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Research Article

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Crop Water Stress Index (CWSI) for Yield Prediction of Cotton (*Gossypium hirsutum L. Cv. N-84*) in a Semiarid Climate

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Abstract This study was carried out to determine crop water stress index (CWSI) to predict cotton yield under Aegean semiarid cropping conditions. The effects of five different irrigation levels (100, 70, 50, 30 and 0 % replenishment of soil water depleted from the 1.20 m soil profile depth) on cotton yields and the resulting CWSI were investigated. The highest yield and total water use were obtained under fully irrigated cotton plots (100 % replenishment of soil water depleted). The yield, water use and water use efficiency of fully irrigated cotton were 5640 kg/ha, 882 mm, and 6.3 kg/ha/mm, respectively. The CWSI was calculated from measurements of canopy (Tc) and ambient air (Ta) temperatures and vapor pressure deficit (VPD) values for five irrigation levels. The CWSI values increased with increased soil water deficit and cotton yields decreased with increasing CWSI values. An average CWSI of 0.26 before irrigation time provided highest cotton yield. The yield was directly correlated with seasonal mean CWSI values and the second order polynomial equation "$Y = 33586CWSI^2 - 36836CWSI + 11150$"can be used to predict the yield potential of cotton under the semiarid climate.

Keywords water use, furrow irrigation, lower baseline, *Gossypium hirsutum*

1. Introduction

Cotton (*Gossypium hirsutum L. cv. N-84*) grown mostly under irrigated conditions is a major commercial crop in the Aegean semiarid region of Turkey. Almost no cotton production areas of Turkey has enough rainfall. So, irrigation is necessary during the growing season to maintain and enhance crop growth and yield [1]. Under these conditions farmers have to understand the water-yield relationship of cotton and how to choose the most water efficient methods of irrigation scheduling [1, 2, 3, 4].

Irrigation management is generally based on the estimation or measurement of evapotranspiration by measuring soil water content in the effective root zone or measuring some meteorological parameters. However, irrigation scheduling based on crop water status should be more advantageous since crops respond to both the soil and aerial environment [5]. Plant stress measurement with hand-held infrared thermometers (IRT) has become increasingly popular after 1980. This technique is based on the fact that transpiration cools the leaf surface. As water becomes limiting, stomal conductance and transpiration decrease and leaf temperature increase [6]. [7] determined an empirical approach for quantifying plant stress by determining "non-water stressed baselines" for crops. Under field conditions, they developed linear relationships for canopy-air temperature difference (Tc-Ta) versus vapor pressure deficit (VPD) of the atmosphere for a crop transpiring at its potential rate. This line, (Tc-Ta) versus VPD, represents the measured temperature difference when the crop is fully irrigated (no stress). The upper limit (Tc-Ta) represents the temperature difference occurring when the crop transpiration rate approaches zero (maximum stress) [6].

A range of studies have reported on the determination of CWSI for different crops. [8] suggested that baselines are strongly location dependent and perhaps species and variety dependent. [9] developed non-water stressed baselines for various crops including cotton. [10] obtained the highest yield in the fully irrigated treatment with an average CWSI value of about 0.13 for cotton. [11] showed that the CWSI values could be used to determine irrigation scheduling and that irrigation should be applied when the CWSI was about 0.45 for cotton in the Mediterranean conditions of Turkey. [12] determined that irrigation should be applied when the CWSI for cotton is in the range 0.30-0.50. [13] stated that the average CWSI values of cotton and grain sorghum grown under varying soil water regimes were negatively correlated with yield.

Productivity response to water stress is different for each crop and this response is expected to vary with climate. Therefore, the critical values of CWSI should be determined for a particular crop in different climates and soils for use in yield prediction and irrigation scheduling. The purpose of this study was to develop a baseline equation that can be used to calculate CWSI for monitoring water status and yield prediction of cotton under Aegean semiarid conditions of Turkey.

2. Materials and Methods

The experiment was conducted at the Agricultural Research Station of Adnan Menderes University, Aydın-Turkey, at 37° 51’ N latitude, 27° 51’ E longitude and 56 m altitude during the 2003 growing season. The climate in this region is classified as semiarid and the averages of annual temperature, relative humidity, wind speed, sunshine duration per day and total annual precipitation are 17.5 C^0, 63 %, 1.6 m/s, 7.6 h and 657 mm, respectively [14]. Additionally, some of the climatic factors of the 2003 growing season are summarized in Table 1.

Table 1: Some climatic data of region for the experimental year

Month	**Average temperature (ºC)**	**Average relative humidity (%)**	**Average wind speed (m s^{-1})**	**Average sunshine duration (h)**	**Rainfall (mm)**
May	22.7	62.4	1.4	9.4	35.3
June	27.6	51.5	1.6	11.0	6.7
July	29.1	53.2	1.5	11.3	12.6
August	28.7	62.5	1.5	10.9	4.2
September	23.4	66.1	1.6	9.2	-

The soil texture in the plot area was loam and sandy loam and the available water holding capacity within 1.20 m of the soil is about 0.281 m. Some physical characteristics of the soil at the experimental site, such as field capacity (FC), wilting point (WT) and available water holding capacity, are presented in Table 2.

Table 2: Some physical characteristics of soils at the experimental site

Soil depth (cm)	**Soil texture**	**Bulk density (g/cm^3)**	**Field capacity (%)***	**Wilting point (%)***	**Available water holding capacity (mm)**
0-30	Loam	1.45	25.8	9.7	70.0
30-60	Sandy-loam	1.50	20.3	7.2	59.0
60-90	Loam	1.46	25.6	8.7	74.5
90-120	Loam	1.42	27.6	9.4	77.5
0-120					281.0

*on dry weight basis

Cotton (*Gossypium hirsutum L. cv. N-84*) was planted on 6 May 2003. Fertilizer applications were based on soil analysis recommendations. A compound fertilizer of (15-15-15 NPK) was applied at rate of 60 kg/ha pure N, P and K at the planting. The required remaining portion of nitrogen was applied to all treatment plots (82 kg/ha Ammonium nitrate 33 %) before the first irrigation.

The plots were arranged in a complete randomized block design with three replications. Each plot was 8 m by 4.2 m (6 rows, 0.7 m row spacing, 0.25 m inter plant spacing). There were 3.0 m space between each plot in order to minimize water movement among treatments. Five irrigation treatments, differing in irrigation rate were evaluated. Irrigation was applied when approximately 50% of the available soil moisture was consumed in the root zone of the control treatment (S_1). The measured soil moisture level at the S_1 treatment was used to initiate irrigation during the growing season. In treatments S_2, S_3, S_4 and S_5, irrigation was applied at the rates of 70, 50, 30 and 0 % of S_1 on the same day, respectively. Closed-end furrow irrigation method was used in all treatments and a flow meter was used to measure the amount of water applied. The soil water level was measured at 9:00 am daily in the control treatment (S_1) and, if necessary, the plots were irrigated.

A neutron probe method (CPN, 503 DR Hydroprobe, Campbell Pacific Nuclear International, Martinez, CA) was used to measure daily soil moisture level at depths of 0.60 to 1.20 m throughout the whole growing season. The soil moisture content in the fist 30 cm layer was measured by the gravimetric method since it was not possible to monitor it with the neutron probe method [15]. The water use (evapotranspiration) was calculated applying the water balance method to the upper 1.20 m soil layer. Evapotranspiration (ET) was calculated using the soil water balance method [16];

$$ET = P + I - D \pm \Delta W$$

where P is the rainfall (mm), I is the irrigation applied to individual plots (mm), D is the deep percolation and ΔW is variation in water content of the soil profile (mm). Since the amount of irrigation water was only sufficient to bring the water deficit to field capacity, deep percolation was neglected.

Canopy temperatures (Tc) were measured using a hand-held infrared thermometer (IRT), (Rayнger ST60 model Raytek Corporation, Santa Cruz, CA). The instrument has a field of view of 3^0 and a 7.0 to 18 μm spectral band-pass filter. The infrared thermometer was operated with the emissivity adjustment set at 0.98. Canopy temperature (Tc) measurements were taken at each plot when the percentage of plant cover was approximately 80-85 %. Canopy temperature was measured on four plants from four directions per plot and then averaged. For each measurements the IRT was held above the plant (0.50 m) at an angle of $20\text{-}30^0$ below the horizontal so that soil background would not influence measurements.

The Tc, dry and wet bulb temperature measurements were made from 11:00 to 14:00 at hourly intervals under clear skies. Dry and wet bulb temperatures were measured with an aspirated pyschrometer at a height of 2.0 m in the open area adjacent to the experimental plots. The mean vapor pressure deficit (VPD) was computed using the corresponding instantaneous wet and dry bulb temperatures and the standard pyschrometer equation [17] using a mean barometric pressure of 101.7 kPa.

The CWSI was calculated using the method developed by [7] as described below:

$$CWSI= [(Tc-Ta)-LL] / (UL-LL)$$

where LL represents the non-water stressed baseline (lower baseline) and UL represents the non-transpiring upper baseline, Tc (^oC) and Ta (^oC) represent canopy and air temperature, respectively.

From the above equation, the non-stressed baselines for canopy-air temperature difference (Tc-Ta) versus VPD relationship were determined using data collected from the control (100 %) treatment (S_1) a day after irrigation. The upper (fully stressed) baseline was determined based on the procedures suggested by [7]. To obtain the upper baseline, the canopy temperatures of the fully stressed crops (in S_5 treatment) were measured several times during the growing season.

Cotton yield was determined by hand harvesting the four adjacent center rows in each plot. The data were analyzed by analysis of variance. The differences among treatments were evaluated using an F test in of yield and the means were compared using Duncan’s Multiple Test procedure.

3. Results and Discussion

The total number of irrigations, total amount of irrigation water and the total water use for each treatment are given in Table 3.

Table 3: Total number of irrigations, soil water depletion, total amount of irrigation water and total water use in growing season

Treatments*	**Number of irrigations**	**Soil water depletion (mm)**	**Irrigation water applied (mm)**	**Total water use (mm)**
S_1	5	182	700	882
S_2	5	216	490	706
S_3	5	232	350	582
S_4	5	239	210	449
S_5	-	272	-	272

* Treatments $S_{1,}$ $S_{2,}$ S_3 and S_4 were irrigated on 08 July, 17 July, 28 July, 08 August and 22 August. Treatment S_5 was not irrigated during the growing season.

The seasonal water use of the S_1 treatment was the highest for the growing season suggesting that the water applied was enough to meet the full crop water requirements. Therefore, the S_1 treatment was used to determine the lower (non-stressed) CWSI baseline. The lowest water use occurred in treatment S_5 since there was no irrigation water applied and the highest water deficit in the crop root zone. The S_5 treatment was used, therefore, to determine the upper (fully-stressed) baseline.

The Tc measurements with the IRT were initiated on DOY 189 (8 July) and ended on DOY 233 (22 August). During the growing season, the upper and lower baselines as outlined by [7]. were determined using data taken from the S_1 and S_5 treatments using linear regression of the differences between Tc and Ta against VPD (Fig. 1).

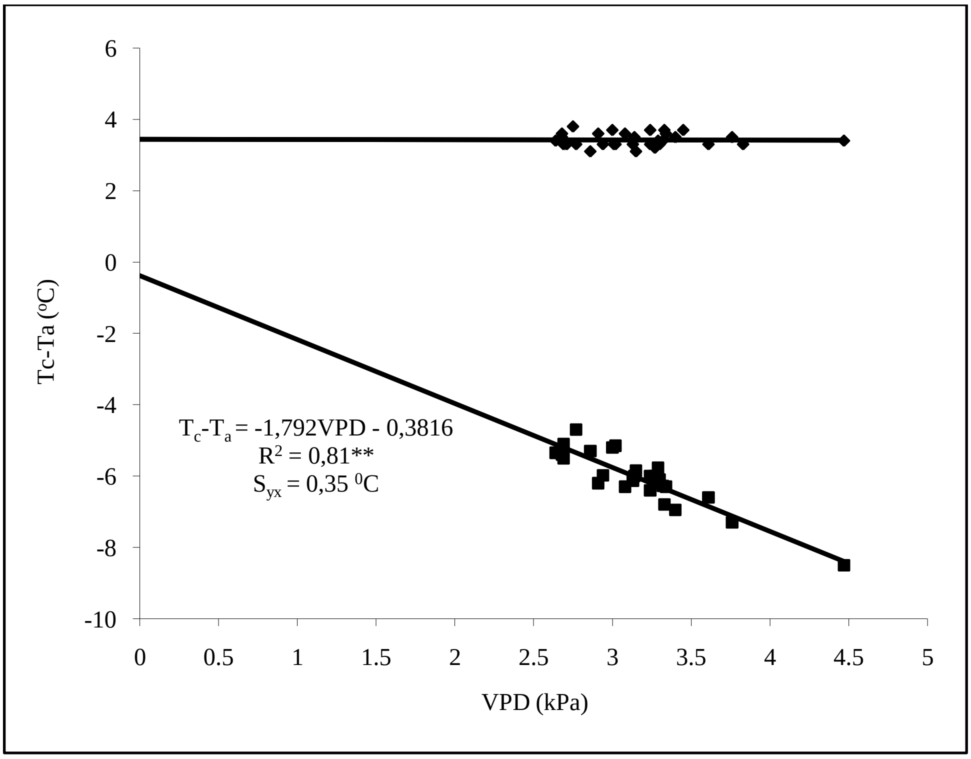

Figure 1: Canopy-air temperature differential (Tc-Ta) versus air VPD for upper non-transpiring baseline and the lower non-water stressed baseline for cotton

The resulting baseline was described by the linear equation;

$$Tc\text{-}Ta = -1.79VPD-0.38 \ (r^2 = 0.81, p<0.01, S_{yx}= 0.35)$$

where Tc-Ta is in °C and VPD is in kPa. This equation differs somewhat from that obtained for cotton in studies. For example; [18] found the equation Tc-Ta = 2.00-2.40 VPD, [6] obtained the equation Tc-Ta =2.0-2.24 VPD, [12] determined the lower limit equation of Tc-Ta= 2.08-1.8 VPD and [19] found Tc-Ta = 2.0-1.92 VPD for cotton in Temple, Texas. On the other hand, [11] determined the lower limit equation of Tc-Ta= 0.257-0.413VPD under Mediterranean conditions. Several factors such as the climate, soil type, IRT calibration and specific cotton variety may have caused differences in the intercept and the slope of the baseline of this study.

The average value of (Tc-Ta) for the upper baseline (fully-stress plants of the treatment S_5) of 3.4 ^{0}C was obtained for the growing season. Our computed upper limits (3.4 ^{o}C) was comparable to previous upper baseline limits for cotton. For example; [6] found the upper limit value as 3.1 ^{o}C in Phoenix, Arizona conditions, and [12] stated that the upper limit range was between 3-4 ^{o}C and that value depended on the intercept of the lower baseline and the air temperature of the region.

The seasonal course of CWSI values for the irrigation treatments ($S_{1,}$ $S_{2,}$ $S_{3,}$ S_4 and S_5) is shown in Figure 2. In this figure, the arrows indicate the days of irrigation. The CWSI values in irrigated plots generally dropped following each irrigation application, then increased steadily to a maximum value just prior to the next irrigation application as the soil water in the crop root zone was depleted. The CWSI values (Fig. 2) ranged from 0 to a maximum value of 0.30 in S_1 treatment, 0.03 and 0.45 in S_2 treatment, 0.05 and 0.47 in S_3 treatment, 0.07 and 0.49 in S_4 treatment and 0.42 and 0.88 in S_5 treatment.

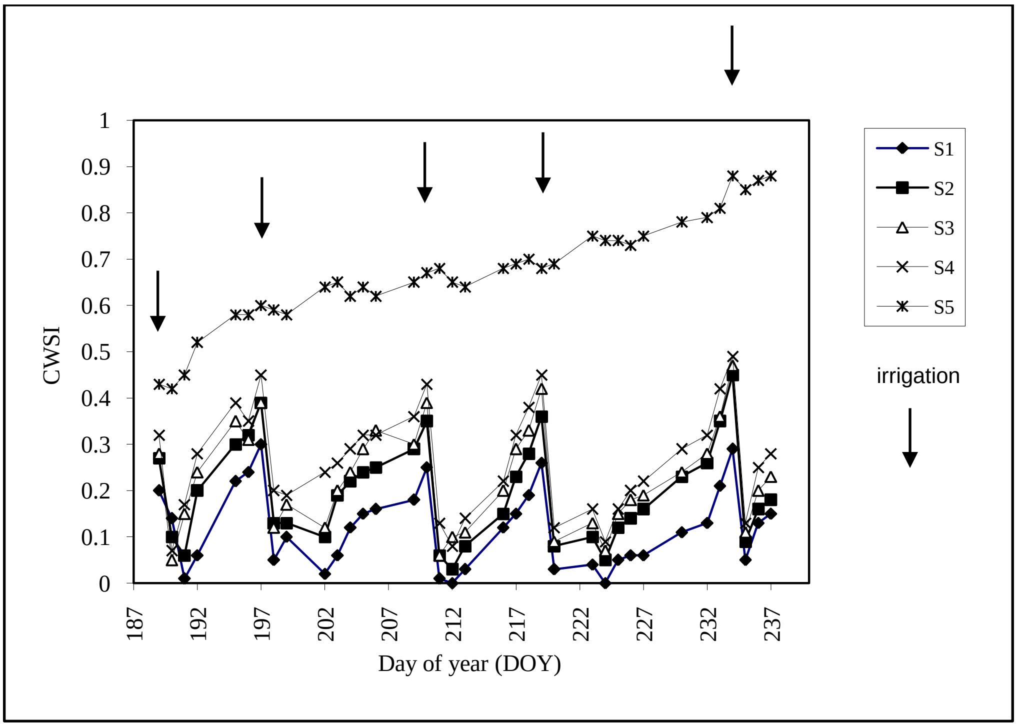

Figure 2: The seasonal variation of crop water stress index (CWSI) for each treatment

The mean CWSI values obtained before irrigation times for each treatment ranged from 0.26 to 0.65 (Table 4).

Table 4: Cotton yields, total water applied, water use and mean CWSI values of growing season

Treatments	Irrigation water applied (mm)	Water use (mm)	Cotton yield (kg/ha)	Water use efficiency (kg/ha/mm)	Seasonal mean CWSI	Mean CWSI before irrigation
S_1	700	882	5640 a*	6.39	0.18	0.26
S_2	490	706	4460 b	6.31	0.23	0.36
S_3	350	582	3720 c	6.39	0.26	0.39
S_4	210	449	3210 d	7.15	0.30	0.43
S_5	-	272	1820 e	6.69	0.70	-

* Numbers followed by different letters indicate statistically significant differences at the 1 % level (Duncan' s multiple range test).

The highest yield was in the S_1 treatment which had a mean before irrigation CWSI of 0.26. [20] stated that cotton, corn, and wheat crops are tolerant of CWSI rise of 0.20 to 0.30 between irrigations without significant yield reductions. For the maximum stressed (non irrigated) plot, $S_{5,}$ the CWSI values approached to 0.88 and stayed near this value. The variations in soil water content are graphed in Figure 3.

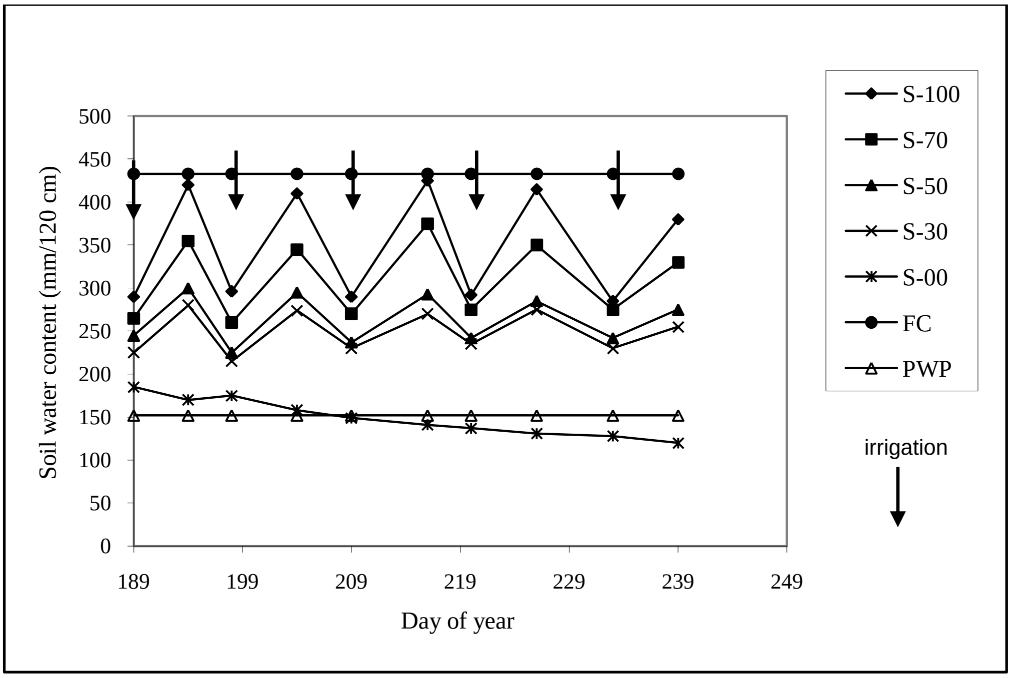

Figure 3: Measured soil water content for each treatment

The soil water content was consistent with the CWSI values in that the lowest irrigation level (non–irrigation treatment) had the largest soil water depletion levels and CWSI values, while higher irrigation levels had the smallest soil water depletion levels and CWSI values.

Cotton yields (Y, kg/ha) were significantly different among treatments (Table 4) and yields were significantly increased ($p<0.01$) by the irrigation level (IR, mm). This relationship was described by the linear equation Y = 5.3202 IR + 1907.9 ($r^2 = 0.99$, $p<0.01$ $S_{yx}= 11.2$ kg/ha).

The seasonal mean CWSI values were related to cotton yield in Figure 4 by a curvilinear solution. Our results showed that cotton yield decreases as the CWSI increases.

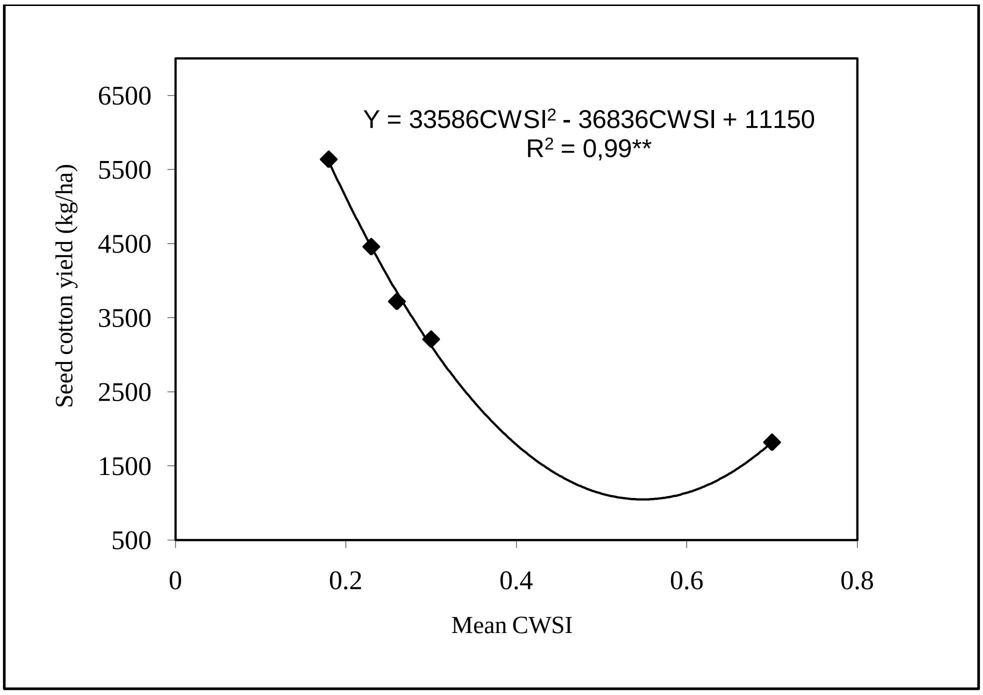

Figure 4: Seed cotton yield (Y, kg/ha) as related to seasonal mean CWSI

This relationship can be described by the equation $Y = 33586CWSI^2 - 36836CWSI + 11150$ ($r^2 = 0.99$, $p<0.01$). The seasonal mean CWSI for treatment S_1 was 0.18 (Table 3) and this treatment resulted in the highest yield.

This result indicated that permitting the seasonal mean CWSI values to exceed this value would result in a decreased seed cotton yield. [6, 10, 11, 12] found linear relationships between yield and seasonal mean CWSI for cotton while, a second order polynomial relationship was found by [13].

4. Conclusion

A field experiment was conducted to relate CWSI values to the amount of irrigation water applied and to the yield of cotton. The CWSI technique offers important advantages for quantifying plant stress between irrigations. The upper (water-stressed) and lower (non-water stressed) baselines and CWSI values were calculated to quantify and monitor crop water stress for cotton in the Aegean semiarid climate. The seasonal mean CWSI was related to seed cotton yield (Y, kg/ha) with yield decreasing as CWSI increased. The curvilinear equation $Y = 33586CWSI^2 - 36836CWSI + 11150$ used to predict the yield response to crop water stress is important in developing strategies and in decision-making by farmers, their advisors, and researchers for irrigation management under water limited conditions. This information can also be an important component of irrigation management models. Based on our study results, the mean CWSI value before applying irrigation that was associated with the highest seed cotton yield was 0.26. However, it can not be concluded that this CWSI value should be used for timing of irrigations for cotton since we did not test irrigation scheduling using CWSI. Further studies are needed to reach such a conclusion. The critical value of CWSI at which a farmer can use to determine when to irrigate cotton in Aegean semiarid climate should be tested with long term experiments.

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