SOIL WATER MEASUREMENT AND THERMAL INDICES FOR CENTER PIVOT IRRIGATION SCHEDULING

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Abstract. *In this two-year study, the relationship between irrigation scheduling using soil water measurements, and two thermal indices was investigated. One-half of a three-span center pivot irrigated field was planted to cotton in circular rows and irrigated with LEPA (low energy, precision application) drag socks in furrow dikes. Infrared thermometers (IRTs), used to measure crop canopy temperature, were mounted on the center pivot spans. Replicated treatments established radially from the pivot point, received four amounts of water, 100%, 67%, 33% and 0%, where 0% was dryland (Dry) and the 100% amount was based on either soil water replenishment to field capacity (manually initiated) or on the automatic irrigation protocol called the Time Temperature Threshold (TTT) method. Three sectors (blocks) of radial plots were irrigated on odd-numbered days of year (DOY) based on neutron moisture meter (NMM) soil water measurements in a 1.5-m profile, while three sectors were irrigated automatically on even-numbered days based on the TTT method. Average cotton lint-yields, dryland, and water use efficiencies for 2007 were not significantly different between the automatic and manual blocks. Averaged paired yields for each irrigation level were only significantly different between manual and automatic blocks in the 67% treatment. A post analysis of the daily theoretical CWSI was performed and compared to a predetermined TTT index for each day during the period of automatic irrigation scheduling, showing that 92% of the automatic irrigation triggers occurred when the TTT index > 450 minutes and the theoretical CWSI was > = 0.5 for the two growing seasons. Combining the theoretical CWSI with a TTT index may improve automatic irrigation scheduling. Yield data for 2008 were not yet available.*

Keywords. center pivot, crop water stress index, irrigation scheduling, time temperature threshold index

INTRODUCTION

In the semi-arid Texas High Plains, approximately 75% of crop irrigation is accomplished by center pivots drawing groundwater from the Ogallala Aquifer. Average groundwater levels from the aquifer have declined by more than 50% (McGuire, 2003). From 1950 to 2005, the number of farms in the state of Texas declined by 33%, while land in farms decreased by only 15% (NASS, 2008). This typifies a national trend; the number of farms is decreasing, while farm size is increasing. For production to be profitable on larger farms, farmers must effectively operate their numerous irrigation systems with low management cost. Automated irrigation scheduling and control to meet crop water needs has the potential to improve water-use efficiency, assist in strategies to produce optimal yields, and decrease management time (Evett et al., 1996; 2006).

Irrigation scheduling can broadly be categorized into three paradigms based on measurements of: (1) weather, (2) soil water, and (3) plant condition (Jones, 2004). One method based on plant condition is the Time Temperature Threshold (TTT) method based on a canopy temperature threshold and a time threshold (Peters and Evett, 2007; Evett et al., 2006). Because it is a feedback method of automatic control, the TTT method does not require extensive supplementary inputs for triggering an irrigation; and it has been shown to allow control of water-use efficiency. Yields and water use efficiencies for drip irrigated soybean and corn were not significantly different using TTT than were those of manually irrigated plots (Evett et al., 2006). In work with center-pivot irrigated cotton, automatic irrigation scheduling was limited to even-numbered days of year (DOY) to allow for control sections to be manually irrigated on odd-numbered DOY (Peters and Evett, 2007).

In preparation for commercial application of the TTT method, it is desirable to make the method robust in the face of challenges such as plant disease and uneven plant stand with resulting uncovered soil. Testing of the TTT method in combination with a second irrigation trigger on a field of a larger-scale may help provide adjustments to this irrigation scheduling and control algorithm for successful commercial application.
A second irrigation trigger to consider for irrigation scheduling is the CWSI, developed in the early 1980s by Idso et al. (1981) who originated an empirical approach, requiring measurement of crop canopy temperature, air temperature and relative humidity. Jackson et al. (1981) developed a theoretical approach that required the additional measured inputs of solar radiation and wind speed, and the calculation of aerodynamic resistance (r_a). Researched extensively, the CWSI has been labeled a sensitive means to monitor and quantify plant stress for a variety of crops. Pinter et al. (1983) determined the CWSI to be inversely correlated to cotton yields. Howell et al. (1984) concluded that the CWSI was responsive to both matric potential stress and soil osmotic potential stress for cotton. Colaizzi et al. (2003a) showed that the Crop Water Stress Index was correlated with soil water depletion for a fully developed canopy when no soil reflectance was present. It was also determined that the Water Deficit Index (WDI), which is a two-dimensional CWSI (Moran et al., 1994) normalized for vegetation cover, was correlated with crop water stress (Colaizzi et al., 2003b). The CWSI has also been used to predict yield response of different crops to water stress and to develop strategies for irrigation management decisions (Erdem et al., 2006; Yuan, et al., 2003).

Most temperature-based indices were developed around the assumption that the infrared radiometer (infrared thermometer) views only vegetation. However, soil background is usually present to some extent throughout the season, especially for cotton even when the canopy completely covers the inter-rows. Some indices such as the Water Deficit Index have attempted to account for soil background, but these require soil-specific parameterizations that are not routinely available, and could potentially confound errors associated with interpreting the ensemble (i.e., vegetation and soil) radiometric temperature. Therefore, IRT measurement protocols typically call for viewing the canopy across rows and at oblique angles to minimize soil background. The objectives of this study were (1) to compare the TTT method of automatic irrigation scheduling to manual scheduling using neutron scattering for soil water measurements; and (2) using a post analysis review, to investigate if the CWSI would be a useful addition to the TTT algorithm for automatic irrigation scheduling and control.

MATERIALS AND METHODS

Cotton [*Gossypium hirsutum* L.] was planted on DOY 149, 2007 (cv PayMaster[1] 2280 BG/RR); and on DOY 141, 2008 (cv Delta Pine 117 B2RF). Both cultivars were from Delta Pine Land Co., Scott, MS, and were Bollgard II® Roundup Ready®. The crop was grown in eighteen-row plots on beds spaced 0.76-m apart and formed in circles under a three span center pivot at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas (35˚ 11’ N, 102˚ 06’ W, 1174 m above mean sea level). Irrigations were applied either manually (Manual) or automatically (Auto) by the TTT method. In order to avoid conflicts between manual and automatic irrigations, manual irrigations were applied only on even-numbered days of the year (DOY) and automatic irrigations were applied only on odd-numbered DOY. One half of the center pivot circle was used for the experiment; and it was divided into six sectors, each of which was a block of treatments (Fig. 1). Treatments were assigned randomly in the radial direction within each block and were doubly replicated within blocks. There were four treatments for each method, Manual or Auto, and they were designated 100%, 67%, 33% and Dry. For the Manual method, irrigations were applied weekly fully replenish soil water to field capacity in the 100% Manual treatment. Automatic irrigations were triggered only for TTTI > 452 min where TTTI is the TTT Index, which is the time in min that the canopy temperature exceeds the temperature threshold of 28ºC for cotton each day. For the Auto method, irrigations of 20 mm were applied in the 100% Auto treatment (20 mm is twice the average weekly peak daily consumption of 10 mm). For both methods, irrigation depths in the 67% and 33% treatments were 67% and 33%, respectively, of the 100% treatment depth for the respective scheduling method; and these amounts were achieved by reducing nozzle sizes. The Dry treatment received no irrigation. Low energy precision application (LEPA) drag socks were used in every other furrow with furrow dikes to inhibit runoff and surface redistribution of water. Manual irrigations were based on soil water contents in the top 1.5 m of soil as determined weekly by neutron

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

moisture meter (NMM) readings to 2.4-m depth in 0.20-m increments beginning at 10-cm depth using methods described by Evett (2008).

Canopy temperature was sensed using infrared thermometers (model IRT/c 5:1, Exergen, Inc., Watertown, MA) mounted on the pivot with an oblique viewing angle. Date were continuously recorded and provided canopy temperatures of the entire cropping field when the pivot was moved around the semi-circle area. Pivot mounted infrared thermometers (IRTs) were wired to a datalogger (Model 21X, Campbell Scientific, Logan, UT). When the irrigation system was moving, the mean temperature of each plot, for the center of the time period during which the plot was sensed by the IRTS, was scaled to a stationary reference temperature using the algorithm of Peters and Evett (2004) to produce an estimated daytime temperature curve for that plot. Stationary (reference) IRTs, wired in 2007 and wireless (O'Shaughnessy and Evett, 2008) in 2008, were located in the field within automatically irrigated treatment plots and provided reference crop canopy temperatures.

The soil was Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (Soil Survey Staff, 2004). Air temperature, relative humidity, solar radiation, and wind speed were measured at 6-s intervals and reported as 15-min mean values at the adjacent Soil and Water Management Research Unit weather station, Bushland, TX (see Evett, 2002 for methods). Average plant height and width measurements were taken every two weeks.

Crop water stress index

The theoretical CWSI was used to calculate a stress index for each day during the irrigation scheduling seasons as:

$$\mathrm{CWSI} = \frac{(T_\mathrm{c} - T_\mathrm{a}) - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}}{(T_\mathrm{c} - T_\mathrm{a})_\mathrm{ul} - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}} \quad [1]$$

where (T_c - T_a) is the measured difference between crop canopy temperature, T_c, and air temperature, T_a, (T_c - T_a)$_{ll}$ is the lower limit representing the temperature difference for a well watered crop and (T_c - T_a)$_{ul}$ is the upper limit representing the temperature difference between the crop canopy and ambient air when the plants are severely stressed (Jackson et al., 1988). The upper limit was calculated using the equation:

$$(T_\mathrm{c} - T_\mathrm{a})_\mathrm{ul} = r_\mathrm{a}(R_\mathrm{n} - G)/\rho C_\mathrm{p} \quad [2]$$

where r_a is aerodynamic resistance, R_n is net radiation (W m^{-2}), G is soil heat flux (W m^{-2}), ρ is the density of air (kg m^{-3}) approximated as a function of elevation, and C_p is heat capacity of air (J kg^{-1} ºC^{-1}). Soil heat flux was estimated as

$$\mathrm{G} = 0.1\mathrm{R}_\mathrm{n} \quad [3]$$

Net radiation was calculated as

$$\mathrm{R}_\mathrm{n} = (1 - \alpha)\mathrm{R}_\mathrm{s} + \mathrm{R}_\mathrm{lw\_in} - \mathrm{R}_\mathrm{lw\_out} \quad [4]$$

where α is albedo (estimated to be 0.23), R_s is short wave irradiance (measured at the weather station), R_{lw_in} is incoming long wave radiation and R_{lw_out} is outgoing long wave radiation. The values R_{lw_in} and R_{ls_out} were evaluated according to Jensen et al. (1990). Aerodynamic resistance, r_a (s m^{-1}), was calculated using

$$r_a = \frac{\ln\left(\frac{z - 0.63h}{0.13h}\right)}{k^2 u} \qquad [5]$$

where z is the reference anemometer height (m), k is the von Karman constant (0.41), u is the wind speed (m s^{-1}) at height z, and h is the vegetation height (m).

The lower limit, $(T_c - T_a)_{ll}$ was calculated using:

$$(T_c - T_a)_{ll} = \frac{r_a R_n}{\rho C_p} \frac{\gamma}{(\Delta + \gamma)} - \frac{e_s - e_a}{(\Delta + \gamma)} \qquad [6]$$

where γ is the psychometric constant (P_a ºC^{-1}), e_s is saturated vapor pressure, e_a is actual vapor pressure, and Δ is the slope of the saturated vapor pressure – temperature relationship, which can be estimated using the equation (Jackson et al., 1988):

$$\Delta = 45.03 + 3.014T + 0.05345T^2 + 0.00224T^3 \qquad [7]$$

where T is the average of the canopy and air temperature $(T_c+T_a)/2$, expressed in (ºC). The saturated vapor pressure was evaluated using

$$e_s = 0.6108 * \exp\left[\frac{17.27T_a}{T_a + 237.7}\right] \qquad [8]$$

where T_a is air temperature (ºC). The actual vapor pressure was taken as e_s (RH/100) where RH is the relative humidity.

Mean values, between 1100 hrs and 1530 hrs, of air temperature (T_a), crop canopy temperature (T_c) from 100% treatment plots in the automatic blocks, RH, incoming short wave radiation (R_s), and wind speed were used to calculate the CWSI. Using mean, rather than point values, is a method similar to Erdem (et al., 2006), and Alderfasi and Nielsen (2001), who used data measurements over time to calculate CWSI.

Time Temperature Threshold Index

The TTTI was calculated as time in minutes for which the crop canopy temperature was above 28ºC. When the pivot was moving, TTTI values were calculated using scaled temperatures per Peters and Evett (2004).

Water use efficiency and yields

Water use (ET, m) was calculated using the soil water balance equation (Evett, 2002):

$$\text{ET} = -\Delta S - R + P + I - D \qquad [9]$$

where ET is evapotranspiration, ΔS is the change in soil water stored in the profile (determined by NMM in the 2.4-m profile, negative when ET is positive), R is total runoff (m), P is the amount of precipitation (m), I is the irrigation water applied (m), and D is the drainage (m). Because the amount of irrigation water was only sufficient to bring the water deficit to field capacity and because furrow dikes prevented most runon and runoff. Drainage and runoff were neglected in our calculations, similar to methods by Schneider and Howell (2000). Water use efficiency (WUE, kg m^{-3}) was calculated as Y_g/ET_i, where Y_g was economic yield (kg m^{-2}) divided by seasonal ET_i (m) for each irrigation level. Irrigation water use efficiency (IWUE, kg m^{-3}) was determined by the equation:

$$\text{IWUE} = \frac{\left(Y_{\text{gi}} - Y_{\text{gd}}\right)}{\text{IRR}_{\text{i}}} \qquad [10]$$

where Y_{gi} is the economic yield (kg m^{-2}) for irrigation level i, Y_{gd} is the dryland yield (kg m^{-2}), and IRR_i is the applied irrigation water (m) (Bos, 1985; Howell, 2002).

Data analysis

Results were analyzed using Proc Mixed Analysis, Analysis of Variance (ANOVA), linear regression, and the Fisher Least Significant Difference (LSD) test using SAS software (SAS 9.1, SAS Institute Inc., and Cary, NC).

RESULTS AND DISCUSSION

Climatic conditions and irrigation summary

The effective experimental irrigation seasons for 2007 and 2008 lasted for a period of 44 and 25 days, respectively. The planting date for both years was in mid May. Harsh climatic conditions for the 2008 growing season, a combination of high temperatures and wind with low RH, slowed early vegetative growth and made it difficult to wet the soil profile to field capacity. Average temperatures and wind speeds in May and June were higher in 2008 than in 2007, while RH was lower (Table 1). In August 2008, temperatures were cooler, RH was higher and wind speeds were less than in August

2007. Heavy rainfall received in August 2008 (DOY 226 to DOY 229), shortened the irrigation season. A plant regulator (Stance™, Bayer CropScience, Research Triangle Park, NC) was applied on DOY 235, 2008 to induce reproductive development and prevent rank vegetative growth.

A greater volume of water was applied to the manually irrigated plots, i.e. 42.9 and 37.1 mm (at the 100% irrigation level) in the 2007 and 2008 growing seasons, respectively (Table 2). The frequency of automatically scheduled irrigations increased from 1 in 7 days to 1 in 4 days in the late flowering and early boll formation period in 2007. Irrigation scheduling began late in 2008, and automatic scheduling occurred roughly every 4 days in the early vegetative stage.

Yield and water use efficiency

In 2007, yields from Automatic and Manual treatment methods were not significantly different ($P = 0.83$) (Table 3). Irrigation levels significantly affected the dry lint yields ($\alpha = 0.05$), but there was no significant interaction between the methods and levels of treatment ($P = 0.18$). The WUE and IWUE values were not significantly different between the manual and automatic irrigated plots in 2007. Overall, the WUE for the dryland plots was not significantly different from any of the irrigated treatment plots due to the mild summer temperatures and above average rainfall. Linear regression demonstrated that cotton lint yields were positively correlated to water use for irrigations < 450 mm (Fig. 2). Yield data for 2008 are not yet available.

Thermal indices

For 2007, there was a weak relationship between the two the CWSI and TTTI thermal indices (ANOVA $r^2 = 0.19$, $F = 12.1$, and $P < 0.001$). The TTTI was not significantly related to the CWSI in 2008; this may be related to the limited number of data points collected in 2008 due to the shortened irrigation season.

Most TTTI triggers occurred when the CWSI > 0.5 (Fig. 3a, b, quadrant I). Less than 5% and 10% of TTTI values > 452 min occurred when CWSI was < 0.5 for both the 2007 and 2008 seasons, respectively (Fig. 3a, b, quadrant II). Data points representing TTTI <452 min and corresponding CWSI < 0.5 can potentially be classified as "non-triggers" (Fig. 3a, b, quadrant III). Data points for which CWSI > 0.5 when TTTI < 452 min represented 32% of the measured data in 2007, occurring generally during the early vegetative stage (Fig. 3a, quadrant IV). This could possibly mean that the TTTI is more robust than the CWSI when soil background is present. In 2008, most of the data points falling into this category did so from DOY 210-216, during cloudy days.

If the calculated theoretical CWSI > 0.5 was used to trigger automatic irrigations (calculations made on odd numbered DOY only), then the number of automatically scheduled irrigations would increase by ten and two for 2007 and 2008, respectively.

Figures 4a and 4b provide a time series depiction of the calculated theoretical CWSI and the TTTI during the automatic scheduling periods for 2007 and 2008.

A disadvantage to considering the use of both of these indices is that under partial canopy, soil temperatures will invariably influence the composite temperature measured by the IRTs. Additional sensors and modeling approaches can help reduce these inherent problems.

CONCLUSIONS

Yield results showed that the TTT algorithm for automatic irrigation scheduling of a center pivot for LEPA irrigated cotton successfully controlled the amount of irrigation water applied without significantly affecting cotton yield as compared with water balance irrigation scheduling done using NMM data. For full irrigation, the TTT method produced significantly greater overall WUE than did water balance irrigation scheduling; but differences were not significant for irrigation at reduced rates of 33 and 67% of full. There was a strong positive correlation between lint yield and water use < 450 mm.

Post analysis comparison of the two thermal indices indicated that they have similar trends, but the daily theoretical CWSI > 0.5 would result in additional irrigations. However, future work investigating the CWSI over a daily time step may prove to be a worthwhile index capable of indicating crop water status. Further research is needed to test new algorithms and compare crop yields and WUE.

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Table 1. Climatic data (monthly averages) for 2007 and 2008 growing seasons.

	Rainfall (mm)		T_a (ºC)		RH (%)		u (m s^{-1})		R_s (MJ m^{-2} d^{-1})	
Month\Seasons	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
May	17.8	4.6	17.27	18.4	70.11	47.32	4.26	5.29	24.44	26.52
June	56.4	57.3	21.6	24.29	64.63	47.14	3.81	5.43	25.94	28.89
July	36.60	49.3	23.98	23.83	62.79	60.77	3.23	4.08	23.26	24.61
August	63.70	73.1	24.54	22.58	64.18	66.06	3.70	3.37	23.26	22.34

T_a is air temperature, RH is relative humidity, u is wind speed, and R_s is solar irradiance.

Table 2. Irrigation summary for the 2007 and 2008 growing seasons.

Growing Season	2007	2008
Planting Day (DOY)	149	141
Start of automatic scheduling (DOY)	197	202
End of automatic scheduling (DOY)	241	227
Irrigation water applied to Manual 100% treatment plots[a] (mm)	182	133
Irrigation water applied to Automatic 100% treatment plots[a] (mm)	139	92

[a] Refers to application depth during the irrigation scheduling

Table 3. Cotton Yields 2007: three-span center pivot, Bushland, TX.

Category	Treatment	Average Dry Lint Yield (g m^{-2})	Total Water Use (mm)	WUE (kg m^{-3})	IWUE (kg m^{-3})
Methods	Manual	82a	390a	0.22a	0.20a
	Automatic	82a	370b	0.22a	0.22a
Irrigation Levels	100%	105a	519a	0.20a	0.19a
	67%	96b	425b	0.23b	0.23b
	33%	73c	333c	0.22ab	0.20c
	0%	55d	243d	0.23ab	
Treatment by Irrigation Level	100%-Manual	102a	543a	0.19a	0.16a
	100%-Auto	108a	494b	0.22b	0.21a
	67%-Manual	102a	436c	0.23b	0.24a
	67%-Auto	90c	414d	0.22b	0.21a
	33%- Manual	72d	338e	0.22ab	0.18a
	33%-Auto	74d	328e	0.23b	0.23a
	0%-Manual	54e	242f	0.23ab	
	0%-Auto	55e	245f	0.23ab	

WUE = water use efficiency
IWUE = irrigated water use efficiency

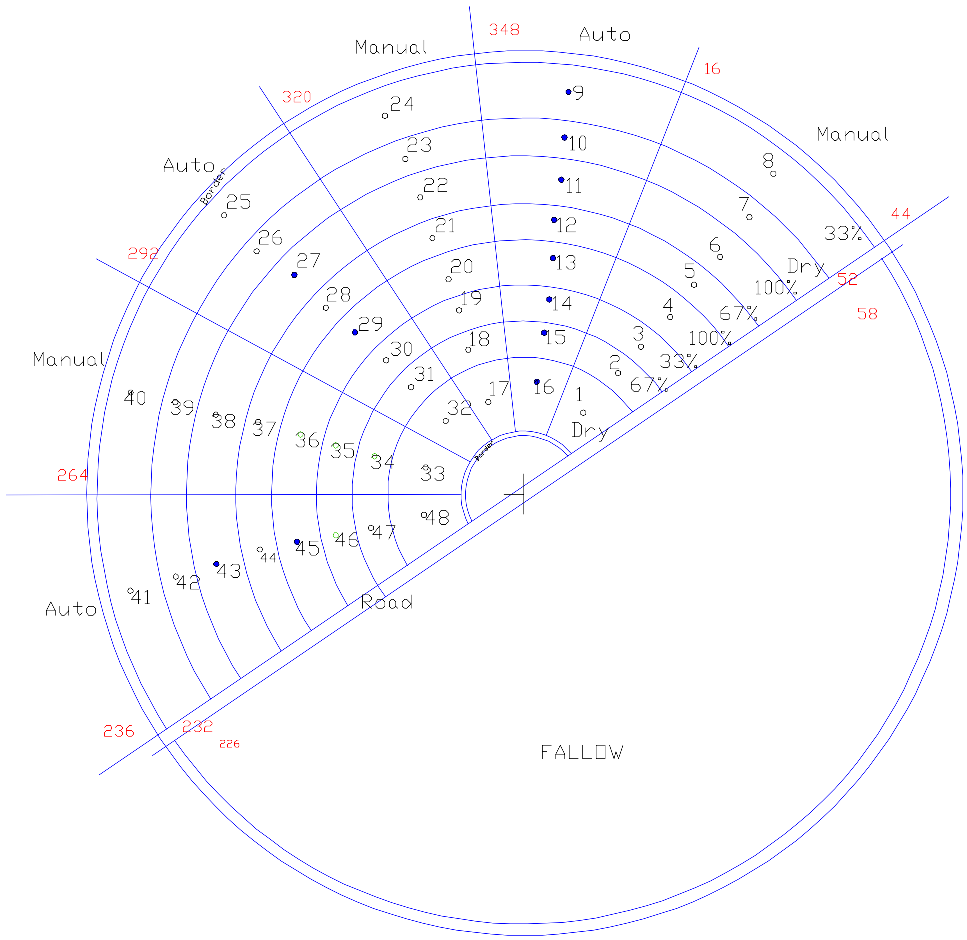


Figure 1. Fully randomized block design for manually (Manual) and automatically (Auto) irrigated treatments, 100%, 67%, 33% and dryland cotton (Dry) under a three-span center pivot system at Bushland, TX, 2007.

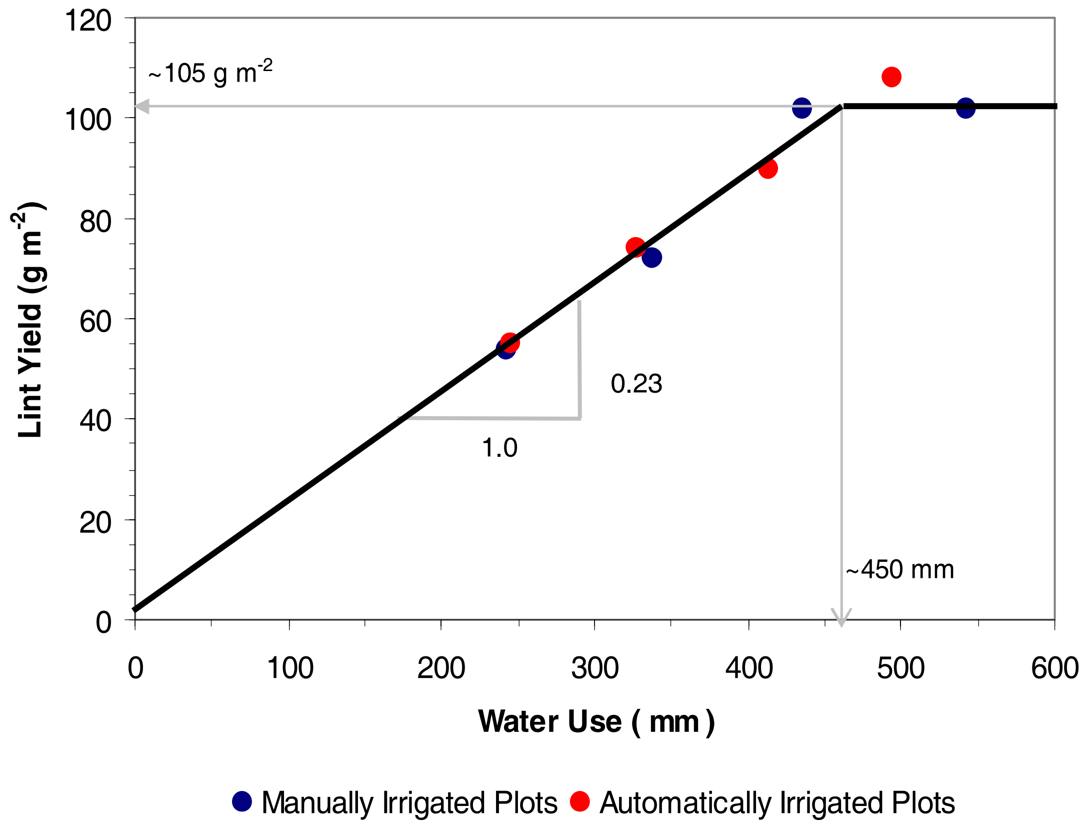
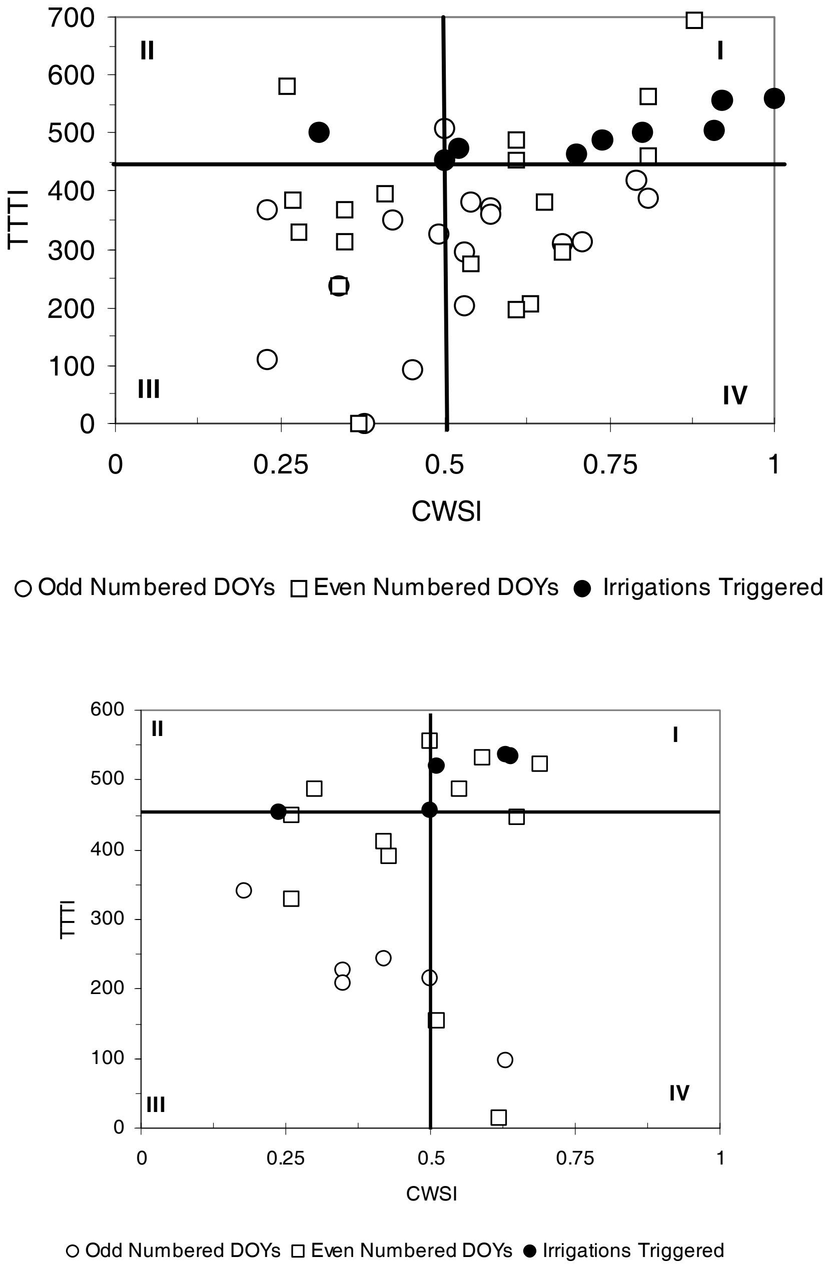


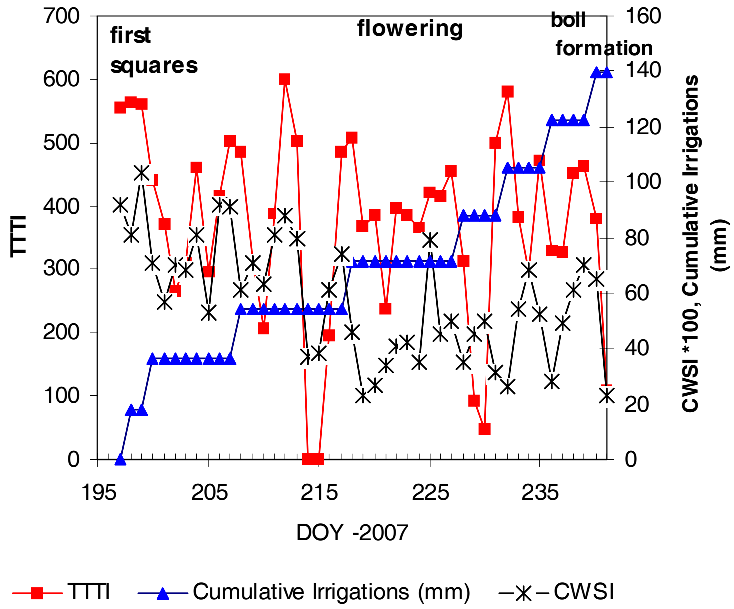
Figure 2. Lint yields versus water use efficiency (WUE) for cotton crop under a three-span center pivot, Bushland, TX, 2007.



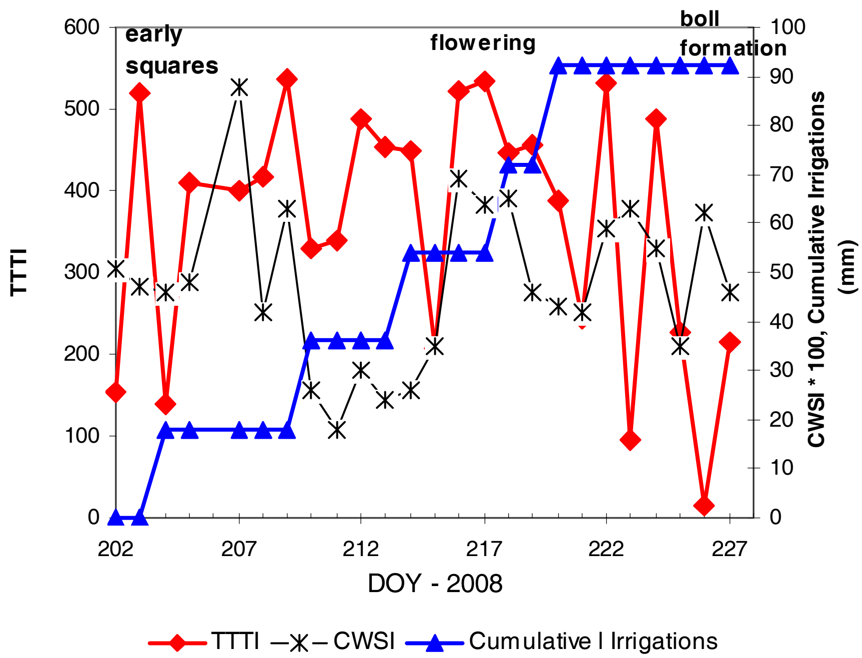
(a)

(b)

Figure 3. Relationship between the TTTI and the theoretically calculated CWSI for the (a) 2007 and (b) 2008 growing seasons. Horizontal and vertical lines divide the graphs into four quadrants labeled I, II, III and IV. The horizontal line is drawn at the TTT index threshold of 452 min; and the vertical bar is drawn at a CWSI value of 0.5. Solid squares represent data points that automatically triggered irrigations in the 2007 and 2008 growing seasons. Data points shown as hollow circles in quadrant I are canopy temperature measurements that would have triggered an automatic irrigation; however because their TTT minutes were accumulated on even-numbered DOY, no automatic irrigation was scheduled.



(a)



(b)

Figure 4. Time series plot of TTTI and the theoretical CWSI for the (a) 2007 and the (b) 2008 season.