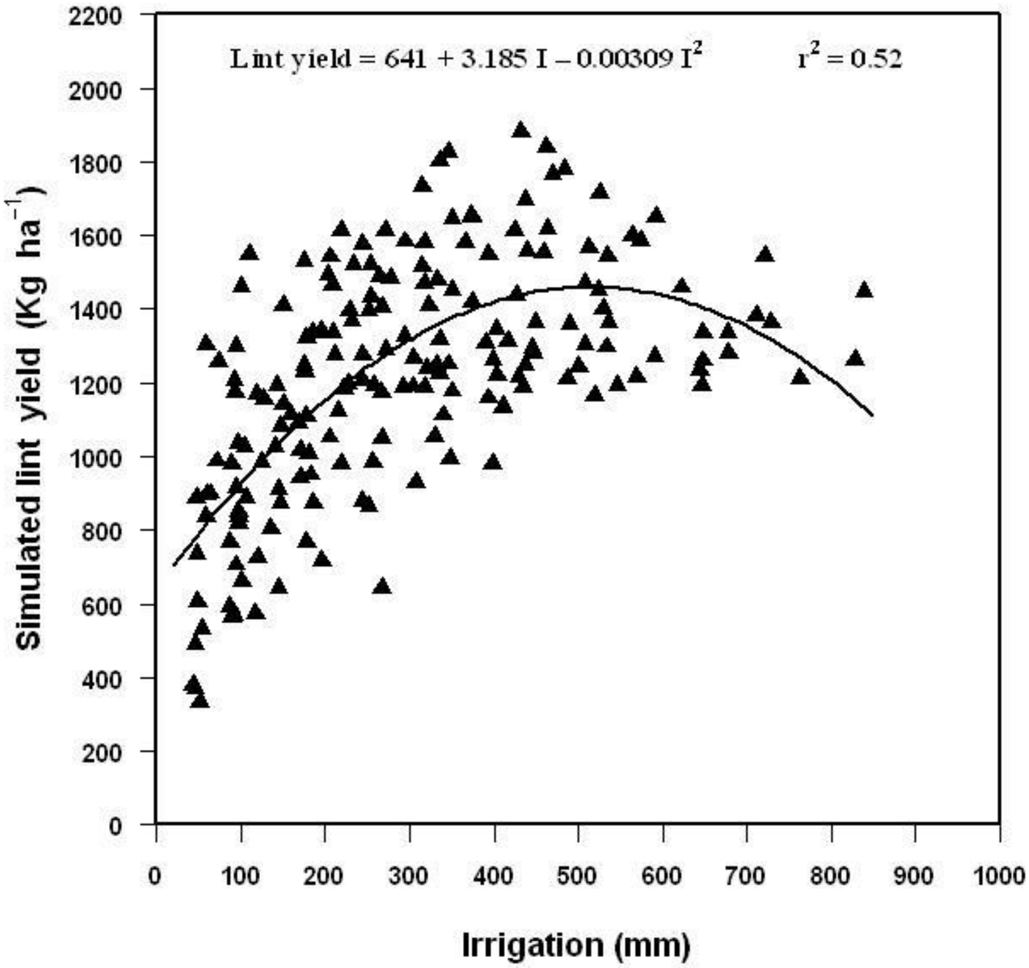

Figure 4.3. Simulated cotton lint yield response to irrigation water received according to six evapotranspiration replacement treatments for 1980 to 2010 growing seasons in the Texas Rolling Plains.

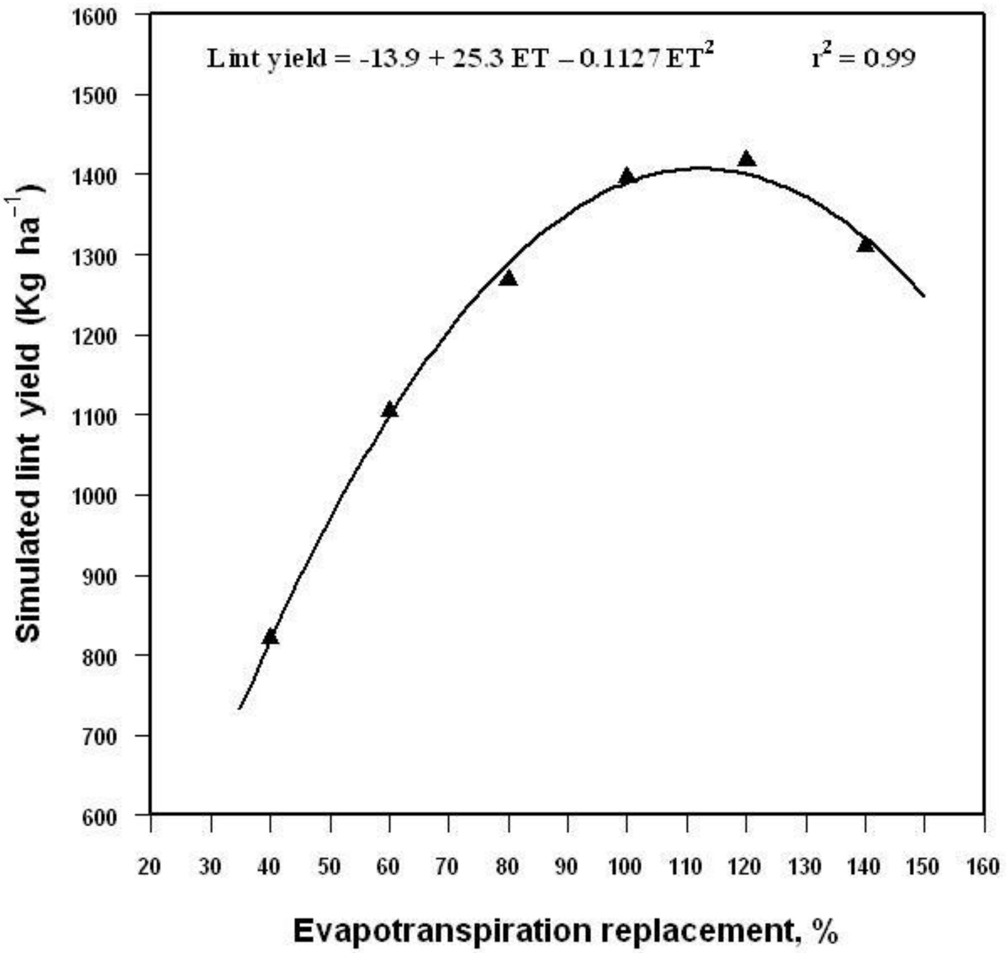

Figure 4.4. Simulated cotton lint yield response to six evapotranspiration replacement treatments for growing seasons from 1980 to 2010. Each point represents an average of 31 values for each treatment during the study period.

Past studies reported similar response of lint yield to irrigation for cotton grown in Texas. Wanjura et al. (2002) reported a peak response of 1464 kg lint yield ha^{-1} at 577 mm of irrigation using a second-order polynomial relationship using data from 12 years of field studies conducted in drip irrigated fields in the Texas High Plains. Baumhardt et al. (2009) reported a maximum lint yield of 913 kg ha^{-1} when irrigation amounts ranged from 210 to 263 mm in the Southern High Plains of Texas. In the Texas Rolling Plains, DeLaune et al. (2012) reported that replacing 104.5% ET resulted in a maximum lint yield of 1163 kg ha^{-1}. Falkenberg et al. (2007) reported that replacing 75% ET did not result in significant lint yield reduction in southwest Texas compared to 100% ET irrigation treatment.

Lint Yield Response to Total Water

Figure 4.5 presents the relationship between lint yield and total water (irrigation + precipitation) during 31 growing seasons from 1980 to 2010. Total amount of water received in the growing season ranged from 74.67 mm to 1203.2 mm and lint yield ranged from 75 kg ha^{-1} to 1880.7 kg ha^{-1}. Dryland lint yield during the simulation period ranged from 75 kg ha^{-1} to 1217 kg ha^{-1}. The average dryland yield was 444 kg ha^{-1}. Similar to lint yield response to irrigation, lint yield increased at a decreasing rate as total water increased (Fig. 4.5). It can be estimated from the quadratic fit to the data that a maximum yield of 1473.3 kg ha^{-1} was realized at 863.9 mm of total water (Fig. 4.5). Yield variations at the same level of total water can be attributed to differences in growing season precipitation amounts and distribution (Fig. 4.1) or occurrence of heat or water stress. Growing season with favorable conditions enhances water uptake, thereby transformation and assimilation of nutrients. Wanjura et al. (2002) documented a significant lint yield decline (40%) in years with severe yield limiting weather conditions in the Texas High Plains.

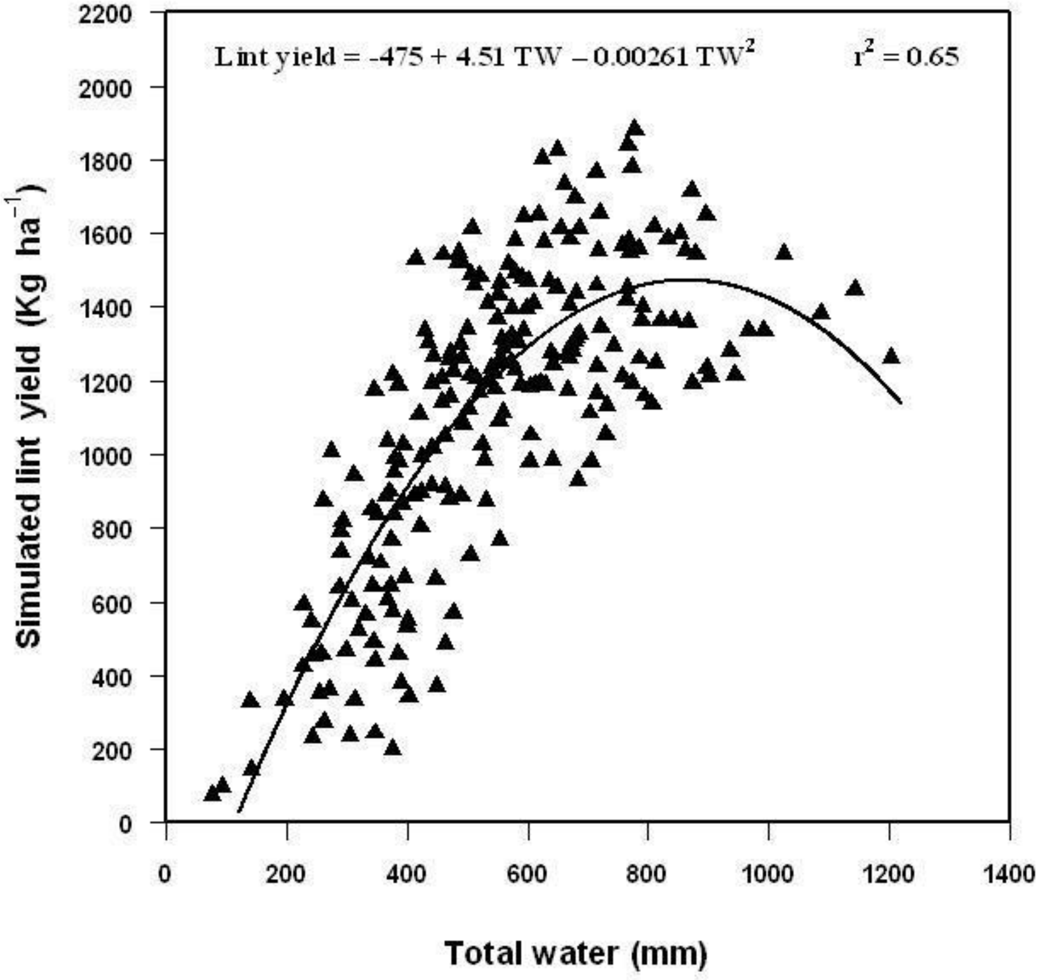

Figure 4.5. Simulated lint yield plotted against total water received (precipitation and irrigation) for growing seasons from 1980 to 2010 in the Texas Rolling Plains. Treatments include one dryland and six evapotranspiration based irrigation replacements.

Water Use Efficiency

In the semi-arid Texas Rolling Plains, attaining high WUE is a priority as there are limited water resources available for irrigation. WUE indicates the amount of yield produced per total of applied water (irrigation plus rainfall). In general, we expect the WUE of dryland treatment less than the irrigated treatment. In our study, there was no significant difference between the WUE of dryland treatment and 140% ET irrigation treatment indicating inefficient use of water at higher irrigation rates in producing unit lint yield (P > t =0.202) (Table 4.3). Deficit irrigation at 60% ET replacement level resulted in the highest WUE in our study (Table 4.3). The WUE at 60% ET irrigation level was 2.44 kg of lint yield ha^{-1} for every mm of water used. This decreased to 2.37 kg of lint yield ha^{-1} mm^{-1} and 2.24 kg of lint yield ha^{-1} mm^{-1} at 80% ET and 100% ET irrigation levels, respectively. Declining WUE at high irrigation levels could be explained by increased soil water loss through evaporation or percolation below the root zones. At our study site, the drip tapes were installed at 0.30 m below the surface of the soil. At 100% ET irrigation and above, the evaporative loss of water was higher than the deficit irrigation treatments due to increased soil surface wetness. Hence, WUE decreased at high irrigation levels. The BWUE was found to increase at a decreasing rate as the amount of irrigation water increased (Fig. 4.6). Irrigating 288 mm resulted in maximizing the BWUE (0.206 kg m^{-3}). There is limited information available about WUE values of SDI-cotton in the Texas Rolling Plains. The reported values of WUE of cotton in the neighboring Texas High Plains were slightly higher than the average values estimated in the current study. In a demonstration project conducted in the Texas High

Plains, the average WUE of SDI-irrigated producer fields for 22 site-years was 2.99 kg of lint yield per mm of total water (TAWC, 2013). In another recent study conducted by Whitaker et al. (2008) in Lubbock, TX, the average WUE of SDI cotton was 2.91 Kg ha^{-1} mm^{-1} and the average total water received was 592 mm. These WUE values are slightly higher than the highest average WUE values during the 30-year simulation period at our study site in the Texas Rolling Plains.

IWUE quantifies cotton lint yield produced per unit of applied irrigation (Fig. 4.6). IWUE during the 30 year simulation period ranged from 0.178 kg m^{-3} to 0.424 kg m^{-3}. Regression analysis showed that IWUE decreased linearly as the amount of irrigation water applied increased (r^2= 0.94). IWUE response to ET-based treatments showed that irrigation at 40 and 60% ET level resulted in the highest IWUE of 3.80 kg ha^{-1} mm^{-1} and 4.24 kg ha^{-1} mm^{-1}, respectively, and there was no significant difference between IWUE responses at these irrigation levels. Irrigation at 140% ET level resulted in the lowest IWUE of 1.71 kg ha^{-1} mm^{-1} (Table 4.3). DeLaune et al. (2012) found that irrigating at 33% of the cotton ET produced the greatest IWUE of 0.49 kg m^{-3} in the Texas Rolling Plains. This was not significantly different from other IWUE values at higher ET replacement treatments in their study except 133% ET.

Table 4.3. Mean and related statistical distribution parameters of irrigation, lint yield, Irrigation WUE (I_{WUE}), benchmark WUE (B_{WUE}), and economic return response to evapotranspiration replacement for 31 (n=31) growing seasons from 1980 to 2010 at the Texas Rolling Plains.

		Evapotranspiration % replacement					
	Dryland	40	60	80	100	120	140
Parameters							
Irrigation	---------------------------------mm---------------------------------						
Mean	-	103	174	260	354	447	535
Median	-	97	170	241	318	417	501
SE†	-	8.4	14.0	16.6	19.6	22.4	25.3
Skewness‡	-	0.71	0.61	0.63	0.69	0.68	057
Lint yield	--------------------------------kg ha^{-1}--------------------------------						
Mean	444	821	1104	1269	1396	1418	1310
Median	455	816	1017	1246	1366	1421	1293
SE	42.4	53.4	54.8	42.6	33.5	38.0	31.8
Skewness	1.2	0.37	0.49	0.51	0.39	0.03	0.37
WUE	-----------------------------kg ha^{-1} mm^{-1}-----------------------------						
Mean	1.53	2.13	2.42	2.35	2.22	1.97	1.62
Median	1.39	2.14	2.51	2.30	2.24	1.94	1.60
SE	0.11	0.13	0.11	0.08	0.07	0.07	0.06
Skewness	0.79	0.03	-0.14	0.57	0.04	-0.25	0.57
IWUE	------------------------------kg ha^{-1} mm^{-1}-----------------------------						
Mean	-	3.50	4.24	3.45	2.91	2.33	1.78
Median	-	3.86	4.29	3.14	2.62	2.19	1.71
SE	-	0.35	0.28	0.20	0.16	0.15	0.12
Skewness	-	0.09	-0.08	0.51	0.25	0.76	1.65
Economic return	--------------------------------\$ ha^{-1}---------------------------------						
Mean	305	542	911	1120	1291	1283	1122
Median	333	521	849	1115	1199	1215	1115
SE	83	72	68	53	49	52	46
Skewness	0.51	0.25	0.78	1.12	1.10	0.35	0.47

† Positive skewness values indicate that the distribution of presented parameter is shifted towards values less than the mean while negative skewness values indicate that the distribution of presented parameter is shifted towards values greater than the mean.

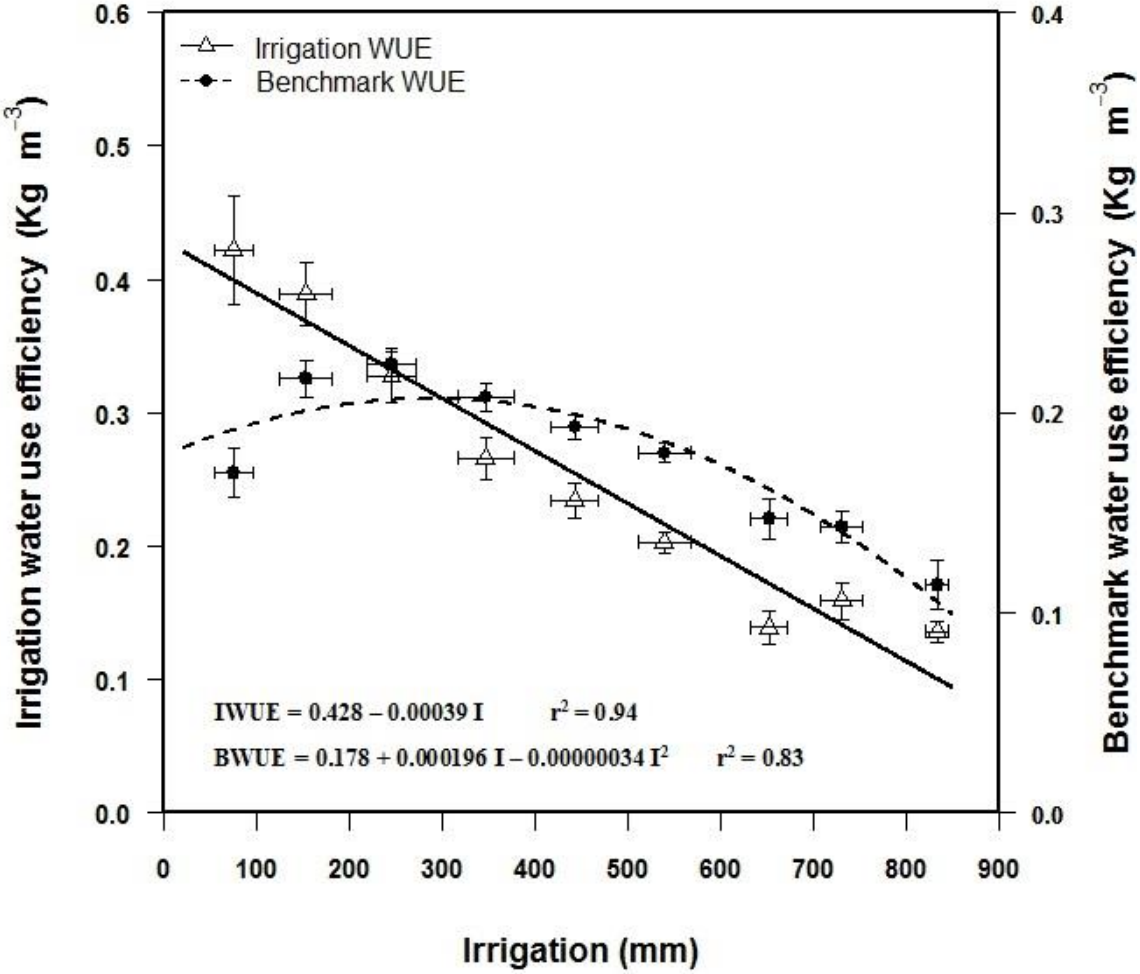

Figure 4.6. Cotton irrigation water use efficiency plotted against irrigation water received according to six evapotranspiration replacement treatments for growing seasons from 1980 to 2010 in the Texas Rolling Plain. Vertical error bars represent the standard error and horizontal error bars represent the standard deviation.

Economic Returns

The returns over total specified expenses for irrigation treatments ranged from $599 to $1425. The total specified expenses include all direct expenses and fixed expenses for the irrigation system, farm implements, and tractors. The relationship between amount of irrigation water applied and economic returns is presented in Fig. 4.7. This relationship is qualitatively similar to the relationship between irrigation amount and lint yield. However, the profit maximizing amount of irrigation was 478 mm while the yield maximizing irrigation amount was 515 mm. This finding is in line with the general observation that the profit maximizing irrigation level is usually lower than the yield maximizing level. This result indicate that even though irrigation application above 478 mm leads to yield increase (till 515 mm), the overall profit goes down. This happened because the revenue increase from additional irrigation is lower than the marginal cost incurred in this irrigation range. DeLaune et al. (2012) also reported that the profit maximizing irrigation level was lower than the yield maximizing level for cotton in the Texas Rolling Plains.

The economic returns corresponding to the ET replacement treatments are presented in figure 4.8. The economic returns increased with increase in ET replacement rates for all treatments except 120% ET and 140% of ET replacement. The ET replacement level that maximizes economic returns was 108% ET. The increase in lint yield from increasing irrigation from 100% to 120% ET replacement was 22 kg ha^{-1} for which 91 mm of additional irrigation water was required. The marginal cost of applying this additional amount of irrigation water at current fuel and labor cost levels was $46 ha^{-1}. At the current lint price levels, the low marginal cost of irrigation is the main reason for the profit maximizing irrigation above 100% ET replacement. The increase in economic returns with increasing irrigation rates was reported by Dagdelen et al. (2009) and DeLaune et al. (2012).

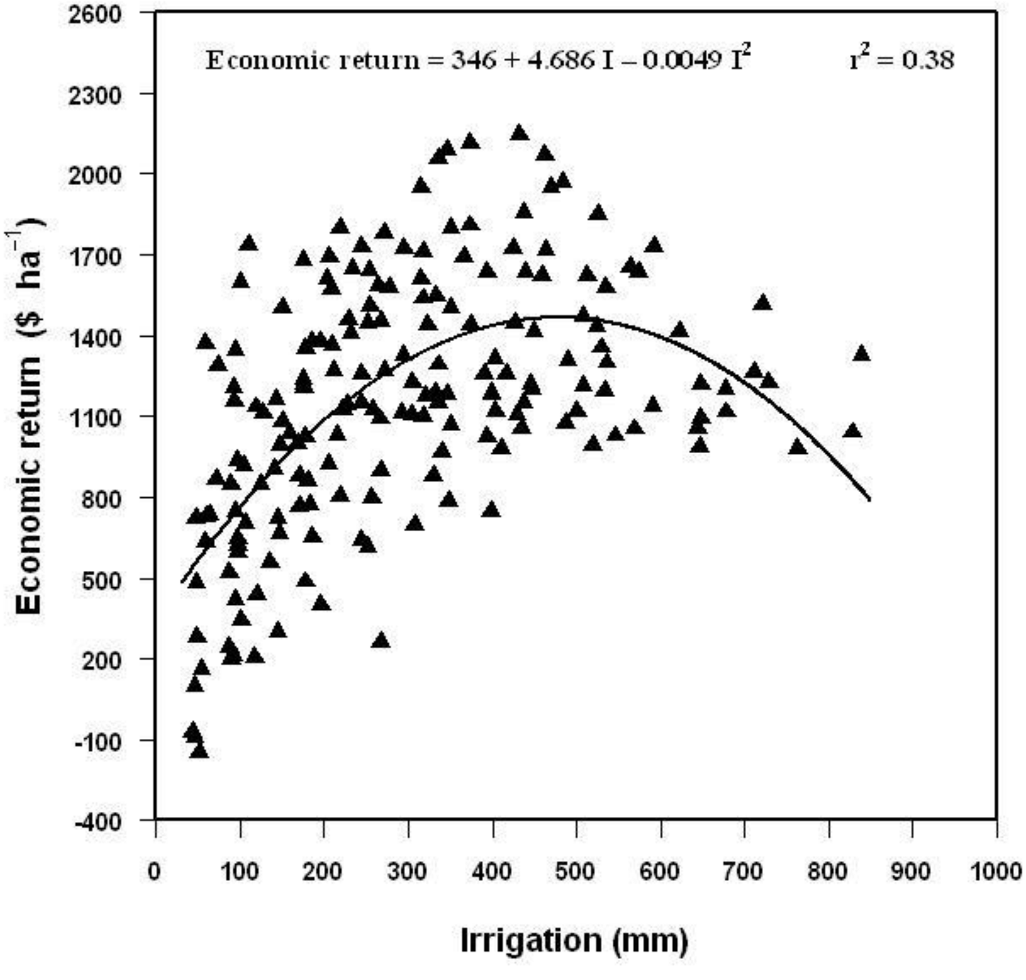

Figure 4.7. Economic returns plotted against corresponding amounts of irrigation water for growing seasons from 1980 to 2010 in the Texas Rolling Plains. Treatments include one dryland and six evapotranspiration based irrigation replacements.

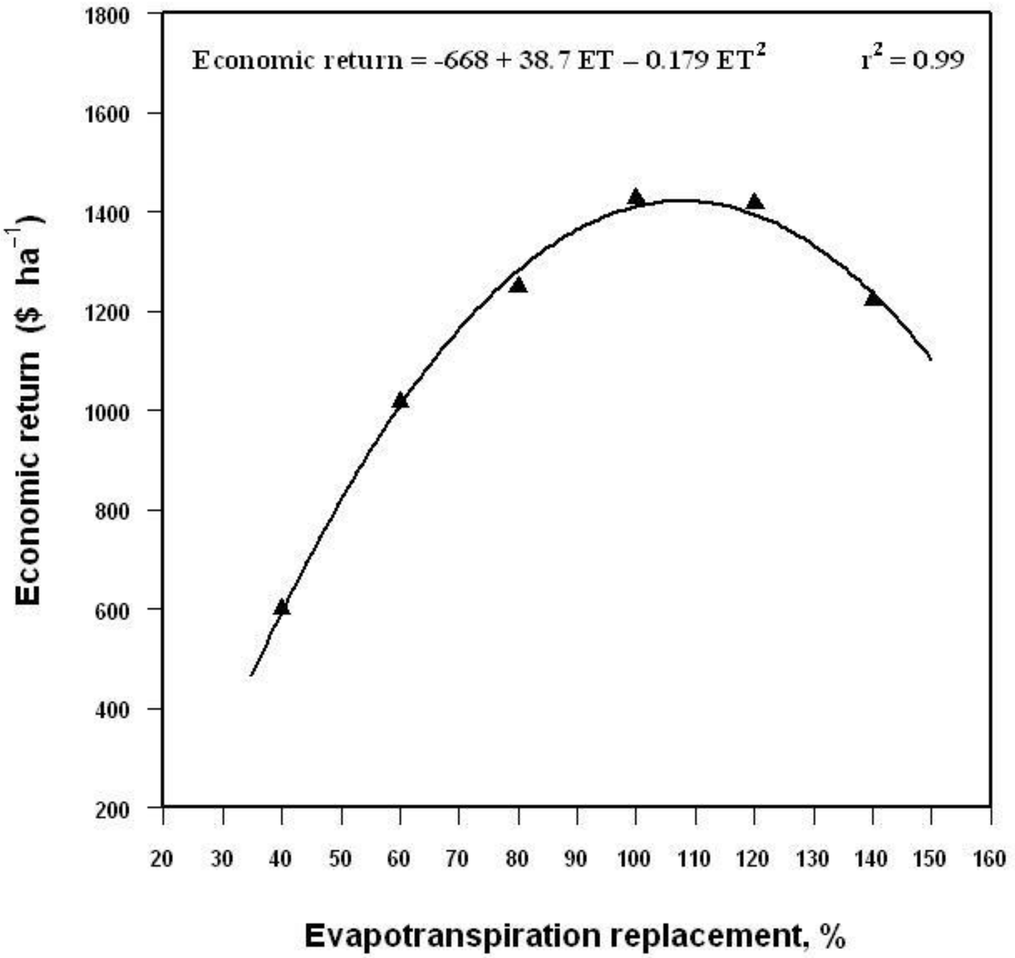

Figure 4.8. Economic returns plotted against corresponding amounts of irrigation water for growing seasons from 1980 to 2010 in the Texas Rolling Plains. Each point represents the average of 31 values for each treatment during the study period.

CONCLUSIONS

This study investigated cotton lint yield, WUE, and economic return responses to various irrigation management according to the crop coefficient approach using historical weather dataset from 1980 to 2010 in the Texas Rolling Plains. Results revealed that replacing 112% ET maximized the yield while economic return was maximized at 108% ET. However, WUE decreased with increasing irrigation. This was due to decreasing marginal yield increments at higher irrigation levels. The IWUE showed a negative linear decrease as irrigation rate increased while the BWUE was increased at a decreasing rate as irrigation rate increased. Deficit irrigation at 60% ET or 80% ET replacement level significantly increased lint yield compared to dryland. Replacing 80% of the ET produced 88% of maximum yield produced at 120% ET with approximately 72% water saving. Our data suggest that, when water resources are limited, deficit irrigation at 60% ET or 80% ET replacement can be used to improve cotton WUE without significant yield and economic reductions in the semi-arid Texas Rolling Plains.

CHAPTER V

APPLICATION OF DSSAT-CERES-WHEAT MODEL TO SIMULATE WINTER WHEAT RESPONSE TO IRRIGATION SCHEDULING IN THE TEXAS HIGH PLAINS

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is a major crop grown in the Texas High Plains for grain and forage production (Musick et al., 1994; Howell et al., 1995; Howell et al.,1997). The acreage planted to wheat in the Texas High Plains accounts for approximately 46% of the total area planted to wheat in Texas (USDA-NASS, 2012). In this semi-arid region, the growth and yield of winter wheat is mainly determined by the amount of water available from precipitation and/or irrigation. In the Texas High Plains, annual precipitation is mostly received during the summer months (Rajan et al., 2013). The average precipitation received during the winter wheat growing season (October – June) in the Texas High Plains is approximately 250 mm (Musick et al., 1994). This amount of precipitation is less than the water requirements for achieving maximum water use efficiency (WUE) and grain yield for winter wheat (Howell et al., 1995; Schneider and Howell, 2001). Several studies have reported a linear or quadratic relationship between evapotranspiration (ET) and grain yield of winter wheat (Musick et al., 1994; Kang et al., 2002; Sun et al., 2006). In the Texas High Plains, the yield of rainfed wheat ranges from 1000 to 3000 kg ha^{-1} while the yield of irrigated wheat ranges from 3000 to 8000 kg ha^{-1} (Schneider and Howell, 2001; Xue et al., 2006). Therefore, supplemental irrigation can significantly increase the yield of winter wheat in the Texas High Plains.

The Ogallala aquifer is the major source of irrigation water in the Texas High Plains. This aquifer has experienced a continuous decline with extraction far exceeding recharge with large-scale irrigated agriculture starting in this region since the 1950's (Ryder, 1996; Nair et al., 2012). Although more efficient irrigation technologies have been introduced over the past 50 years, these developments have not slowed the depletion of the aquifer. The available storage of water in the Texas portion of the Ogallala aquifer in 1990 was estimated to be approximately 403.5 million acre-feet. This value had fallen by 12% to 354.0 million acre-feet by 2004 due to mining of water at an unsustainable rate (Rajan et al., 2014). In many portions of the aquifer, the decline has been much greater. It has been projected that the majority of the aquifer has a usable lifetime of less than 60 years before it is depleted to levels incapable of supporting irrigated agriculture in the region if the current practices are continued (Mulligan et al., 2007).

In the past several years, the growing concern for the depletion of the Ogallala aquifer has resulted in several proposals to conserve the aquifer and extending the usable lifespan of the aquifer water (TAWC, 2013). The High Plains Underground Water Conservation District (HPUWCD) has enacted a “50/50 rule” in the Texas High Plains region for conserving water from the Ogallala aquifer. The goal of this 50/50 rule is to have a minimum of 50% saturated thickness of the Ogallala aquifer still available after

50 years. Pumping limits have been proposed to limit the allowable annual water extraction from the Ogallala aquifer to provide a total irrigation of 53, 46 and 38 cm per contiguously owned acre of land for the periods of 2012–2013, 2014–2015, and 2016 and beyond, respectively (HPUWCD, 2012).

Reducing the overall application of irrigation water and thereby conserving water resources is possible through deficit irrigation (Wang and Nair, 2012). Deficit irrigation is defined as the application of irrigation water less than the full ET requirement of the crop. Deficit irrigation also includes supplemental irrigation that is used in arid regions to prevent dryland yield fluctuations (Fereres and Soriano, 2007). Irrigation only at certain stages of crop growth has been widely adapted in areas where water resources are limited (Zhang et al., 1998; Kang et al., 2002; Li et al., 2005; Xue et al., 2006). In semi-arid regions like the Texas High Plains, producers can apply deficit irrigation at certain specific growth stages of the crop to mitigate adverse effects of water stress on plants. For example, Xue et al (2006) reported that supplemental irrigation of winter wheat between the jointing and flowering stages significantly improved grain yield and WUE due to increased photosynthetic activity and remobilization of pre-anthesis carbon reserves. Others found that irrigation below the full potential ET requirement did not necessarily reduce the winter wheat yield (Kang et al., 2002; Sun et al., 2006). Li et al. (2005) reported a quadratic relationship between ET and grain yield. When exposed to soil drying, winter wheat develops a deeper root system and modifies its canopy structure when grown in water limited environments. It is important to determine the critical growth stages for applying the limited water available for irrigation to reduce the impact of water shortage on winter wheat grain yield and maintain economic returns.

The DSSAT-CSM-CERES-Wheat model V4.5 is a component of the Decision Support System for Agrotechnology Transfer-Cropping system model popularly known as DSSAT-CSM (Jones et al., 2003; Hoogenboom et al., 2004). The CERES (Crop Estimation through Resource and Environment Synthesis) cereal model simulates the growth and development of cereal crops including wheat in response to weather and management factors (Ritchie and Otter, 1985). The DSSAT- CSM- CERES model offers the opportunity to test the effects of deficit irrigation management practices on winter wheat biomass accumulation, grain yield, and WUE. It has been proven that the DSSAT-CSM-Wheat is an effective tool for determining management practices that can reduce the economic uncertainties for agricultural production (Jones et al., 2003; Hoogenboom et al., 2004). The successful performance of CERES-Wheat in simulating wheat growth and yield in response to management and environmental factors has been reported under a wide range of soil and climatic conditions (Ritchie and Otter-Nacke, 1985; Ritchie et al., 1998; Eitzinger et al., 2004; Arora et al., 2007; Timsina et al., 2008; Thorp et al., 2010; Dettori et al., 2011; Qi et l., 2013). The objectives of this study were (1) to calibrate the DSSAT-CERES-Wheat model to accurately predict winter wheat growth and yield in the Texas High Plains using experimental datasets available from this region, and (2) to test winter wheat grain and biomass yields, harvest index, and WUE responses to different irrigation scheduling practices using long-term weather datasets available for the Texas High Plains region.

MATERIALS AND METHODS

DSSAT-CSM-CERES-Wheat Model

The DSSAT-CERES-Wheat model is widely used to simulate the effects of weather, soil characteristics, genotype, and management factors on the growth and development of dryland and irrigated wheat (Rinaldi, 2004; Arora et al., 2007; Timsina et al., 2008; Thorp et al., 2010). The soil water balance in DSSAT is modeled based on precipitation, soil evaporation, transpiration, drainage, surface runoff, and infiltration. Each soil layer has a specified drained upper limit (DUL), lower limit (LL), and saturated water content (SAT) which the model used to estimate water flow among the soil layers. The assumption is that saturated downward flow occurs when a layer has a water content greater than DUL. Unsaturated upward flow occurs when a layer has a water content between LL and DUL. The excess water in the deepest soil layer is drained and will not be available for root absorption. Soil evaporation is independently estimated following the two-stage soil evaporation model by Ritchie (1972). Plant transpiration is determined based on available water in the soil layers and the distribution of roots. Precipitation runoff is estimated using the USDA Natural Resources Conservation Service (NRCS) curve number method (Jones et al., 2003), while the remaining water percolates into the soil profile.

In DSSAT, wheat development is divided into nine growth stages and modeled from pre-sowing to harvest based on thermal units. Biomass accumulation is computed as the product of photosynthetically active radiation (PAR) and radiation use efficiency (RUE). Number of growing leaves depends on leaf appearance rate and duration of the grain filling period (P5). Potential growth of organs is controlled by optimal temperature, and optimal nutrients, and water status. Biomass partitioning coefficients are affected by the duration of different growth phases. Grain yield is simulated based on grain number (G1), plant population, and grain weight at physiological maturity (G2). A detailed description of the DSSAT-CSM-CERES-Wheat model can be found in Jones et al (2003).

Experimental Datasets

Data from two field studies conducted in the Texas High Plains were used to calibrate and evaluate the performance of the DSSAT-CERES-Wheat model. The first field experiment was conducted at Bushland, TX (Lat. 35°11′N, Long. 102°06′W, elevation 1170 m), in the 1992-1993 growing season (Xue et al., 2006). The soil type at this location was Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll). In this study, researchers investigated winter wheat growth and yield responses to various irrigation treatments applied at different plant developmental stages (Zadoks et al., 1974). The experiment had a completely randomized design with nine irrigation treatments in six replications. The nine irrigation treatments ranged from dryland (T1) to full irrigation (T9) (Table 5.1). All treatments received 25 mm of irrigation prior to sowing to ensure uniform emergence. Wheat was planted on October 1, 1992, at a seeding rate of 70 kg ha^{-1} and row spacing of 25 cm. Fertilizer was applied one week before planting at a rate of 140 kg N ha^{-1} and 40 kg P ha^{-1}. Cultural practices are described in detail by Xue et al. (2006). Measured data included leaf area index (LAI), leaf water potential, soil water potential, grain weight, grains per spike, grain and biomass yields, harvest index (HI), and seasonal ET.

The second field study was conducted at the same site in the 1997-1998 and 1998-1999 growing seasons to investigate the effect of deficit irrigation in winter wheat (Schneider and Howell, 2001). Irrigation was applied according to the ET-based irrigation scheduling method by Allen et al. (1998). Replacement irrigation consisted of 25% ET, 50% ET, 75% ET, and 100% ET irrigations. A dryland treatment was also included. Wheat was planted on 2 October 1997 and 29 September 1998. The experiment used a split-split plot design. Nitrogen was applied in a single preplant application at the rate of 123 kg N ha^{-1} in 1998 and 140 kg N ha^{-1} in 1998. In both growing seasons, 112 kg P ha^{-1} was applied in a pre-plant application. Detailed descriptions of cultural practices of this experiment can be found in Schneider and Howell (2001). Measured data included grain and biomass yields, HI, and seasonal ET.

Table 5.1. Irrigation treatments used for calibration of the DSSAT-CERES-Wheat model and model simulations using long-term weather data. Details include amount of water applied (mm) and the growth stages it was applied.

Trt	Jointing DOY 97	Booting DOY 113	Anthesis DOY 134	Grain filling DOY 146	Total irrigation (mm)	Irrigation+ Precipitation
T1	Dryland				0	254
T2	100				100	354
T3		100			100	354
T4			140		140	394
T5				140	140	394
T6	100		120		220	474
T7		100		120	220	474
T8	100	100	100		300	554
T9	100	100	100	100	400	654

Model Calibration and Evaluation

DSSAT requires daily weather data, soil profile data, crop management data, and genotype coefficients as general input. Historical daily weather data for Busland, TX, for the 1992-1993, 1997-1998, and 1998-1999 growing seasons were obtained from the Texas High Plains ET Network (https://txhighplainset. tamu.edu). Daily weather data included minimum and maximum air temperatures, precipitation, and total solar irradiance. Characteristics of the Pullman clay loam soil as described by Taylor et al. (1963) and Unger and Pringle (1981) were used to set up the soil profile. Tables 5.2 and 5.3 describe the soil physical and hydrological properties of the Pullman clay loam soil. Phenological parameters of the default winter wheat ecotype in the DSSAT-CERES-Wheat model (cvNewton) were adjusted based on the vernalization requirements of TAM 202 winter wheat cultivar in the Great Plains (Xue et al., 2006). Following calibration of the crop phenology parameters, growth and yield coefficients were manually adjusted using an iterative procedure to obtain a close match between simulated and measured data. The genetic coefficients used in the calibration procedure are presented in Table 5.4.

Table 5.2. Soil physical properties for Pullman clay loam soil in Bushland, TX.

Depth, cm	Clay	Silt	Stones	Organic C	Total N	CEC
	--------------------------	------------------	%	------------------	--------------------------	cmol kg^{-1}
12	29.2	31.6	0	0.90	0.11	18.4
23	38.8	29.6	0	0.74	0.10	19.6
45	43.8	32.7	0	0.54	0.08	20
71	42.6	32.6	0	0.39	0.05	23.9
97	37.9	34.3	0	0.36	0.05	20.9
135	38.6	31.8	0	0.13	0.05	17.4
165	36.9	21.2	0	0.20	0.04	10.4

CEC: Cation exchange capacity.

Table 5.3. Soil hydrological properties for Pullman clay loam soil in Bushland, TX.

Depth (cm)	LL	DUL	SAT	WR	BD (g cm^{-3})
	SALB=0.19	U=6	SWCON=0.10	CN2=82	
13	0.22	0.38	0.47	1	1.26
23	0.22	0.37	0.44	0.8	1.48
45	0.21	0.37	0.44	0.6	1.56
71	0.20	0.37	0.40	0.4	1.62
97	0.21	0.36	0.40	0.2	1.65
135	0.23	0.34	0.38	0.1	1.56
165	0.27	0.35	0.38	0.05	1.67

LL: lower limit of water extraction; DUL: drained upper limit; SAT: saturated water content; WR: root weighting factor; BD: bulk density; SALB: soil albedo; U: upper limit for wet soil evaporation; SWCON: profile drainage coefficient; CN2: runoff curve number.

Table 5.4. Genetic coefficients for the winter wheat default cultivar (NEWTON) in the DSSAT-CSM-Wheat model. Genetic coefficients presented include default values in the model and the final value used in the calibration.

Parameter	Description	DSSAT default value	Calibrated value
		Crop development	
P1V	Days, optimum vernalizing temperature, required for vernalization	40	45
P1D	Photoperiod response (% reduction in rate/10 h drop in pp)	75	80
P1	Duration of phase from emergence to double ridges, (ºC d)	400	420
P2	Duration of phase terminal spikelet to end leaf growth, (ºC d)	280	300
P3	Duration of phase end leaf growth to end spike growth, (ºC d)	190	200
P4	Duration of phase end spike growth to end grain fill lag, (ºC d)	190	500
P5	Grain filling phase duration, (ºC d)	500	700
PHINT	Interval between successive leaf tip appearance, (ºC d)	95	100
		Crop growth	
LAFV	Increase in potential area of leaves, vegetative phase (fr/leaf).	0.15	0.12
LAFR	Increase in potential area of leaves, reproductive phase (fr/leaf).	0.01	0.32
PARUE	PAR conversion to dm ratio, before last leaf stage (g/MJ).	2.7	3.9
PARU2	PAR conversion to dm ratio, after last leaf (g/MJ).	2.7	2.5
LA1S	Area of standard first leaf (cm).	2.0	2.5
SLAS	Specific leaf area, standard first leaf (cm^2/g)	400	440
LAXS	Maximum area of leaves on main stem (cm^2).	800	900
SLAMN	Specific leaf area, minimum, fr non stressed.	0.5	0.8
		Crop yield	
G1	Kernel number per unit canopy weight at anthesis (g).	26	25
G2	Standard kernel size under optimum conditions (mg).	25	32
G3	Standard non-stressed mature tiller wt (incl grain) (g dwt).	2	2.8

Model Performance Indicators

Model performance was evaluated using several indices based on simple and squared differences between observed and simulated data. These included the coefficient of determination (r^2), normalized Root Mean Square Error (nRMSE), coefficient of residual mass (CRM), index of agreement (D-index), and Nash-Sutcliffe coefficient (E). Normalized RMSE (Eq. 14) measures the relative difference (the mean of observed data, $\overline{M}$) between simulated (E_i) and observed (M_i) data. The simulation was considered 'excellent' when the nRMSE was less than 10%, 'good' when the nRMSE was greater than 10% but less than 20%, 'fair' when the nRMSE was greater than 20% but less than 30%, and 'poor' when the nRMSE was greater than 30%.

$$\text{nRMSE} = \sqrt{\sum_{i=1}^{n} \frac{(E_i - M_i)^2}{n}} \times \frac{100}{\overline{M}} \qquad \text{[Eq. 14]}$$

CRM (Eq. 15) indicates whether the model tends to over- or underestimate observed data (Loague and Green, 1991). A negative value indicates a tendency of the model to overestimates the observed data, while a positive value indicates a tendency of the model to underestimate the observed data.

$$\text{CRM} = 1 - \frac{\sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} M_i} \qquad \text{[Eq. 15]}$$

The D-index (Eq. 16) ranges from 0 to 1 and is based on a measure of dispersion (Willmott, 1982). A D-index of 1 indicates a perfect agreement between observed and simulated data. D-index values less than 0.50 suggest greater diversity and inconsistency in the model predications. D-index values closer to 0.0 indicate that the model predications are equal to the average of observed data, i.e. $E_i \sim \overline{M}$, indicating no agreement between observed and simulated values.

$$\text{D-index} = 1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}\left(|E_i - \overline{M}| + |M_i - \overline{M}|\right)^2} \quad \text{[Eq. 16]}$$

Nash-Sutcliffe efficiencies (Eq. 17) can range from -∞ to 1. An efficiency of 1 (E=1) indicates a perfect match between observed and simulated data, while E less than 0 indicates that the observed mean is a better predicator than simulated data.

$$E = 1 - \frac{\sum_{i=1}^{n}(M_i - E_i)^2}{\sum_{i=1}^{n}(M_i - \overline{M})^2} \quad \text{[Eq. 17]}$$

Model Simulations Using Long-Term Weather Data

The DSSAT-CERES-Wheat model was used to simulate winter wheat stover and grain yield responses to deficit and full irrigation treatments using historical weather datasets from Bushland, TX, which was considered representative of the Texas High Plains climate in this study. A weather dataset including daily minimum and maximum air temperatures, daily precipitation, and solar radiation from 1980 to 2012, was obtained from the Texas High Plains ET Network (https://txhighplainset.tamu.edu). Irrigation treatments similar to those described in Xue et al. (2006) were used in the model (Table 5.1). Initial irrigation of 25 mm was applied to all treatments to achieve uniform emergence. The soil water level along the profile was assumed to be near saturation. Prior to planting, nitrogen was applied at a rate of 140 kg N ha^{-1} and phosphorus was applied at a rate of 40 kg P ha^{-1}. Similar cultural practices as described in Xue et al. (2006) were used in the model. Grain yield was adjusted to 125 g kg^{-1} water content. Harvest index (HI) is the ratio of grain yield to total above ground biomass yield. WUE (kg ha^{-1} mm^{-1}) was calculated as the ratio of grain yield (kg ha^{-1}) to ET (mm) and IWUE (kg ha^{-1} mm^{-1}) was calculated as IWUE $= \frac{(\text{grain yield}_x - \text{Dryland grain yield})}{\text{Irrigation}_x}$. Results were classified into three categories according to seasonal precipitation rate: seasons with below-average precipitation (< 200 mm), average precipitation (200-300 mm), and above-average precipitation (> 300 mm). There were 14 seasons with precipitation < 200 mm, 10 seasons with precipitation between 200-300 mm, and 9 seasons with precipitation > 300 mm in the 33-year dataset (Fig. 5.1).

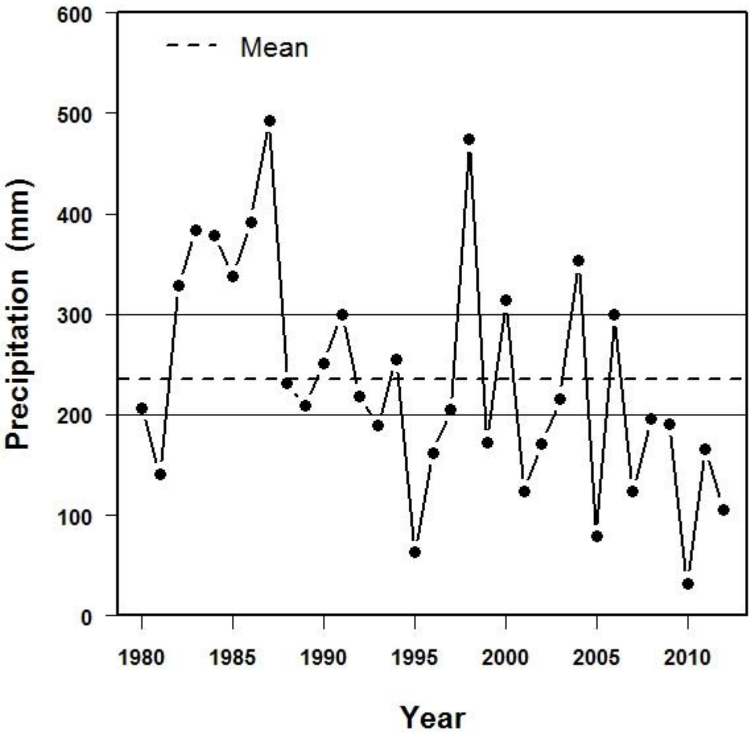

Figure 5.1. Long term precipitation of the Texas High Plains from 1980 to 2012 during winter wheat growing season from October to June. There were 14 seasons with precipitation < 200 mm, 10 seasons with precipitation 200-300 mm, and 9 seasons with precipitation with > 300 mm.

RESULTS AND DISCUSSION

Model Calibration and Evaluation

The primary goal of this modeling study was to calibrate the DSSAT-CSM-Wheat model for accurate simulation of winter wheat growth and yield responses to irrigation practices in the Texas High Plains. The adjusted genetic coefficient values used for model calibration are presented in Table 5.4. These adjusted values enabled the model to simulate seven or eight leaves at maturity as commonly observed for winter wheat in the Texas High Plains (Miller, 1999). Conversion rate of PAR to dry matter was set at 3.9 and 2.5 g MJ^{-1} during the vegetative (PARUE) and reproductive (PARU2) stage, respectively. This resulted in a good simulation of biomass yield when compared with measured values (Table 5.4). The LAI simulation (maximum simulated LAI of 7.0 and max observed LAI of 6.5 under full irrigation) was improved by setting the leaf area adjustment factor during the vegetative phase (LAFV) to 0.12, and to 0.32 during the reproductive phase (LAFR). The maximum area of leaves on main stem (LAXS) was set to 900. The genotype coefficient, G1 controls kernel number per unit canopy weight at anthesis, G2 controls kernel size under optimum conditions, and G3 controls abortion rate of tillers exposed to water or heat stress. These parameters greatly affect grain yield simulation and were adjusted based on measured grain yield data by Schneider and Howell (2001) and Xue et al. (2006). Using a value of 25 kernels per unit gram weight of canopy (G1) and 32 mg of kernel weight under optimum conditions (G2) were found to provide the best fit of simulated versus observed grain yields (Tables 5.4 and 5.5).

Table 5.5. Comparison of observed (OBS) and simulated (SIM) grain yield (Mg ha^{-1}), biomass yield (Mg ha^{-1}), and evapotranspiration (ET) (mm) observed by Xue et al. (2006) (n =9) and Schneider and Howell (2001) (n=10) in the Texas High Plains and predicated by DSSAT-wheat model. Mean, standard error (SE), number of observations (n), correlation of determination (r^2), normalized root mean square error (nRMSE), coefficient of residual mass (CRM), index of agreement (D-index), and Nash-Sutcliffe coefficient (E) are shown.

	Grain yield		Biomass yield		ET	
	OBS	SIM	OBS	SIM	OBS	SIM
Mean	5.32	5.56	16.84	16.85	604	526
SE	0.31	0.33	1.04	1.34	29	20
Min	2.46	2.62	8.23	5.28	414	345
Max	7.17	7.43	24.72	25.71	824	660
N	19		19		19	
r^2	0.79		0.92		0.85	
nRMSE (%)	12.9		11.3		16.0	
CRM	-0.04		-0.0008		0.12	
D-index	0.93		1.0		0.82	
E	0.74		0.82		0.41	

Several simulated growth and yield characteristics were tested against observed data from the two field studies at Bushland, TX. These results are presented in Table 5.5 and Figure 5.2. Figure 5.2 illustrates simulated grain yield plotted versus observed grain yield for the 1992-1993, 1997-1998, and 1998-1999 growing seasons. The OLS linear regression explained 78% of the total variance, indicating a good agreement between simulated and observed values. The Student's t test showed that the slope of the regression line was not significantly different from 1 ($p > t = 0.529$) and the intercept was not significantly different from 0 ($p > t = 0.333$). The nRMSE of 12.9% indicated a good agreement between simulated and observed grain yields (Table 5.5). This was also confirmed with other goodness-of-fit tests including CRM (close to 0) and D-index (close to 1). Simulated biomass yield was compared with observed data and results indicated good biomass yield predication. The nRMSE was only 11.3% and the CRM was close to 0. This was also confirmed with a D-index of 1 and a Nash-Sutcliffe of 0.82 (Table 5.5).

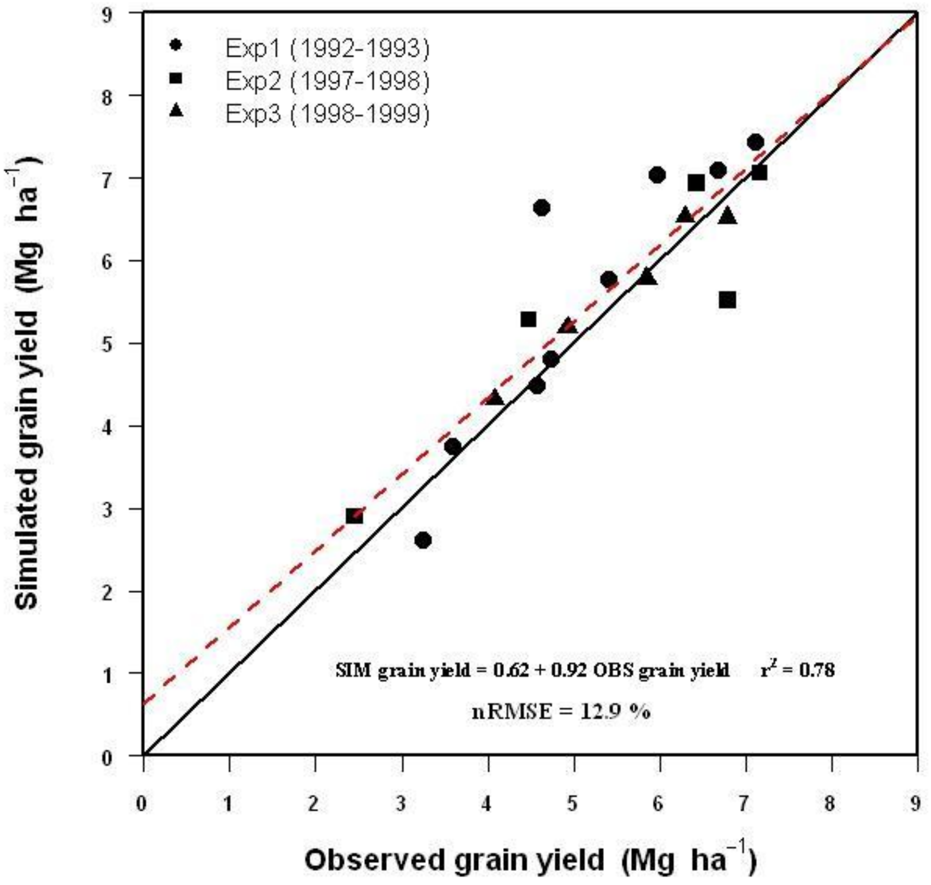

Figure 5.2. Simulated grain yield regressed against observed grain yield recorded for field experiments conducted in 1992-1993, 1997-1998, and 1998-1999 growing seasons on a Pullman clay loam soil in the Texas High Plains. The solid line is the 1:1 line and the dashed line is the ordinary least-squares linear regression line.

The comparison of simulated versus observed ET showed a good predication by the model as indicated by the nRMSE (Table 5.5). The CRM value of 0.12 indicated that the model was slightly underestimating ET. Nonetheless, acceptable performance of the ET predication was indicated by the D-index and Nash-Stutcliffe coefficient (Table 5.5). Several studies have reported that the DSSAT-CERES-Wheat model underestimates potential ET (Allen et al., 1989; Steiner et al., 1991; Howell et al., 1995; Tubiello et al., 1999; Kang et al., 2009). Studies also reported that small changes in daily drainage and ET are not simulated accurately by the DSSAT-model (Soldevilla-Martinez et al., 2013). Therefore, other components of soil water balance such as soil moisture content, surface run off, and drainage should also be considered for optimizing ET simulation with a more mechanistic approach.

Model Simulations Using Long-Term Weather Data

Grain and biomass yields

The calibrated model was used to investigate the winter wheat grain and biomass yields, harvest index, and WUE, responses to different irrigation scheduling practices using historical weather dataset from 1980 to 2012 for the Texas High Plains. Simulated grain yield was significantly affected by the timing and amount of irrigation (Table 5.6 and Fig. 5.3). The response of wheat yield to irrigation was the highest when the growing season precipitation was below average (< 200 mm). The average dryland yield during these seasons was 2.43 Mg ha^{-1}. With full irrigation, grain yield increased to 6.62 Mg ha^{-1}. Among single irrigation treatments, irrigating at the grain filling stage was found to result in better yield than irrigating at jointing, booting, and anthesis stages when the growing season precipitation was below average. Deficit irrigation at grain filling stage nearly doubled dryland grain yield at seasons with below average precipitation (Fig. 5.3a). It was also observed that double irrigation at booting and anthesis produced 89% of maximum full irrigation grain yield (Fig. 5.3a).When the growing season precipitation was average (200-300 mm), dryland yield increased to 3.94 Mg ha^{-1}. Applying 140 mm of irrigation at the grain filling stage, increased the grain yield by 67% compared to the dryland yield (Fig. 5.3b). It was also noted that this treatment produced 24% higher grain yield than other deficit irrigation at jointing and booting stages (Fig. 5.3b). In those years, irrigation at 100 mm jointing and 120 mm at anthesis produced a comparable grain yield to that produced by full irrigation (Fig. 5.3b). When the growing season precipitation was above average (> 300 mm), the dryland grain yield increased to 4.33 Mg ha^{-1}. Single irrigation treatments (i.e, 100 mm at jointing or booting or 140 mm at anthesis or grain filling), resulted in further increase in grain yield. It is also important to note that deficit irrigation of 140 mm at grain filling produced similar yield to full irrigation when precipitation was high (Fig. 5.3c). Comparison of grain yields from single irrigation at grain filling or double and triple irrigation treatments (T5 to T8 in Fig. 5.3c) with full irrigation (T9) showed no significant differences at those high precipitation seasons. The 33 years simulation demonstrated that deficit irrigation at anthesis and grain filling had an advantage compared to other single irrigation treatments at earlier growth stages. In addition, double irrigation at jointing and anthesis produced a comparable yield that was not significantly different from full irrigation (Table 5.6 and Fig. 5.3d).

Likewise grain yield, simulated biomass yield was significantly affected by the timing and amount of irrigation (Fig. 5.4 and Table 5.6). However, there was a noticeable difference between grain yield and biomass yield response to deficit irrigation treatments. Unlike grain yield, biomass yield was the lowest for deficit irrigation at anthesis/grain filling while was the greatest for deficit irrigation at jointing/booting stage (Table 5.6 and Fig 5.4). This trend was observed at seasons with below, about, and above average precipitation rates (Fig. 5.4). When the precipitation was below average (<200 mm growing season precipitation), irrigating at jointing stage increased the biomass yield by 92% compared to dryland. This increase in biomass yield was 53% and 40% during average and above-average precipitation years, respectively. Over the 33 yrs simulation periods, comparison of double irrigation treatments, T6 vs. T7, indicated that irrigating at jointing and anthesis had 17% higher biomass yield than irrigating at booting and grain filling (Table 5.6). It was also observed that double irrigation treatments at jointing and anthesis produced biomass yield similar to full irrigation (Table 5.6 and Fig. 5.4d).

Table 5.6. Mean and related statistical distribution parameters of grain and biomass yields, harvest index, water use efficiency (WUE), and irrigation water use efficiency (IWUE) in response to different irrigation treatments described in table 5.1 for 33 (n=33) growing seasons from 1980 to 2012 at the Texas High Plains.

	T1	T2	T3	T4	T5	T6	T7	T8	T9
Grain yield (kg ha^{-1})									
Mean	3408e†	4732d	4488d	5495c	5775c	6466ab	6348b	6673ab	6734a
median	3402	4831	4780	6294	6442	6709	6749	6887	6824
SE‡	220	256	284	336	316	178	219	152	137
Skweness§	-0.29	-0.42	-0.03	-1.04	-1.25	-1.39	-2.14	-2.33	-3.21
Biomass yield (kg ha^{-1})									
Mean	9794f	15538b	14484bcd	13202de	11687e	18086a	15399bc	19726a	19747a
median	7939	14767	13319	11967	10278	18163	13981	19818	19785
SE	784	792	827	876.76	854	802	856	761	774
Skweness	0.04	-0.26	-0.12	-0.01	-0.10	-0.40	-0.25	-0.37	-0.25
Harvest index									
Mean	0.35cd	0.30e	0.31e	0.42b	0.49a	0.36c	0.41b	0.34d	0.34d
median	0.36	0.28	0.30	0.43	0.51	0.37	0.43	0.36	0.36
SE	0.20	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Skweness	0.60	0.90	0.97	-0.49	0.22	0.09	-0.14	-0.15	0.06
WUE (kg ha^{-1} mm^{-1})									
Mean	8.24d	9.06c	8.71cd	11.6b	13.0a	11.2b	11.9b	10.8b	10.8b
median	8.73	9.02	8.65	11.6	12.2	11.1	12.2	11.0	11.2
SE	0.38	0.38	0.40	0.70	0.66	0.36	0.39	0.33	0.28
Skweness	-0.42	0.17	0.12	-0.46	-0.25	-0.12	-0.29	-0.56	-0.66
IWUE (kg ha^{-1} mm^{-1})									
Mean	-	10.6cd	8.70de	13.2ab	14.0a	12.5ab	12.0bc	10.0d	7.8e
median	-	8.6	7.80	12.9	14.3	12.4	11.7	10.0	7.9
SE	-	1.17	0.83	1.26	1.33	0.69	0.79	0.60	0.54
Skweness	-	1.00	0.52	-0.01	-0.17	0.07	0.37	0.15	-0.06

† Means followed by the same litter are not significantly different at $P < 0.05$ according to student t-test.
‡ SE; standard error of the mean.
§ Skweness; Positive skewness values indicate that the distribution of presented parameter is shifted towards values less than the mean while negative skewness values indicate that the distribution of presented parameter is shifted towards values greater than the mean.

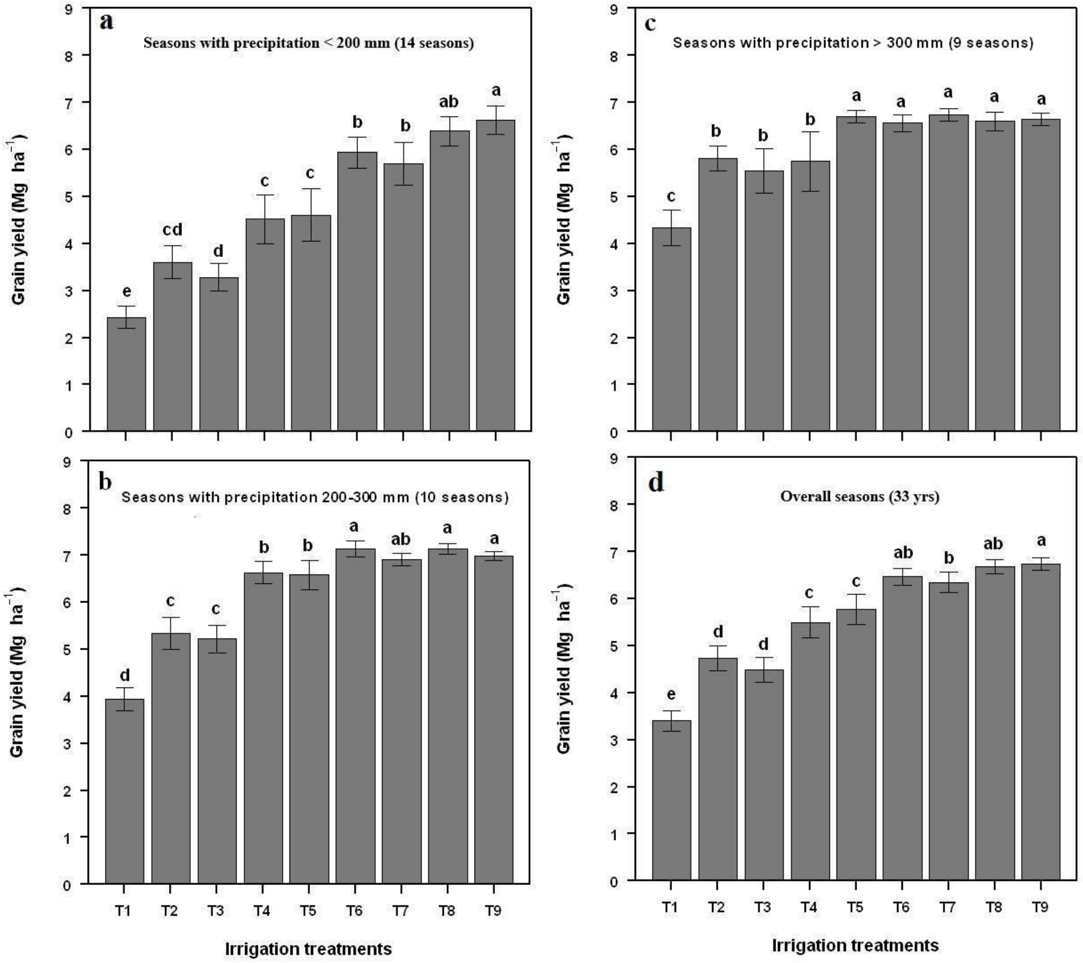

Figure 5.3. Results of DSSAT-CSM-Wheat for grain yield as affected by one dryland (T1), four single irrigation (T2 to T5), two double irrigation (T6 and T7), one triple irrigation (T8), and one quadruple irrigation (T9) treatments using historical weather dataset from 1980 to 2012 in the Texas High Plains. Seasons were classified according to precipitation amounts into below average (a), about average (b), above average (c), and overall seasons (d).

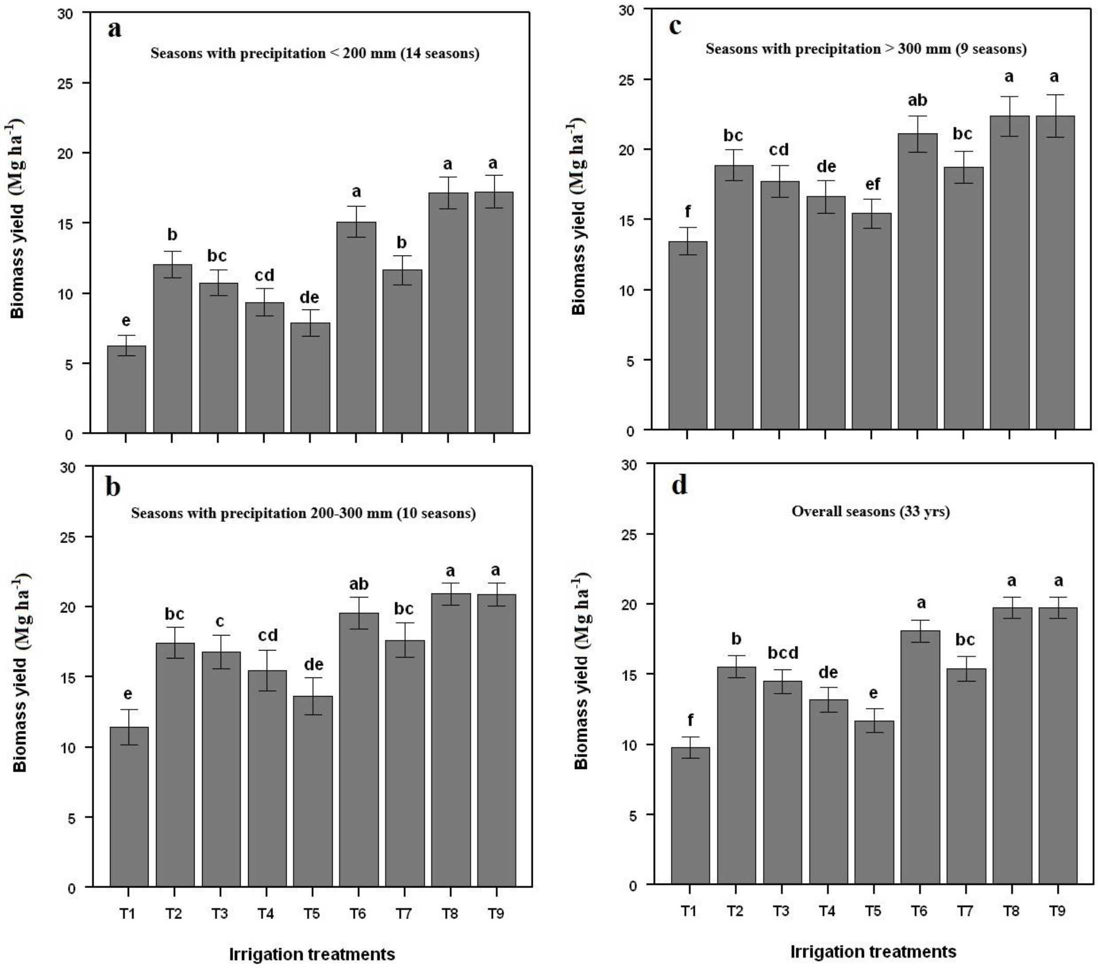

Figure 5.4. Results of DSSAT-CSM-Wheat for biomass yield as affected by one dryland (T1), four single irrigation (T2 to T5), two double irrigation (T6 and T7), one triple irrigation (T8), and one quadruple irrigation (T9) treatments using historical weather dataset from 1980 to 2012 in the Texas High Plains. Seasons were classified according to precipitation amounts into below average (a), about average (b), above average (c), and overall seasons (d).

The results from this simulation experiment show that when availability of irrigation water is limited, the timing of deficit irrigation has a significant impact on grain and biomass yields. During the winter wheat growing period in the Texas High Plains, less precipitation is received generally during the jointing stage (March-April) of the crop compared to the booting and anthesis stages (May-June). Many plant physiological processes occurring at the jointing stage determine the biomass yield potential in winter wheat (McMaster et al., 1994). Some important processes occurring at this stage include primordia initiation and differentiation, and development of flag leaf (Miller, 1999). Hence, avoiding water stress during the jointing stage should contribute significantly to both grain and biomass yields in winter wheat. Results from our simulation experiment also support this. Compared to the other single irrigation treatments, deficit irrigation at grain filling produced more grain yield while deficit irrigation at jointing produced more biomass yield. This shows the importance of considering the growth stage on which limited available water for irrigation should be applied.

Harvest index

The increase of HI in wheat is generally associated with decrease in above-ground dry matter production due to reduced plant height (Sayre et al., 1997; Brancourt-Hulmel et al., 2003; Zhang et al., 2012). In the semi-arid Texas High Plains, irrigation is an important factor in determining HI of winter wheat. HI of irrigation treatments averaged over the 33 year simulation period is presented in Table 5.6. In general, HI ranged from 0.31, for the single irrigation treatment of 100 mm at the booting stage, to

0.49, for the single irrigation treatment of 140 mm at the grain filling stage. The HI for the full irrigation treatment, 0.34, was similar to the HI of dryland (Table 5.6). In another semi-arid environment, Kang et al. (2002) reported similar range of winter wheat HI to range from 0.28 under dryland to 0.30-0.44 under various irrigation levels with an average 240 mm growing season precipitation.

Higher HI by irrigating 140 mm at grain filling was due to irrigation increasing grain yield but not biomass yield (Figs 5.3 and 5.4). This could be attributed to reduced vegetation growth by water stress early in the season while late water supplies slowed grain filling period allowing more assimilates to migrate to fruiting storage organs. Zhang et al. (2008) reported a positive relationship between HI and dry matter mobilization efficiency at grain filling. They found that moderate deficit irrigation at grain filling increased the mobilization of assimilates stored in vegetative organs to grains and therefore higher grain yield. Zhang et al. (1998) reported higher winter wheat harvest index due to single irrigation at stem elongation compared with four irrigation continued to the end of growing season.

Water use efficiency

Water use efficiency (WUE) calculated as a ratio of grain yield to seasonal ET showed significant differences in response to irrigation treatments (Table 5.6). The WUE ranged from 8.24 kg ha^{-1} mm^{-1} under dryland condition to 13.0 kg ha^{-1} mm^{-1} under single irrigation at grain filling. Deficit irrigation at anthesis/grain filling significantly increased WUE compared to dryland or other single irrigation treatments. Lower value of WUE at full irrigation was because of higher ET rather than lower grain yield. This indicates that high irrigation may increase seasonal ET but not necessarily grain yield and therefore lower WUE. Similar observations were reported in other studies on winter wheat WUE in response to irrigation. Winter wheat WUE calculated as a ratio of grain yield to seasonal ET was found to decrease by full irrigation, 11.9 vs. 13.2 kg ha^{-1} mm^{-1}, compared to deficit irrigation in another semi-arid environment of the North China Plain (Sun et al., 2010).

Irrigation water use efficiency (IWUE) was calculated as the ratio of the marginal grain yield increases to total applied irrigation (Fig. 5.5). In general, we except IWUE to decrease as irrigation rate increase. The IWUE during the 33 yrs simulation period ranged from 7.8 kg ha^{-1} mm^{-1} by full irrigation to 14.0 kg ha^{-1} mm^{-1} by deficit irrigation at grain filling. For seasons with below average precipitation, the highest IWUE of 13.1 kg ha^{-1} mm^{-1} was produced by irrigating 140 mm at the grain filling stage while the lowest IWUE of 9.85 kg ha^{-1} mm^{-1} was produced by full irrigation (Fig. 5.5a). Deficit single irrigation at grain filling had 36% and 33% higher IWUE than average IWUE produced by other single irrigation treatments at jointing, booting, or anthesis (T2 to T4) and full irrigation treatment (T9), respectively. This trend was also observed with seasons with about or above average precipitation (Fig. 5.5b and c). When precipitation was above average, the IWUE was gradually decreased as irrigation rate increased. Similar trend was observed overall the 33 yrs simulation period. Overall seasons, applying 100 mm at grain filling had 29% and 79% higher IWUE compared with other single irrigation treatments at jointing, booting, or anthesis (T2 to T4) and full irrigation, respectively (Fig. 5.5d)

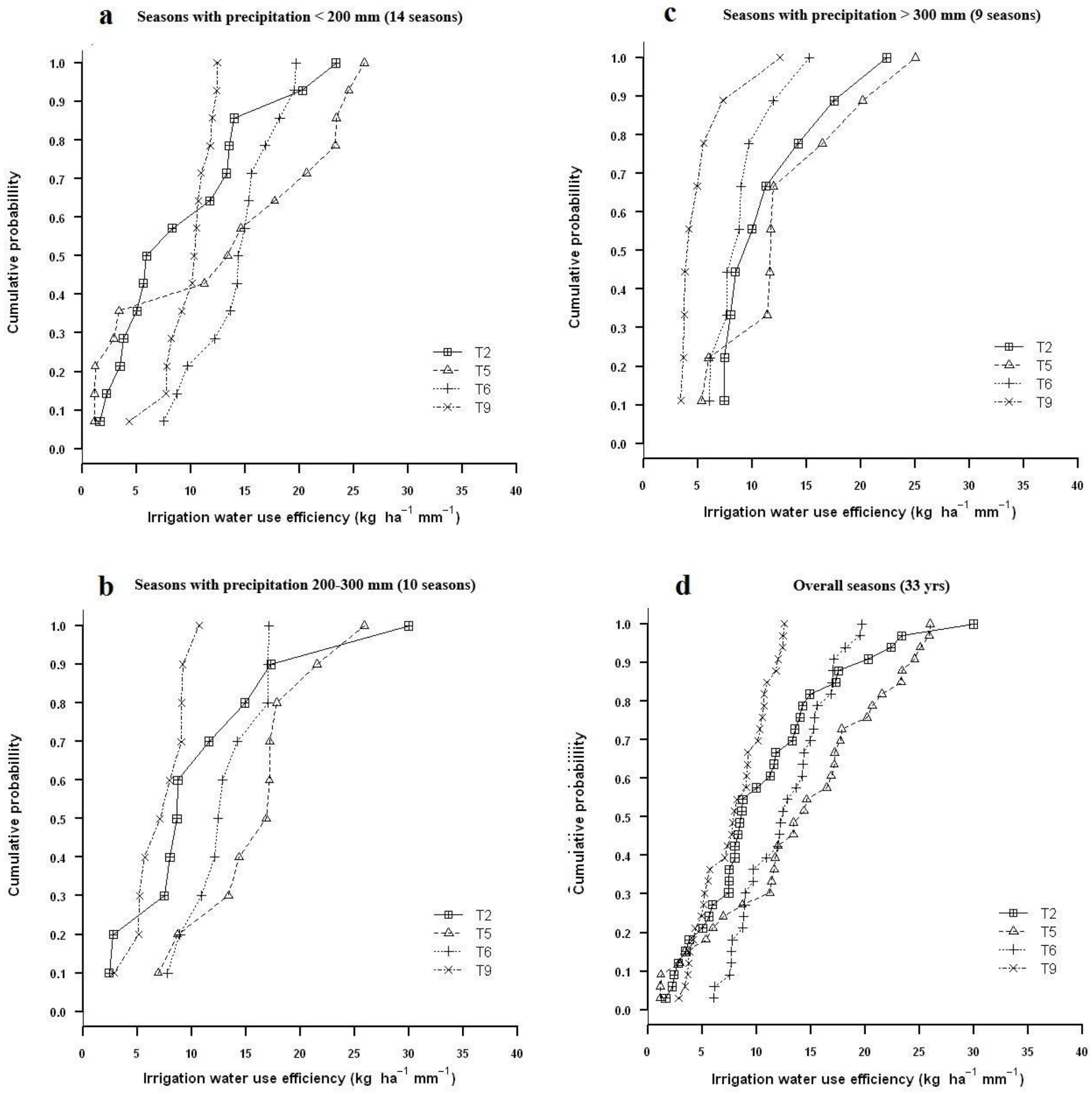

Figure 5.5. Cumulative probability distribution of winter wheat irrigation water use efficiency defined as a ratio of marginal grain yield increases to applied irrigation as affected by two single irrigation (T2 and T5), one double irrigation (T6), and one quadruple irrigation (T9) treatments using historical weather dataset from 1980 to 2012 in the Texas High Plains. Seasons were classified according to precipitation amounts into below average (a), about average (b), above average (c), and overall seasons (d).

These results indicate that deficit irrigation at grain filling stage significantly increases the WUE compared to other deficit irrigation at jointing or booting or full irrigation. Similar results of decreased IWUE due to increased irrigation were reported in other studies on wheat (Zhang et al., 1998; Huang et al., 2005; Li et al., 2005). Some attributed that to a deeper root system distribution developed by plants exposed to soil drying and therefore more available water for absorption (Zhang et al., 1998). Others found that plants reduce their leaf area and vegetation development in response to soil drying and therefore less water need (Zhang et al., 1998; Huang et al., 2005). Similar IWUE values were obtained in other studies as deficit irrigation had higher IWUE of 12.2-15.0 kg ha^{-1} mm^{-1} versus 4.70-9.50 kg ha^{-1} mm^{-1} by full irrigation (Li et al., 2005).

Relationship between grain yield or WUE and ET

The relationships between grain yield or WUE and ET were best described by the second order polynomial regression (Fig. 5.6). According to the regression equation, grain yield and WUE were maximized to 6.50 Mg ha^{-1} and 10.95 kg ha^{-1} mm^{-1} at ET of 700 and 510 mm, respectively (Fig. 5.6a and b). This suggests that irrigation scheduling that replaces average ET within this range should be used for attaining relatively high grain yield and WUE at the same time. In another semi-arid environment, Li et al. (2005) found that grain yield and WUE of winter wheat to reach their maximum at 382 and 509 mm of seasonal ET, respectively. In our study, grain yield and WUE responses to irrigation treatments indicate that higher irrigation will result in increased ET but not necessarily grain yield. This could be attributed to relatively higher soil evaporation as a result of more frequent wetting of soil surface. Benefits of reduced irrigation on grain

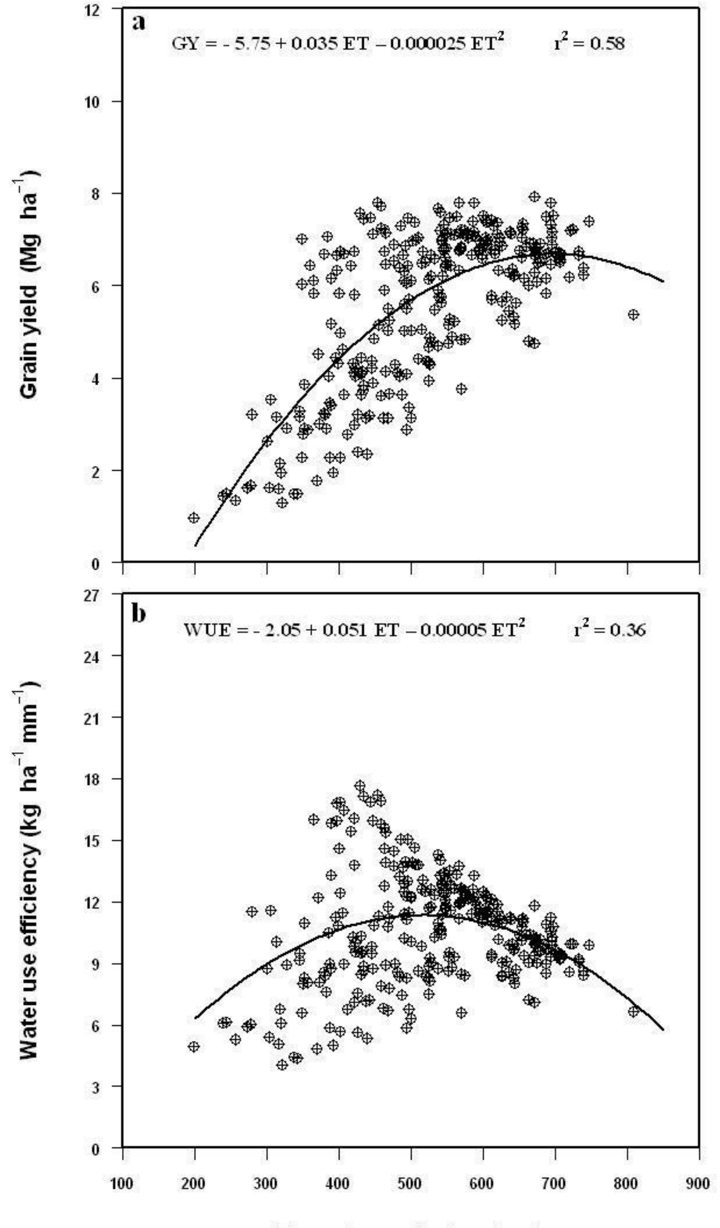

Figure 5.6. Relationship between grain yield and evapotranspiration (a) and between water use efficiency and evapotranspiration (b) as affected by one drylan (T1), four single irrigation (T2 to T5), two double irrigation (T6 and T7), one triple irrigation (T8), and one quadruple irrigation (T9) treatments during 33 growing seasons from 1980 to 2012 in the Texas High Plains.

yield and WUE in our study could be attributed to deeper root system following soil drying at grain filling stage. Zhang et al. (1998) stated that plants decreased leaf area development as affected by soil drying to save water for grain filling. Therefore, high soil moisture increased the seasonal ET but not grain yield (Kang et al., 2002).

CONCLUSIONS

The CERES-Wheat model was calibrated, evaluated, and applied to an extended climate to investigate winter wheat yield and WUE responses to irrigation scheduling in the Texas High Plains. Evaluation of the model was conducted analyzing simulations of grain and biomass yield, and evapotranpiration. The genetic coefficients obtained from the calibration greatly improved the model predication of crop phenology, biomass accumulation, grain yield, and evapotranspiration. The nRMSE and other related goodness of fit statistics indicated excellent to good match of simulated grain and biomass yields and evapotranspiration.

Simulation scenarios of winter wheat response to irrigation scheduling using 33 yrs of historical weather data indicated that double irrigation at jointing and antesis produced a similar yield to full irrigation with higher WUE. Increased WUE by deficit irrigation was mainly attributed to increased harvest index. Among single irrigation treatments, deficit irrigation of 140 mm at grain filling produced higher grain yield and WUE while 100 mm at jointing produced higher biomass yield. Advantage of deficit irrigation increasing dryland yield was more pronounced at seasons with below average precipitation < 200 mm. The relationship between seasonal ET and grain yield or WUE was described by the second order polynomial regression. Based on this analysis, it was concluded that irrigation schedules at jointing and anthesis replacing between 430 and 583 mm of the ET achieve high grain yield and WUE simultaneously. These results demonstrate that the CERES-Wheat model, following calibration and validation, with proper input parameters can be used to provide effective irrigation scheduling scheme for winter wheat in semi-arid climate such as the Texas High Plains.

CHAPTER VI

SUMMARY

In the semi-arid Texas Rolling Plains, the growth and yield of cotton (*Gossypium hirsutum* L.) is driven by the amount of water available to the crop through irrigation and precipitation. A field study was conducted in 2012 and 2013 at Chillicothe, TX, to investigate the growth, yield, water use efficiency (WUE), and spectral reflectance responses of cotton under different irrigation and tillage treatments. A split-split plot design with three replications was used with irrigation as the main plot (dryland, 45% evapotranspiration replacement, 90% evapotranspiration replacement, and irrigation based on a remote sensing method developed by researchers in the current study), tillage (conventional and minimum) as sub plot, and varieties (PHY499, DP1044, PHY375, and FM9170) as sub-sub plot. Lint yield, WUE, and fiber quality were significantly affected by irrigation and irrigation by variety interaction. Increasing irrigation level resulted in a linear increase in lint yield and WUE. The irrigation by variety interaction showed that the 90% evapotranspiration (ET) replacement treatment involving PHY375 produced the greatest lint yield and WUE. Tillage did not significant affect lint yield, WUE, and fiber quality. Increasing irrigation water amounts resulted in a linear increase in fiber length and strength, and a linear decrease in fiber micronaire.

Plant height showed significant differences in response to irrigation. Replacing 90% ET resulted in significantly taller plants compared to other irrigation treatments. Varieties showed significant differences in plant height. PHY499 was the tallest variety among the varieties tested in this study. Irrigation significantly affected the leaf area index (LAI) development. Among the varieties, PHY499 consistently produced higher LAI at all irrigation levels. Vegetation indices calculated using spectral reflectance measurements included the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI). In this study, NDVI was positively correlated with NDWI and LAI. However, later in the growing season NDVI did not increase although the green lead area increased. This lack of increase in NDVI was primarily due to saturation of the reflectance signal. The Crop Water Stress Index (CWSI) calculated using canopy and air temperature measurements indicated that for deficit irrigation treatments, the average CWSI was > 0.50. It was also observed that the CWSI and NDWI were negatively correlated. Further investigation is necessary on using NDWI and CWSI for irrigation management for cotton in the Texas Rolling Plains.

A modeling study was performed to investigate the cotton yield, water use efficiency (WUE), and economic return responses of dryland and irrigated cotton in the Texas Rolling Plains. The cotton growth simulation model Cotton2K was calibrated and validated using field data described above. Calibrated model was used to run simulation scenarios involving seven irrigation treatments (40%, 60%, 80%, 100%, 120%, and 140% ET replacements and dryalnd) using historical weather data from 1980 -2010 for the Texas Rolling Plains. Results revealed that replacing 112% ET maximized the yield while economic return was maximized at 108% ET. However, WUE decreased with increasing irrigation. This was due to decreasing marginal yield increments at higher irrigation levels. The Irrigation WUE showed a negative linear decrease as irrigation rate increased while the Benchmark WUE was increased at a decreasing rate as irrigation rate increased. Deficit irrigation at 60% ET or 80% ET replacement level significantly increased lint yield compared to dryland. Replacing 80% of the ET produced 88% of maximum yield produced at 120% ET with approximately 72% water saving. Our data suggest that, when water resources are limited, deficit irrigation at 60% ET or 80% ET replacement can be used to improve cotton WUE without significant yield and economic reductions in the semi-arid Texas Rolling Plains.

Winter wheat (*Triticum aestivum* L.) is another major field crop grown in Texas. A modeling study was performed using the DSSAT-CERES-Wheat model to investigate winter wheat growth and yield responses to irrigation management in the Texas High Plains. The DSSAT-CERES-Wheat model was calibrated to predict winter wheat growth and yield with reasonable accuracy using data from field studies conducted in the Texas High Plains. Calibrated model was used to test winter wheat biomass, grain yield, WUE, and ET responses to different irrigation scheduling practices using long-term weather datasets available for the Texas High Plains region (1980-2012). Results of winter wheat response to irrigation indicated that deficit irrigation between jointing and anthesis could significantly increase winter wheat grain yield and WUE. Application of 100 mm of irrigation at jointing and 120 mm at anthesis was found to produce a grain yield and WUE similar to full irrigation with significant amount of water saving. The advantage of deficit irrigation was more pronounced for seasons with average (200-300 mm) and below average (< 200 mm) precipitation.

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