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Full Length Research Paper

The crop water stress index (CWSI) for drip irrigated cotton in a semi-arid region of Turkey

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This study was carried out to determine the crop water stress index (CWSI) for drip irrigated cotton grown on a heavy clay texture soil (*Palexerollic Chromoxerert*) under semi-arid climatic condition of East Mediterranean region for three years (2005 to 2007) in Adana, Turkey. Four irrigation treatments designated as full (I_{100}) with no water stress and slight (DI_{70}), moderate (DI_{50}) and strong water stress (continuous stress, dry land) (DI_{00}) were tested. The treatments of DI_{70} and DI_{50} received water amount of 70 and 50% of the control treatment and the DI_{00} was not irrigated except for germination water given at the beginning of the growing season. Irrigation was initiated when leaf water potential (LWP) reached to -15 bar for full (I_{100}), -17 bar for DI_{70} and -20 bar for DI_{50} irrigation treatments. After first irrigation, all the treatments were irrigated at one week interval. The deficit irrigation affected, the irrigation water use, seed cotton yield, dry matter and some yield components such as plant height and number of boll per plant of cotton. Average values of water use, seed cotton yield, dry matter and water use efficiency of full irrigated cotton were 578 mm, 3.28 tha^{-1}, 13.44 tha^{-1} and 0.59 kgm^{-3}, respectively. CWSI values were calculated from the measurements of canopy temperatures by infrared thermometer (IRT), ambient air temperatures and vapor pressure deficit values for all the irrigated treatments. A non-water stressed baseline (lower baseline) equation for cotton was developed using canopy temperature measured from full irrigated plots as, $T_c - T_a = -1.7543VPD + 1.56$; R^2=0.5327 and the non-transpiring baseline (upper baseline) equation was built using canopy temperature data taken from continuous stress plots as, $T_c - T_a = -0.0217VPD + 3.2191$. The trends in CWSI values were consistent with the varying soil water content due to the deficit irrigation programs. The relationships between mean CWSI and plant parameters considered in this study were linear except for irrigation water amount. Both dry matter and seed cotton yield decreased with increased soil water deficit. Seed cotton yield (SY) and seasonal mean CWSI values relationship were obtained as, $SY = -2.3552CWSI + 3.5657$; R^2=0.499. This relationship can be used to predict the seed cotton yield. The results suggest that the cotton crop for this particular climate and soil conditions, should be irrigated when CWSI approaches 0.36. The CWSI approach, according to results of this study, can be accepted as a useful tool to schedule irrigations for cotton.

Key words: Crop water stress index (CWSI), evapotranspiration, cotton, drip irrigation.

INTRODUCTION

Irrigation scheduling in term of timing and amount of water application to a crop, can be based either on soil water balance methods, meteorological models that estimate crop evapotranspiration or on measurements of crop parameters (Cremona et al., 2004). The latter approach appears to be particularly attractive as plant-integrate soil and meteorological variables in their response to water deficits (Jackson, 1982). Water deficit is one of the most important factors limiting plant growth, meta-

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bolism, yield and evapotranspiration. Accurate and timely determination of water deficit effect on yield reduction is of great importance. Many easy and efficient methods have therefore been developed for determination of water deficit and for yield prediction of water-stressed crops. Most of these methods are generally based on soil, plant and meteorological measurements. These methods are time consuming and produce point information that give poor indications of the overall status of the field concerned (Jackson, 1982), unless very large numbers of samples are processed (Hatfield, 1990).

Canopy surface temperature measured with infrared thermometers is an important tool for crop water stress monitoring, which has been in practice for some decades (Alderfasi and Nielsen, 2001; Colaizzi et al., 2003; Gonzalez-Dugo et al., 2005). Although, this technology has a long history of development, it is yet to be adopted by farmers to schedule irrigations. Tanner (1963) first evaluated crop canopy temperature with an infrared thermo-detector to monitor crop water content. It was found that canopy temperature was usually lower than air temperature under sufficient soil water conditions. The basic assumption was that transpiration cools the leaves and as available soil moisture decreases, transpiration is reduced and therefore, the temperature of leaves increases. The relationships between canopy temperature and soil water content was particularly important since the potential of using canopy temperature as an indicator of crop water stress or plant water status and as a tool for irrigation schedule was then recognized (Payero et al., 2005, Wen-zhong et al., 2007).

Remote sensing of canopy temperature (T_c), provides an enormous advantage (Idso et al., 1980). The simplicity, rapidity and the non-destructive nature of infrared thermometry measurement and sampling has easily made it applicable to the different areas of agriculture such as disease and insect damage assessment (Nicolas et al., 1991), plant water stress assessment (Jackson et al., 1981), irrigation scheduling (Clawson and Blad, 1982) and yield prediction of water-stressed crops (Idso et al., 1977).

Considerable research was conducted to develop many indexes using the canopy temperature, T_c, for predicting crop water stress (Idso et al. 1977; Jackson et al. 1977). Ehler et al. (1978) demonstrated that, canopy minus air temperature (T_c-T_a) was linearly related to air vapor pressure deficit (VPD) and (T_c-T_a) was a reliable indicator of plant water stress by relating it to measured plant water potential. Idso et al. (1981) developed an empirical approach for determining water stress of crops by estimating non-water-stressed baselines, which represents the lower limit of temperature of a particular crop canopy if transpiring at the potential rate. Lower and upper baselines could be established empirically for both non-water-stressed and for non-transpiring crop conditions, respectively. They used these baselines to calculate what they called the crop water stress index (CWSI) as an indicator of crop water stress. However, this empirical method does not account for net radiation and wind speed, and the baselines vary with crop species and seasons (Idso, 1982).

Jackson et al. (1981) and Jackson (1982) presented a theoretical method for calculating CWSI. They showed that the lower baseline was a function of net radiation, crop resistance (aerodynamic and surface) and vapor pressure deficit, while the upper baseline was a near-horizontal line that depended on available energy and crop aerodynamic properties. This theoretical approach then requires knowledge of crop resistance properties and net radiation, in addition to measured T_c-T_a and VPD, which makes it difficult to apply this method in practice (Payero et al., 2005).

As a result of many works conducted, the CWSI derived from canopy-air temperature differences (T_c-T_a) versus the air vapor pressure deficit (VPD), was accepted to be a promising tool for quantifying crop water stress, crop water status and yield performance under drought conditions (Jackson et al., 1981; Idso and Reginato, 1982; Jackson, 1982).

The CWSI approach was successfully used for irrigation scheduling in field crops like maize (Clawson and Blad, 1982; Gençoğlan and Yazar, 1999; Yazar et al., 1999; Steel et al., 2000; Irmak et al., 2000; Payero and Irmak, 2006), wheat (Alderfasi and Nielsen, 2001; Yuan et al., 2004; Wang et al., 2005), vegetables (Cremona, et al., 2004; Erdem et al., 2006) and others plants (Payero et al., 2005; Ajayi and Olufayo, 2004; Wen-zhong et al., 2007).

In the last few years, several studies were conducted with the objective of the determination of the CWSI of different varieties of cotton (Idso and Reginato, 1982; Wanjura et al., 1984; Fangmeier et al., 1989; Ödemiş and Baştuğ, 1999; Gonzalez-Dugo et al., 2005; Kırnak et al., 2005), to establish a relationship between the CWSI and cotton yield (Pinter et al., 1983; Howell et al., 1984) and also with the leaf water potential (Pinter and Reginato, 1982; O'Toole et al., 1984; Cohen et al., 2005). However, a few studies have been done to evaluate the CWSI applications in Turkey, especially in the Mediterranean and South-east Anatolia regions, where crop water stress is frequent and widespread. Therefore, the main objecttives of this work were to monitor and quantified water stress and to develop empirical CWSI parameters for drip irrigated cotton grown under semi-arid Mediterranean climatic conditions.

MATERIALS AND METHODS

A field experiment was conducted for three seasons from 2005 to 2007 at the Research Fields of the Agricultural Structures and Irrigation Department of the Çukurova University, Faculty of Agriculture (36°59'N, 35°18'E and 20 m above sea level), Adana, Turkey a typical Mediterranean climate with cool, rainy winters and hot, dry summers prevails in the area. Long-term average rainfall in the area is about 650 mm, most of which is received during the

Table 1. Climatic data for the cotton experiment when compared with long-term data from Adana.

Year	Average[1] climatic factor	Month						
		April	May	June	July	August	September	October
2005	Ta, °C	14.5	19.3	24.7	28.6	29.0	25.6	19.6
	RH, %	64.2	63.6	63.9	67.6	64.1	61.3	53.6
	WS, m s^{-1}	1.1	1.1	1.1	1.2	1.1	0.9	0.9
	Rs, $MJm^{-2}s^{-1}$	17.8	20.5	26.1	24.4	22.6	18.5	14.9
	Rain, mm	56.0	74.0	5.0	0.0	19.0	34.5	37.0
2006	Ta, °C	18.4	22.2	25.7	28.2	29.4	25.9	22.1
	RH, %	66.4	62.0	64.1	66.7	66.2	59.3	64.6
	WS, m s^{-1}	1.0	0.9	1.1	1.2	1.2	1.1	0.9
	Rs, $MJm^{-2}s^{-1}$	16.0	25.2	24.3	24.8	21.6	18.5	13.1
	Rain, mm	13.0	25.0	12.0	16.0	0.0	54.0	115.0
2007	Ta, °C	16.1	23.7	25.7	28.8	29.2	26.1	23.4
	RH, %	61.5	65.4	63.2	61.9	64.6	58.7	55.3
	WS, m s^{-1}	0.9	0.9	1.3	1.5	1.3	1.0	0.9
	Rs, $MJm^{-2}s^{-1}$	20.1	19.8	24.6	26.3	22.3	19.9	13.5
	Rain, mm	67.0	33.5	3.7	0.5	0.0	0.0	12.5
Long-term	Ta, °C	17.1	21.4	25.2	27.7	28.1	25.4	21.0
	RH, %	69.0	67.0	66.0	68.0	67.0	63.0	60.0
	WS, m s^{-1}	1.8	1.8	1.9	2.0	1.9	1.6	1.3
	Rs, $MJm^{-2}s^{-1}$	16.5	19.4	20.7	20.7	19.1	16.3	11.6
	Rain, mm	51.4	46.7	22.4	5.4	5.1	14.8	43.6

[1]Ta, air temperature; RH, relative humidity; WS, wind speed at 2 m height; Rs, solar radiation.

Table 2. Some soil characteristics of the experimental field.

Soil layer (cm)	Texture	FC* (w w^{-1})	PWP* (w w^{-1})	As* (g cm^{-3})	pH	EC* (dS m^{-1})	Organic matter (%)	Initial mineral (N, mg kg^{-1})	K_2O** kg ha^{-1}	P_2O** kg ha^{-1}
0-30	C*	34	18	1.19	7.87	0.21		0.06		
30-60	C	37	18	1.16	7.61	0.12	1.34	0.06	473	25
60-90	C	38	19	1.15	7.81	0.14	1.07	0.05	473	29
90-120	C	38	19	1.25	7.97	0.13		0.04		
120-150	C	37	19	1.24	7.64	0.18		0.04		

*FC, Field capacity; PWP, permanent wilting point (percent water by weight); C, clay; As, bulk density; EC, electrical conductivity; ** K_2O and P_2O_5; were measured in upper 0 to 20 and 20 to 40 cm depths.

winter season when most of plants are not grown. Additionally, some average of climatic factors for the growing seasons of the experimental years are summarized in Table 1.

Soil at the site was classified as a Palexerollic chromoxerert with heavy clay texture (Dinç et al., 1991). Some physical and chemical properties of the soil are presented in Table 2. The soils have no salinity and drainage problems and the water table is more than 6 m deep (Ünlü, 2000).

Delta Pine SG-125 cotton cultivar (*Gossypium hirsutum L., cv.*) was planted with 0.70 m row distance and then, when plants were fully established and had three or four leaves, thinning was done to 10 to 15 cm spacing. Planting dates were 133, 118, and 116 day of year (DOY) and the first harvest dates were 265, 248 and 247 DOY, respectively, in 2005, 2006 and 2007.

A completely randomized block experimental design with three replications was used. Each plot was 50 m long and 8.4 m wide, consisting of 12 plant rows. Some plant rows in the plots were used for getting observations and measurements, while the middle of 20 m of central 6 rows were used for the cotton yield measurements (84 m^2).

Four irrigation treatments designated as full (I_{100}) with no water stress and slight (DI_{70}), moderate (DI_{50}) and strong water stress (continuous stress, dry land) (DI_{00}) were tested. The full irrigation was the control treatment where irrigation water amount was calculated by Equation 1. The remaining treatments DI_{70}, DI_{50} and DI_{00} were essentially deficit irrigation treatments, which received water amount of 70 and 50% of the control treatment and the last was the continuous stress treatment which was not irrigated except for the germination water given at the beginning of the growing season.

$$I=E_{pan} \times K_{cp} \times C_p \qquad (1)$$

Where, I is the amount of irrigation water in mm; E_{pan} is the cumulative free surface water evaporation during irrigation interval in mm; the water evaporation data was measured with a screened Class A pan located at the meteorological station near the experimental field. K_{cp} is the pan-crop coefficients which were taken as 0.91 for the first year and then 0.75 for the other years. C_p is the plant cover in %; it varied depending on crop development during the irrigation seasons. Cotton plants in the treatments reached to full cover at the different time after sowing which depended on years and irrigation levels.

Irrigation was initiated when leave water potential (LWP) reached to -15 bar for full (I_{100}), -17 bar for DI_{70} and -20 bar for DI_{50} irrigation treatments. During the first irrigation, soil moisture deficit in 120 cm depth instead of Epan and C_p values were used for calculating water amount in the Equation 1. After the first irrigation, all treatments were irrigated with one week intervals. Irrigation applications were continued until almost mid August when 10% of bolls on the plant were fully opened as generally practiced in the region.

A drip irrigation system was used for irrigation of the plots. Polyethylene pipe with 16 mm diameter with in-line drippers at 0.50 m interval was placed to one side of each cotton row. The average discharge of emitters was 4 l/h at the 1.0 bar. The fertilizers practices, pest and diseases control were used during all the experimental years. Fertilizers doses applied to the treatments were determined according to recommendations for cotton in the region (Kanber et al., 1994) and was given directly to the trickle lateral lines by fertigation control unit. Different fertilizer concentrations of 40, 10 and 15 ppm, were used for nitrogen, phosphorus and potassium respectively. Pest and diseases control were carried out as needed with recommendations of Plant Protection Department of University of Çukurova. Evapotranspiration, ET (mm) for all treatments was calculated from;

$$ET=P+IW+C_{cap}-DP-TW\pm\Delta W \qquad (2)$$

Where, P and IW are rainfall and total irrigation water depth (mm), respectively; ΔW is the change of soil water content (final minus initial), which was calculated by subtracting the total soil water content at 1.2 m depth of soil profile determined during the calculated period, (mm); C_{cap} is the capillary contribution from ground water table to the crop root zone, (mm); DP is the deep percolation from the root zone, (mm) and TW is the surface runoff water losses, (mm). In the experimental area, since there were no water table and run off loses, C_{cap} and TW were zero. DP was assumed to be negligible because of frequent irrigation, drip system characteristics and high soil moisture deficit before irrigation.

During the growing season (from sowing to harvest), soil-water content in all the treatments was routinely measured at sowing and harvest, especially just before irrigation, using a neutron water gauge (Hyroprobe 503, CPN Corporation, California, USA), with access tubes installed in mid-way along the plant rows, in middle of each plot and replicated in three blocks, to a depth of 120 with 30 cm increments.

The canopy temperature (T_c) readings were taken using a hand-held infrared thermometer (Everest Interscience Inc., Model 510B, Infrared AG Multimeter) which has 3° field view and equipped with a 7 to 18 µm spectral band-pass filter. The infrared thermometer (IRT) was operated with the emissivity adjustment set at 0.98. The canopy temperature was measured on the effective area of a plot from 4 directions (east, west, north and south) with full sunlight, at a distance of 0.50 m from the crop, with oblique measurements at 20 to 30° from the horizontal to minimize soil background in the field of view and then averaged. The T_c measurements were monitored on each bright, sunny day (clear skies) between 11:00 to 14:00 h solar time. The calibrations of the instruments were checked in a laboratory before the start of the experiments and systematic recalibrations were performed during the studies. The IRT data collection was initiated when average leaf area was about 1.1 (when the ground was well covered so as to avoid taking measurements of the soil surface) and ended at about average leaf area index of 4.4 (at the physiological maturity). The data-averaging feature of the infrared thermometer was employed to reduce variability in T_c. An average of 12 to 15 instantaneous readings was taken from the southeast and southwest sides of each plot by pointing the IRT diagonally across the plots (Nielsen, 1990). At least 10 readings after discarding maximum and minimum values of the total readings in each direction were considered for computing an arithmetic average. A standard meteorological station (Chambell CR10X) was situated in the area adjacent to the experimental site. It furnished hourly as well as daily averages of T_a, relative humidity, wind speed and solar radiation. Sunshades were utilized to minimize direct solar incidence on the sensors. The mean air temperature (T_a) determined from the average of the meteorological station readings during the measurement periods and RH measurements was used to calculate the VPD of the air with procedures given by Allen et al. (1998).

$$es = 0.6108\ \exp\left[(17.27 \times T_a)/(T_a + 237.3)\right] \qquad (3)$$

$$ea = es \times (RH / 100) \qquad (4)$$

$$VPD = es - ea \qquad (5)$$

Where, *es* is the saturation vapor pressure (kPa); T_a, the air temperature (℃), RH, the relative humidity of the air (%) and VPD, the vapor pressure deficit of the air (kPa). The mean VPD was computed as the average of the calculated instantaneous VPDs values. The CWSI was calculated by Equation 6 (Idso et al., 1981).

$$CWSI = \frac{\left[(T_c - T_a) - LL\right]}{(UL - LL)} \qquad (6)$$

Where, T_c is the canopy temperature (℃), T_a the air temperature (℃), LL is the non-water-stressed baseline (lower baseline) and UL is the non-transpiring upper baseline.

The procedure given by Idso et al. (1981) was used for determining the CWSI values. In this approach, the measured crop canopy temperatures were scaled relative to the minimum canopy temperature expected under non-water-stress conditions and the maximum temperature under severe water stress. The non-water-stressed baseline for the canopy-air temperature difference (T_c-T_a) versus the vapor pressure deficit (VPD) relationship was determined using data collected only from the control treatment (I_{100}). The upper (fully stressed) baseline was determined according to the procedures explained by Idso et al. (1981). To verify the upper baseline, the canopy temperatures of the fully stressed plants (ID_{00} treatment) were determined several times from July 1 (DOY 182) to the July 28 (DOY 209).

Cotton leaf water potential (LWP) was measured from 10:00 to 14:00 h (solar time) one day before and after irrigation with three replications in the all plots of each treatment. For LWP measurements, leaves which are on the upper most fully expanded, 4th to 5th leaf from top and completely exposed to full sunlight, from selected plants were cut and mid-day leaf water potential (LWP) was measured on leaf blade strip using a pressure chamber (3005 Plant Water Status Console, Soil Water Equipment Corp., Santa Barbara, CA, USA). Diurnal leaf water potential changes, from predawn to sun set were monitored in all the treatments at three occasions; in June at growth stage of bud formation, July and August at boll development stage, respectively.

Plant vegetative growth was quantified by measuring the increment in plant height, leaf area index (LAI) and biomass, and plant cover at one week interval throughout the growing season. Three plants in the row per plot of each treatment were randomly selected and labeled for the measurement of plant height and cover. Additionally, at the end of each growing season, these tagged plants were used for measuring some yield and the yield components, that is, plant height, number of boll per plant and some fiber quality properties such as, fiber length, fiber uniformity, micronaire and fiber resistance and percentage.

In order to determine total dry matter above the ground level, all plants within 1.0 m^2 in each plot were removed at ground level until harvest. Plants samples were dried at 65°C until stable weight was achieved. Seed cotton yield of each plot was monitored by hand harvesting for two times except for treatment DI_{50} which had only one time harvesting. First harvest was done when approximately 50% boll on a plant in the treatment I_{100} was fully opened. When bolls on the remaining plant were opened, the last harvest was done at the end of September or first week of October.

All the harvested seeds of cotton was weighed for each plot as final yield in all the years. The cotton water use efficiency (WUE_{ET}), irrigation water use efficiency (WUE_I) and harvest index (HI) were calculated using the following formulas:

$$WUE_{ET} = \frac{Y}{ET} \tag{7}$$

$$WUE_I = \frac{Y}{IR} \tag{8}$$

$$HI = \frac{Y}{BM} \tag{9}$$

Where, Y is the total seed cotton yield of each treatment ($kgha^{-1}$); ET is the total evapotranspiration calculated from Equation 2 for cotton growing season (m^3); IR is the volume of irrigation water applied to each treatment (m^3) and BM, is the final biomass of each treatment, $kgha^{-1}$.

RESULTS AND DISCUSSION

The growing seasons for cotton extended from April to October. As shown in Table 1, average monthly climate conditions for cotton growing seasons in the trial years were approximately similar to the long term climatic conditions that prevailed at the Research Fields of the Agricultural Structures and Irrigation Department of the Çukurova University, Adana. However, substantial variations were observed from year to year. For example, the 2006 growing season rainfall was 235 mm, which was about 19 and 25% higher than those in the long-term mean rainfall of 189.4 mm and average rainfall in the other trial years of 171.5 mm, respectively. On the other hand, rainfall in June and July of 2006 were a little greater than those in other trial years. Additionally, average relative humidity in 2006 was 64.2% which was greater than those in the other years of 2005 and 2006 by 63 and 61.5%, respectively. Moreover, average monthly relative humidity in 2006 was higher in July and August when high crop water requirement occurred. Higher rainfall and relative humidity in 2006 may be considered as a reason why less irrigation water was applied that year.

Crop water use, cotton yield and yield components

Tables 3 and 4 summarize the water use, water use efficiencies, cotton yield and yield component data for the experiment. Irrigation applications and amount of water were different in the treatments. They were caused by the date of the first irrigation and the length of irrigation seasons during the experiment (Table 3). Maximum total irrigation water was given to treatment I_{100} and minimum to DI_{50}. Averagely, seasonal irrigation water varied from 370 (I_{100}) to 169 mm (DI_{50}). The continuous stress treatment was only irrigated for germination after planting. All treatments have minimum irrigation water in the year of 2006. It can be attributed by the climatic condition of the relevant year. On the average for all the seasons, treatment DI_{70} used 28% less water than treatment I_{100}; but the yield for this treatment was 4.0% less than that of treatment I_{100}. Similarly, treatment DI_{50} used 54% less water than treatment I_{100}; but its yield DI_{50} was 17.0% less than treatment I_{100} (Table 4).

Irrigation date, water amount and consequently soil water content for I_{100} treatment is shown in Figure 1. Generally, irrigation water amount in the applications for cotton varied from 100 mm for I_{100} to 8 mm for DI_{50} in 2005 and 25 to 11 mm in 2006 and 34 to 10 mm in 2007 for the same treatments, respectively. From Figure 1, treatment I_{100} never completed soil moisture deficit in 1.20 m depth before irrigation events throughout irrigation season. Average soil moisture depletion levels for treatment I_{100} varied from 0.37 of available soil water in 2005 to 0.60 of available soil water in the other years. This was about 150 and 93 mm of plant available soil water and during the experiment, 0.64 to 0.10 percent of the soil moisture deficit was met by irrigations depending on the year, application and growing stages. Because of depletion levels of available soil water and irrigation water amount that was met in the soil moisture deficit, a yield reduction could be expected in treatment I_{100}. So it is likely that I_{100}, experienced soil deficits that was large enough to impact yield, especially around the end of the irrigation season. These soil water deficits explain why even I_{100} treatment had CWSI values over 0.3-0.7 sometimes in the last two years. This may be due to drip irrigation system properties which wet some part of the soil and affected the crop rooting and soil moisture uptake that was detected with CWSI measurements.

As expected, the highest seasonal water use occurred in the full irrigation treatment as averagely 578 mm. Other deficit irrigation treatments were 484 and 385 mm for DI_{70}

Table 3. Water use and water use efficiencies data[1].

Year	Treatment	Number of irrigation	SIW[2] (mm)	Rain-fall (mm)	Soil water depletion (mm)	ET (mm)	WUE_{ET} (kgm^{-3})	WUE_I (kgm^{-3})	HI ($kgkg^{-1}$)
2005	I_{100}	8	493	79	99	671	0.47 [c]	0.63 [d]	0.20 [b]
	DI_{70}	8	316	79	122	517	0.68 [b]	1.10 [c]	0.29 [ab]
	DI_{50}	7	163	79	139	381	0.88 [a]	2.05 [b]	0.38 [a]
	DI_{00}	0	45	79	148	272	0.55 [bc]	3.31 a	-
	SED						0.043	0.071	0.020
	CV						6.6	4.0	7.0
2006	I_{100}	9	289	54	134	477	0.82[a]	1.35 [b]	0.31
	DI_{70}	9	234	54	137	425	0.80 [a]	1.45 [b]	0.31
	DI_{50}	8	175	54	147	376	0.70[b]	1.50 [b]	0.32
	DI_{00}	0	76	54	154	284	0.55c	2.07 [a]	-
	SED						0.034	0.070	0.016 ns
	CV						4.7	4.4	5.0
2007	I_{100}	10	329	70	188	587	0.48	0.86 [c]	0.23
	DI_{70}	9	248	70	191	509	0.51	1.04 [bc]	0.23
	DI_{50}	8	168	70	160	398	0.54	1.29 [b]	0.27
	DI_{00}	0	49	70	167	286	0.45	2.60 [a]	-
	SED						0.024 ns	0.051	0.014 ns
	CV						4.9	3.5	5.0

[1]Treatments with same letter are in the same statistical group ($p \leq 0.05$) according to LSD test; [2] SWI (seasonal irrigation water). For seed germination and emergence, pre irrigation water was applied as 45 mm (3 applications in 2005, DOY: 133,136,140), 76 mm (3 applications in 2006; DOY: 117, 122, 132) and 49 mm (3 applications in 2007, DOY: 116, 123, 143). During the all experimental years, first two germination irrigations were made just after planting, and last application on day after emergence. In continuously stress (dry land) treatment, germination water was just applied in the each year. Ns = not significant.

and for DI_{50}, respectively. Seasonal water use in the full irrigation treatment (I_{100}), was in agreement with the results of drip irrigated cotton reported by Ertek and Kanber (2003). They reported 615 to 449 mm water use of full drip irrigated cotton for the same area. In recent time, Önder et al. (2009) explained average 445 mm water use for obtaining high seed cotton yield of drip irrigated cotton at the Amik Plain in the east Mediterranean of Turkey. Similar results were given by Aujla et al. (2005) and Wanjura et al. (2002). However, the result of this study is in disagreement with results by Yavuz (1993) for the same region. In Harran Plain, much higher seasonal water use values of 898 and 1408 mm were reported by Çetin and Bilgel (2002), whereas, Yazar et al. (2002) reported 814 mm of water use for cotton grown under drip irrigation conditions on the same land.

Water and irrigation water use efficiencies (WUE_{ET}, WUE_I) and harvest index values of treatments were statistically significantly different ($p \leq 0.01$) except the values of WUE_{ET} taken in 2007. Generally, the values of WUE_I were higher than those of WUE_{ET} in all the treatments. This could be attributed to water used from soil storage. In year 2005, both WUEs values for I_{100} treatment were the lowest because cotton plant was excessively grown due to much water application, as seen in Table 3 which resulted from the highest K_{cp} coefficient used. The peak WUE_I values were measured from dry-land DI_{00} and ID_{50} treatments with 2.27 and 1.44 kgm^{-3} (averagely). In general, the values of both WUEs in this present results for cotton were different than those of other previous researchers who have used different irrigation methods and programs in different regions (Orgaz et al., 1992; Kanber et al., 2001; Ünlü, 2000; Ertek and Kanber, 2001; Yazar et al., 2002; Aujla et al., 2005; Dağdelen et al., 2006; Horst et al., 2007; and Önder et al., 2009). Harvest index values for treatments were statistically significantly different ($p \leq 0.01$) in the first year of the experiment. The peak harvest indexes were taken from deficit irrigation treatments. As explained by Grimes and El-Zik (1990), harvest index is generally higher at low water supply, reflecting a greater biomass in reproductive growth as water stress severity is increased. Similar results were reported by Orgaz et al. (1988), Alvarez-Reyna (1990), Heuer and Nadler (1999) and Ünlü (2000).

As shown in Table 4, deficit irrigation resulted in a lower seed cotton yield when compared with full irrigation (I_{100}) practice ($p < 0.01$). The highest seed cotton yield, averaging at 3282 $kgha^{-1}$, was obtained from I_{100} treatment plots. This was followed by DI_{70} with 3151 $kgha^{-1}$

Table 4. Yield and yield components data[1].

Years	Treatment	Seed Yield (kg ha^{-1})	Plant height (cm)	Dry matter (t ha^{-1})	Number of boll per plant	Fiber length UHM (mm)	Fiber uniformity UN, (%)	Fibers resist. STR (g tex^{-1})	Micronaire
2005	I_{100}	3126^a	146.8^a	15.44^a	20.5 ^{ab}	29.1	86.7	28.0	5.0
	DI_{70}	3495^a	116.5^b	12.08^b	21.75 ^{a}	29.5	87.3	27.7	4.8
	DI_{50}	3341^a	76.5^c	8.87^c	12.75^b	28.2	85.8	28.5	4.8
	DI_{00}	1489^b	-	-	-	28.2	85.3	27.1	4.8
	SED	234	3.0	1.9	13.0	2.0	1.0	3.0	3.0
	CV	8.0	3.365	0.171	2.32	0.52 ns	1.19 ns	0.86 ns	0.13 ns
2006	I_{100}	3899^a	94.0 ^{a}	12.49^a	14.2				
	DI_{70}	3379^b	86.0 ^{a}	10.95^b	10.2				
	DI_{50}	2623^c	71.5 ^{b}	8.20^c	10.8				
	DI_{00}	1571^d	-	-	-				
	SED	123	5.0	1.8	18.0				
	CV	4.0	4.137	0.144	2.08 ns				
2007	I_{100}	2822^a	89.0	12.4^a					
	DI_{70}	2579^{ab}	85.3	11.14^a					
	DI_{50}	2167^b	76.0	8.00^b					
	DI_{00}	1274^c	-	-					
	SED	115	8.0	4.4					
	CV	5.0	6.657 ns	0.347					

[1]Treatments with same letters were not statistically different ($p \leq 0.05$) according to LSD test. Results for fiber qualities represent only the first year of the experiment; ns= not significant.

and DI_{50} with 2710 kgha^{-1}, while at the continuous stress (dry-land) treatment (DI_{00}) seed cotton yield was 1445 kgha^{-1}. However, both deficit irrigation practices gave 54 to 47% higher yields than that from continuous stress condition-cotton (DI_{00}). Cotton yields in this experiment were the same or slightly lower than those from previous experiments using surface and pressurized irrigation methods (Önder et al., 2009; Çetin and Bilgel, 2002; Yavuz 1993; Ertek and Kanber, 2001; Wanjura et al., 2002; Aujla et al., 2005).

The data on plant height, number of bolls per plant, dry matter and leaf area indexes for different treatments under drip irrigation and deficit irrigation practices caused significant decline in all the parameters taken into consideration. In all the trial years, except 2007, the highest plant height was measured in the full irrigation treatment. There were statistical differences between treatments ($p \leq 0.01$). The application of deficit irrigation water through drip resulted in average decrease of 28% in DI_{50} and 10% in DI_{70} in plant height when compared with the full irrigation. Similar and comparable results were obtained by Aujula et al. (2005), Dağdelen et al. (2006) and Önder et al. (2009). Dry matter accumulation was significantly affected ($p \leq 0.01$) by the water deficit for all the trial years. The highest dry matter was obtained from full irrigation treatment. Average dry matter accumulations were 16 and 39% in ID_{70} and ID_{50} treatments, respectively less than that in the I_{100} treatment.

The highest boll number was taken from the mild deficit irrigation level ($p \leq 0.01$) in the first year. In year 2006, there were not statistically significant differences among the treatments. Therefore, the higher yield of the plots which were irrigated at the mild deficit level in the first year and at the full irrigation level in the second year could be related to the higher boll numbers per plant. Ertek and Kanber (2003) had 11 to 20 bolls per plant using drip irrigation in the Cukurova Region. Similar results on the number of bolls were reported by Çetin and Bilgel (2002) in Harran Plain and Mert (2005) in Amik Plain. Recently, Önder et al. (2009) also showed that the boll number per plant increased with the application of irrigation water amount.

As seen in Table 4, there were no statistically differences between the treatments for quality components of the cotton lint considered. However, fiber length was generally shortened in response to soil moisture deficits. The fiber length from the dry land (ID_{00}) and severe water stress (ID_{50}) plants were 4% shorter in UHM category than that from the irrigated plants. Irrigation increased fiber uniformity by 3 and 2% when compared with that in

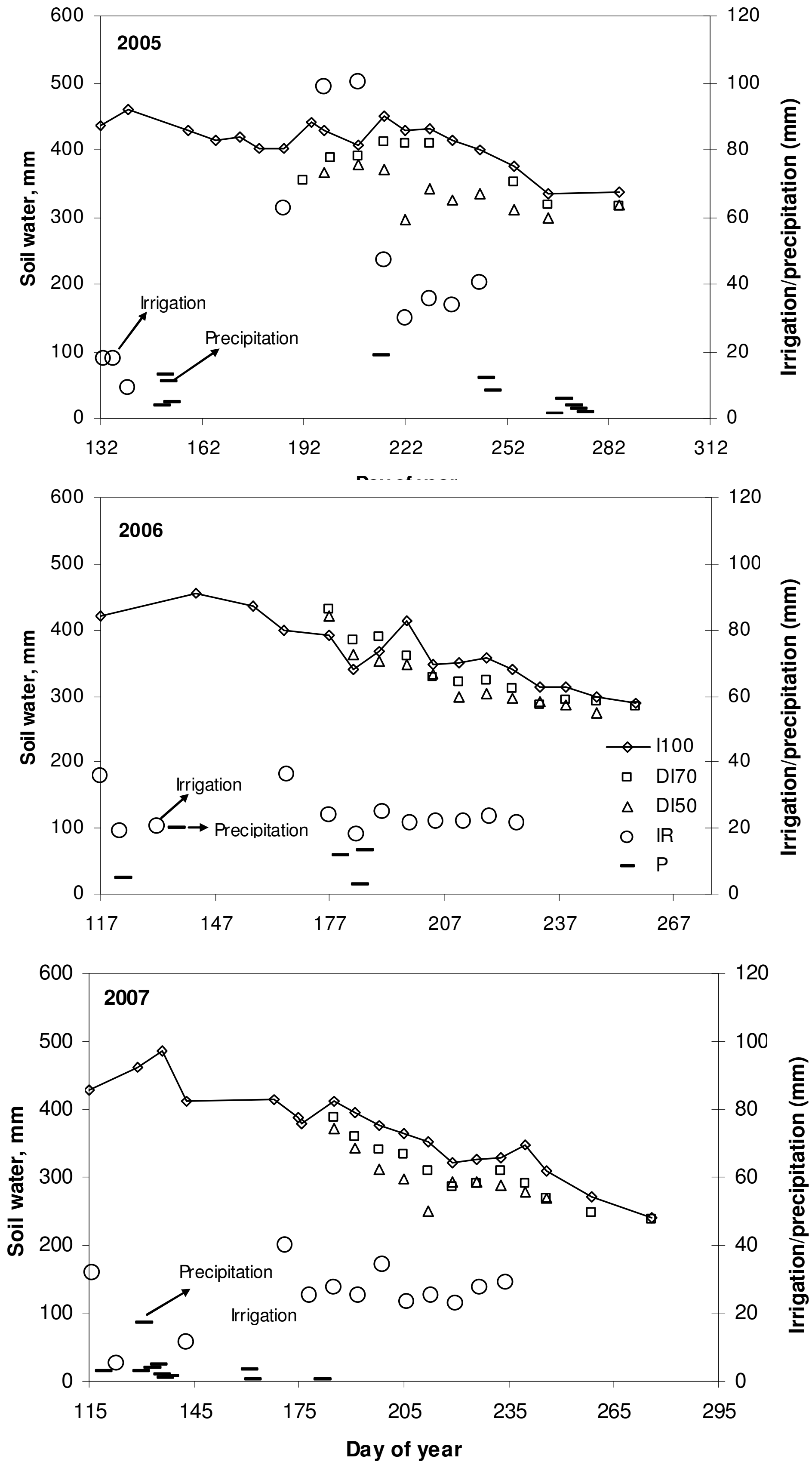

Figure 1. Variation of soil water content in 1.20 m soil depth for treatments, and irrigation water amount for I_{100} during the experimental years.

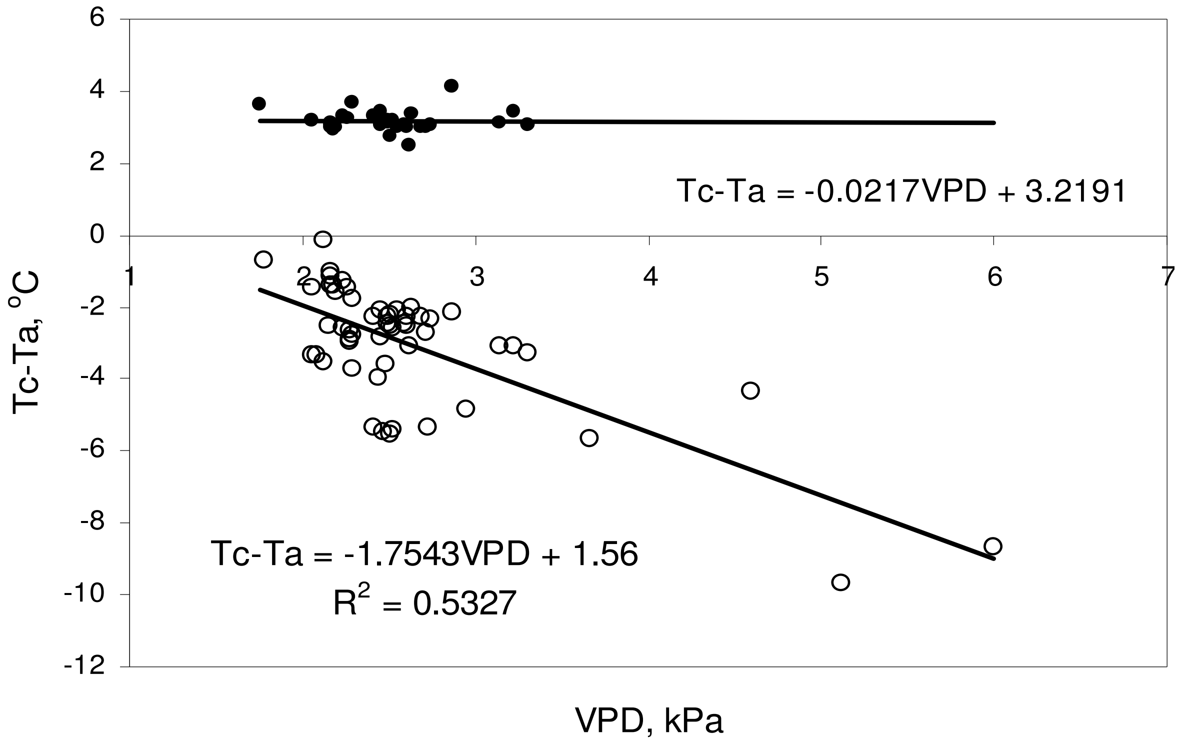

Figure 2. T_c minus T_a as a function of vapor pressure deficit (VPD) for non-stressed cotton plant grown at Adana, Turkey. Horizontal line shows the upper limits for plant which was stressed so severely that transpiration ceased.

Table 5. Cotton non-water stressed baselines obtained from different studies.

Equation	Source
Tc-Ta = -1.71-1.90 VPD; R^2 = 0.46	Pinter and Reginato (1982)
Tc-Ta = 0.257-0.413 VPD; R^2 = 0.46	Ödemiş and Baştuğ (1999)
Tc-Ta = 3.8768 -2.3989 VPD; R^2 = 0.75	Kırnak et al. (2005)
Tc-Ta = 0.51-1.44647 VPD; R^2= 0.81	Usman et al. (2009)
Tc-Ta =1.56-1.7543VPD; R^2 = 0.5327	Our study

dry land and in severe water stress plants, respectively.

Any irrigation effect on fiber resistance was too inconsistent to be definitively assessed. Micronaire was increased by 4% when compared with fibers of the dry land or severe water plants. Lint properties of cotton response to irrigation varied depending on genotype, irrigation management and climatic conditions. This research showed that some lint properties such as fiber length, fiber uniformity and micronaire were reduced when soil moisture deficits got large enough, which is similar to the findings of other researchers (Guinn and Mauney, 1984; Gerik et al., 1996; Saranga et al., 1998; Pettigrev, 2004). The fact that some of the lint components did not respond to irrigation like the results reported by Önder et al. (2009) and Kimball and Manuney (1993), is probably because of the differences in the genotype utilized and in the degree of the moisture deficit stress that was developed in this study.

Seasonal water stress evaluations

The unstressed baseline (non-water stress baseline, LL) for cotton was developed using leaf and air temperatures (T_c and T_a) and vapor pressure deficit (VPD) during 2005 to 2007 cropping seasons. The lower baseline was determined as T_c-T_a=1.56-1.7543VPD with R^2=0.5327; n=55 ($p \leq 0.01$) (Figure 2). This equation was valid from 3.3 to 1.8 kPa for the range of VPD and 27.4 to 31.7°C for the range of T_c. The lower baseline equation in this study differed from other results for cotton obtained by some researchers (Table 5). The slope of this equation was more or less similar to those reported by Pinter and Reginato (1982) and Usman et al. (2009), for cotton at Arizona and Faisalabad; but it was lower than the results reported by Kırnak et al. (2005) at Şanlıurfa where dry and hot climate prevails and higher than the result taken by Ödemiş and Baştuğ (1999) at Antalya, which has cooler climate. The computed baseline intercept was within the range of the previous baselines. Intercept in the equation was smaller than those given by Pinter and Reginato (1982) and Kırnak et al. (2005). The smaller intercept was probably due to the cooler environment in Adana than in Arizona and Şanlıurfa. Differences between the equations could have been as a result from several factors which affect the baseline relationship as stated by Yazar et al. (1999) and Erdem et al. (2006). These factors are relative humidity, IRT calibration, IRT aiming or field of view and microclimate factors (like clouds or wind).

The upper limit that was determined for the fully-stressed treatment and T_c-T_a was obtained as 3.2°C for all the growing seasons. T_c-T_a value in this study differed somewhat from those given for cotton from other studies. For example Pinter et al. (1983) found the upper limit as 2.9°C for Arizona, Reginato (1983) reported 3.1°C, Howell et al. (1984) stated that, T_c-T_a values vary from 3 to 4°C depending on cross section between upper and lower baselines and air temperature. Usman et al. (2009) stated the upper base line as 2.0°C for Faisalabad, Iran. In Turkey, T_c-T_a values were given as 3.9°C for Antalya (Ödemiş and Baştuğ, 1999) and 4.59°C for Şanlıurfa (Kırnak et al., 2005).

The seasonal variations of the crop water stress index values of cotton under different stressed conditions are shown in Figure 3. In general, CWSI in the treatment of DI_{50} was greater than that in the I_{100}, as a result of the higher leaf temperature which was caused by water stress level in the growing seasons. The minimum value of the CWSI occurred in I_{100} during the beginning of the growing seasons averagely on DOY 180 to DOY 200 for years 2006 and 2007 and their average values were -.20 and -0.37, respectively. In 2005, minimum values of CWSI were also obtained from treatment I_{100} with 0.06, in the year; CWSI values in the I_{100} treatment changed around the zero line. The maximum values of CWSI were calculated as about 0.6 for 2005 on DOY 199; 0.87 on DOY 226 for 2006 and 0.91 on DOY 219 for 2007. All the maximum values occurred over the DI_{50}. CWSI values in all the treatments followed cyclical patterns which were harmonious with the irrigation events. After irrigations, the CWSI values decreased and then increased again depending on the soil water content between irrigation intervals. The rate of increase in CWSI between irrigations, as explained by Pinter and Reginato (1982), is directly related to the evaporative demand of the atmosphere and the physical size of plants and inversely related to the availability of water stored in the soil. In the last two trial years when small K_{cp} value of 0.75 was used for calculating irrigation water, negative CWSI values were obtained on all the treatments after some irrigation at the beginning of the growing season. The negative CWSI values did not occur after DOY 200 and DOY 195 in 2006 and 2007, respectively. In 2005, CWSI values were higher in all treatments than those in other years, which could be associated with the fairly wet soil profile caused by more water application due to the higher K_{cp} value used and inadequate developing root system which did not permit high plant uptake rates to meet the large atmospheric evaporative demand. As Idso et al. (1982) and Barbosa da Silva and Ramana Rao (2005) reported for cotton in Arizona and semi-arid region of Northeast Brazil, respectively and Yazar et al. (1999) for maize in Bushland, Texas demonstrated that the ability of crop to meet the atmospheric demand at a certain VPD or potential transpiration will depend on the extractable soil water in the root zone. The occurrence of negative values of CWSI has been presented in many other studies (Wanjura et al., 1984; Jalali-Farahani et al., 1993). The CWSI values ranged from very low values to relatively high values, particularly in hot weather with strong wind speed conditions and even when soil profile was relatively wet. The maximum and minimum values of CWSI were different according to treatments and years. The average maximum and minimum values were obtained as -0.49 to 0.38 for I_{100},-0.47 to 0.66 for DI_{70} and -0.38 to 0.79 for DI_{50}. Trends in CWSI values showed the high consistency with water and stress levels; the ID_{50} treatment which had the lowest water level had the highest stress level and I_{100} treatment which had the highest water level, had the lowest stress. Soil water contents in the treatments (Figure 1) were consistent with the CWSI values (Figure 3). For example, the lowest irrigation level (DI_{50}) had the largest soil depletion level and the highest CWSI values, whereas the higher irrigation level (I_{100}) had the smallest water depletion level and smallest CWSI values. In all the treatments, CWSI values increased toward the end of the growing seasons due to the decreased soil water content in the root zone (Figure 1).

Some parameters of cotton such as seasonal irrigation water, water use (evapotranspiration), leaf water potential and water use efficiencies in relation to average CWSI values are shown in Figure 4. In this study, it was found that there were close relationships between mean CWSI and the applied irrigation water, water use, water use efficiency and leaf water potential. Although, relationship obtained in this study between mean CWSI values and irrigation water was defined as second degree polynomial equation, others were determined as linear functions. Howell et al. (1984), Wanjura et al. (1990) and Cohen et al. (2005) reported similar results for the relationships between different irrigation parameters and mean CWSI of cotton. CWSI increased the irrigation water use efficiency in drip irrigated cotton, but total water use efficiency (WUE_ET) was affected by CWSI values. Generally, good correlation between CWSI and LWP was obtained. They were inversely related and therefore, as CWSI increased, the water content in leaf decreased. This result suggests that, leaf water potential data can be quickly obtained by canopy temperature measurements and this result agrees with that of Pinter and Reginato (1982) and Cohen et al. (2005) who found close correlation

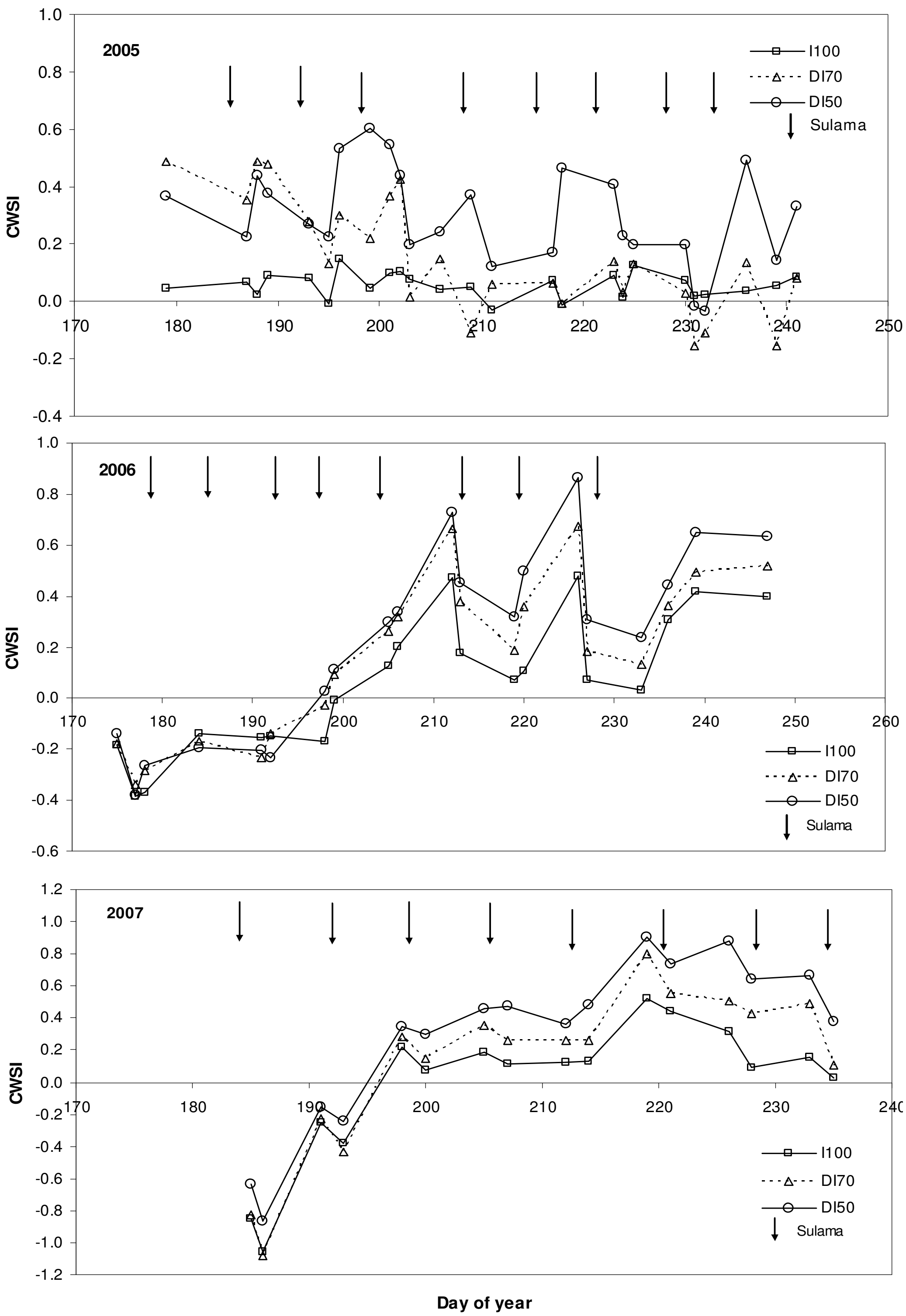

Figure 3. Seasonal variation of crop water stress index values (CWSI) of cotton crop during the trial years. Arrows along upper axis represent irrigation events.

between observed leaf water potential and predicted leaf water potential which was calculated from canopy temperature.

Seed cotton yield, dry matter and other yield components such as number of boll per plant, plant height and harvest index data in relation to the seasonal mean CWSI values are shown in Figure 5. The relationships between these considered parameters and mean CWSI

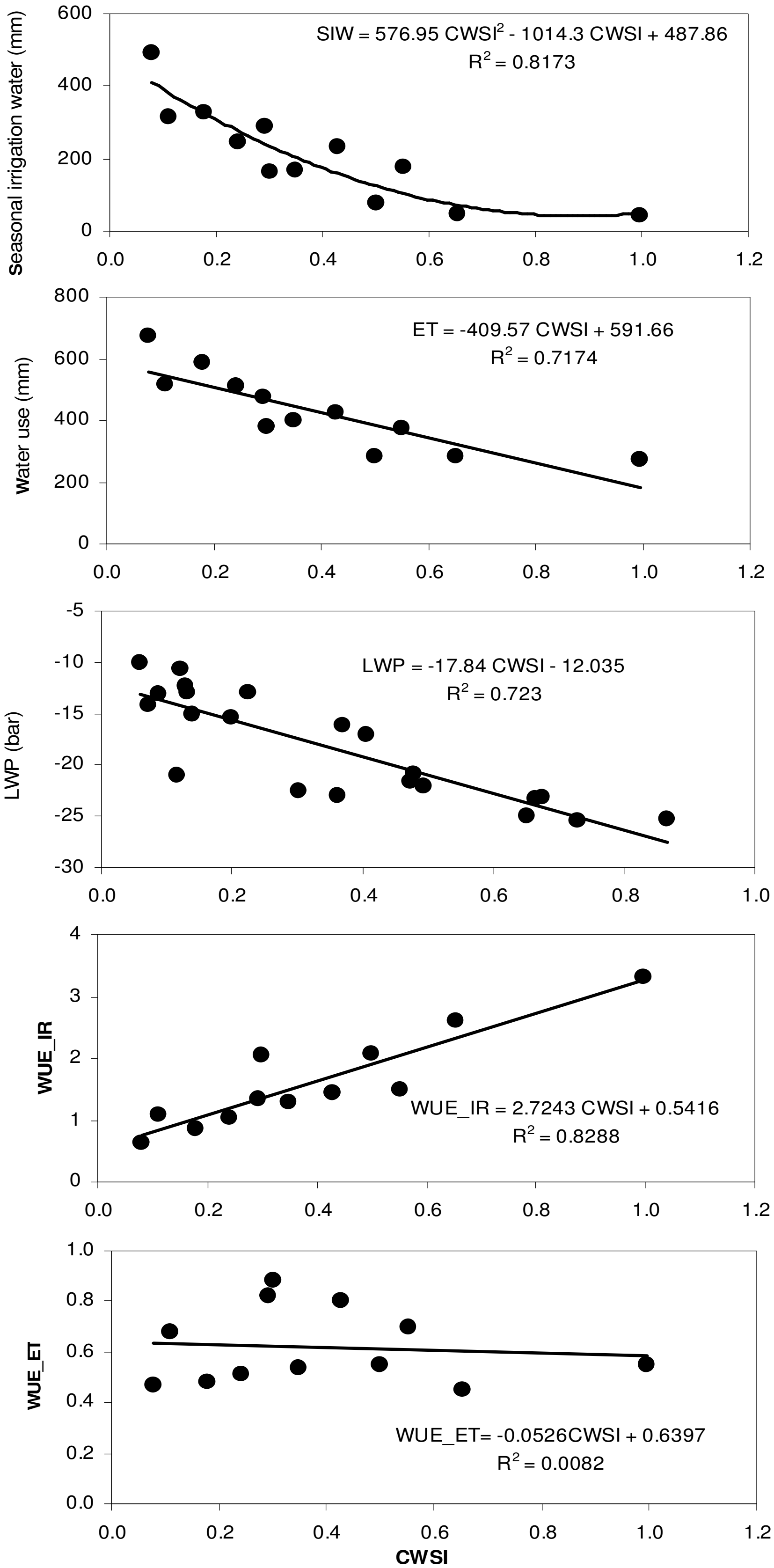

Figure 4. Relationships between applied irrigation water, water use, leaf water potential (LWP), water use efficiencies and seasonal mean CWSI for cotton.

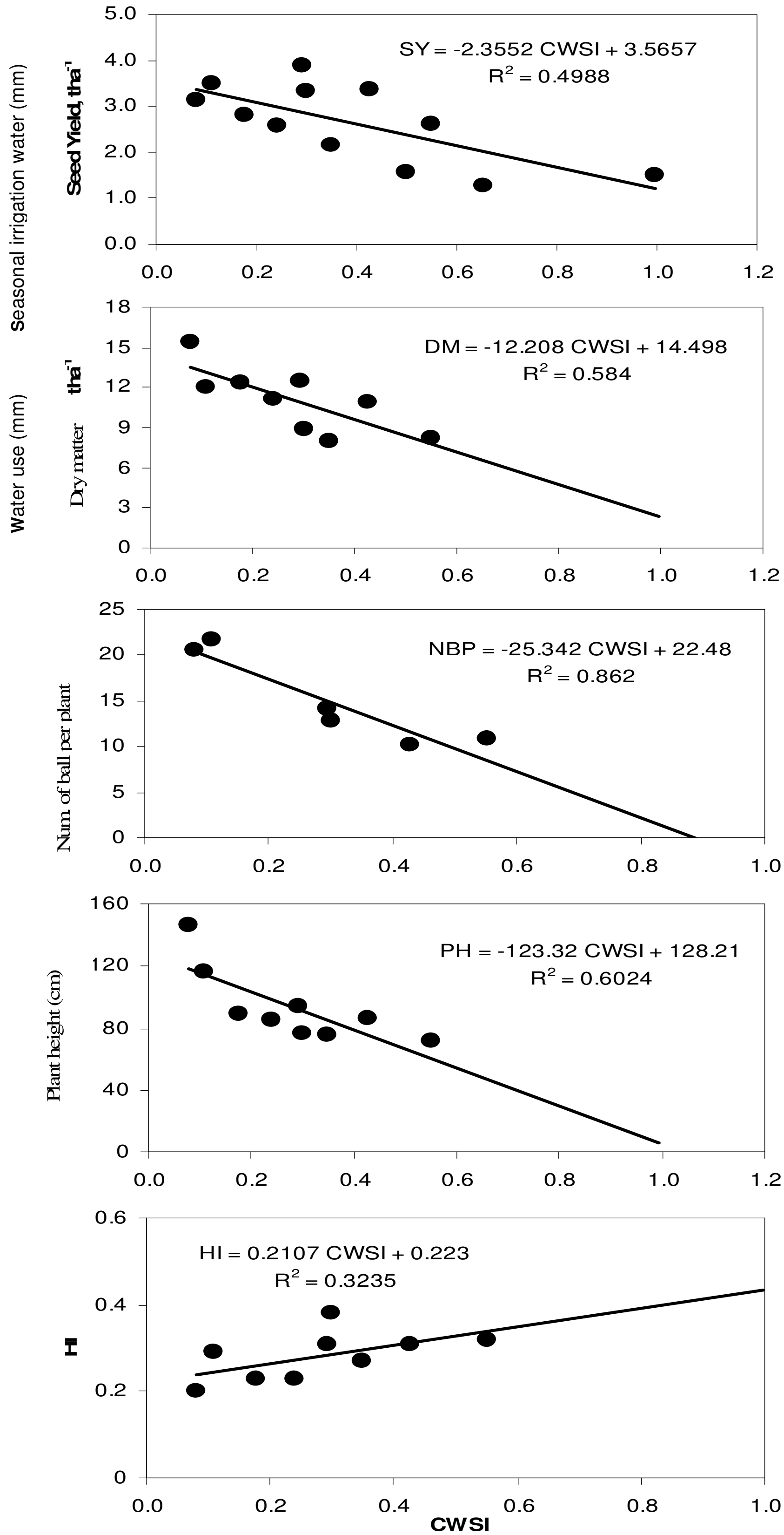

Figure 5. Relationships between seed cotton yield, dry matter and some other yield components and seasonal mean CWSI for cotton.

values were significant and linear; which were acceptable within the range of CWSI values of this study. Note that, the correlation between CWSI and harvest index was not highly significant. It is interesting that the yield components of plant height and number of boll per plant had higher correlation coefficients with CWSI values. This may be due to errors made during the measurement of canopy temperature which include the influence of varying amount of soil viewed by the IR thermometer early in the season when the plants were small and also later in the season when lodging opened part of the canopy. Because of the importance of application of CWSI approach, the equation on the seed cotton yield and mean CWSI relationship was obtained as SY = -2.3552 CWSI + 3.5657 (R^2 = 0.499, P ≤ 0.01) which can be used for yield prediction. These results are in agreement with that of Reginato (1983), Howel et al. (1984), Fangmeir et al. (1989), Wanjura et al. (1990), Ödemiş and Baştuğ (1999), Kırnak et al., (2005) and Usman et al. (2009), who reported linear relationships between seed cotton yield and some yield components and seasonal mean CWSI.

From Table 4 and Figure 5, it can be seen that seed cotton yield and dry matter began to decrease to a significant extent when a mean CWSI value of 0.36 was reached. This CWSI value matched treatment DI_{70}. The average yields for the irrigated treatments were not statistically different for a CWSI range from 0.08 (I_{100}) to 0.30 (DI_{50}) in 2005; whereas in the other two years, there were statistical differences between the mean yields of the treatments (Table 4). The first significant decrease of yield was met when mean CWSI value was 0.38 (ID_{70}) in 2006 and 0.34 (DI_{70}) in 2007. This shows that a critical CWSI value may occur near 0.38 to 0.34 averaging 0.36 when cotton yield will begin to decrease with greater soil water deficit. There are different results taken from different regions which were reported by scientists about threshold values of CWSI of irrigated cotton. For example, Howell et al. (1984) showed that irrigation should be applied when the CWSI value for cotton is in the range of 0.30 and 0.50. Similar result was indicated by Barbosa da Silva and Ramana Rao (2005). They suggested that, cotton crop should be irrigated when CWSI approaches 0.3 despite the difficulties of its determination under their particular climate and soil conditions. Ödemiş and Baştuğ (1999) and Usman et al. (2009) also reported that, cotton plant should be irrigated when CWSI was 0.45 for Antalya, Turkey and 0.40 for Faisalabad, Iran, respectively. As stated by Yazar et al. (1999), the CWSI is a good indicator of plant response to available soil water level, but it does not indicate the amount of water required to recover from water stress. Some predictable difficulties which are caused by locality and weather limitations and irrigation scheduling mistakes, limited the ability of CWSI usage as a guide for programming irrigation events.

Conclusions

The data from this experiment revealed that, the canopy temperature of cotton under different irrigation programs can be used to determine CWSI values. Lower and upper baselines were determined from measurements of T_c-T_a and VPD values and the CWSI was calculated for each irrigation treatment. Plant canopy temperature, air temperature and atmospheric vapor pressure deficit had much influence on water use and irrigation requirement of crops. Therefore, CWSI was proved to be a promising tool for irrigation scheduling of cotton. The seasonal CWSI values for each irrigation treatment were calculated as the average for the entire season. The trends in CWSI values were consistent with the soil water content for different treatments. The seasonal mean CWSI values were related with the seed cotton yield and dry matter. Plant height and number of boll per plant also produced close relationships with mean CWSI. These yield components were most affected by water deficit. Results showed that, seed cotton yield declined as CWSI increased. Contrary to this, irrigation water use efficiency for drip irrigated cotton was affected by CWSI values. However, total water use efficiency was not affected by water deficit. The seed cotton yield with mean CWSI relationship can be described by equation SY = -2.3552 CWSI + 3.5657 and can be used for yield prediction. The results suggest that, the minimal yield reductions for this particular climate and soil conditions, were obtained at a threshold CWSI value of 0.36 or less for cotton. However, further studies are needed for determining the timing of the irrigations. The critical value of CWSI that a farmer can use to determine when to irrigate cotton in semi-arid climate should be tested with long term experiments.

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