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Abstract: This study was designed to evaluate different threshold crop water stress index (CWSI) values to schedule irrigation for sunflower (*Helianthus annuus* L.) grown under furrow irrigation. Irrigations were started when CWSI values reached 0.2, 0.4, 0.6, 0.8 and 1.0 (non-irrigation). The CWSI values were computed from measurements of canopy temperature, air temperature and atmospheric vapor pressure deficit. Total irrigation water amounts of 679, 584, 470 and 227 mm were applied to the $T_{0.2}$, $T_{0.4}$, $T_{0.6}$ and $T_{0.8}$ treatments, respectively. The maximum seasonal evapotranspiration (ET), 809 mm was measured from the $T_{0.2}$ treatment. Irrigation levels significantly affected seed yield. Although the highest seed yield (4.38 t ha^{-1}) was obtained from the $T_{0.2}$ treatment, the $T_{0.4}$ and $T_{0.6}$ treatments were not significantly different from the $T_{0.2}$ treatment. Therefore, based on these results, a CWSI value of 0.6 can be used for the irrigation time of sunflower under Tekirdağ conditions.

Key Words: Crop water stress index (CWSI), infrared thermometer, furrow irrigation, evapotranspiration

Bitki Su Stresi İndeksi Değerlerinin Ayçiçeğinin Sulama Zamanı Planlanmasında Kullanımı

Özet: Bu çalışma, karık sulama yöntemi ile sulanan ayçiçeğinin sulama zamanının planlanmasında farklı bitki su stresi indeksi (CWSI) değerlerinin kullanım olanaklarının araştırılması amacıyla yürütülmüştür. Araştırmada, CWSI değerleri; yüzey sıcaklığı, hava sıcaklığı, buhar basıncı açığı dikkate alınarak hesaplanmış ve sulamalara bu değer, 0.2, 0.4, 0.6, 0.8 ve 1.0'a (susuz) ulaştığında başlanmıştır. Araştırma sonucunda, toplam uygulanan sulama suyu miktarları; $T_{0.2}$, $T_{0.4}$, $T_{0.6}$, $T_{0.8}$ ve deneme konuları için sırasıyla, 679, 584, 470 ve 227 mm olarak değişmiştir. Deneme konuları arasında maksimum bitki su tüketimi, 809 mm ile $T_{0.2}$ konusundan ölçülmüştür. Farklı sulama seviyeleri ayçiçeği dane verimini etkilemiştir. En yüksek dane verimi 4.38 t ha^{-1} ile $T_{0.2}$ deneme konusundan elde edilmesine rağmen, $T_{0.4}$ ve $T_{0.6}$ deneme konularıda istatistiksel olarak aynı grup içerisinde yer almıştır. Tüm sonuçlar değerlendirildiğinde, Tekirdağ koşullarında ayçiçeği sulamasında CWSI değeri 0.6'ya ulaştığında sulamaya başlanmasının daha uygun olacağı sonucu çıkmıştır.

Anahtar Sözcükler: Bitki su stres indeksi (CWSI), infrared termometre, karık sulama, bitki su tüketimi

Introduction

Sunflower (*Helianthus annuus* L.) is an important oilseed crop in Turkey and its production has greatly increased with the introduction of hybrids. Most of the production is in the Trakya region, with an estimated area of 320,000 ha. Mostly sunflower is grown without irrigation, but irrigation is sometimes used in sub-humid and semi-arid regions where precipitation is limited, as in the Trakya region. It is possible to increase production by well-scheduled irrigation programs.

Irrigation scheduling is commonly defined as determining when to irrigate and how much water to apply. Successful irrigation depends upon understanding and utilizing irrigation scheduling principles to develop suitable irrigation management. Irrigation scheduling helps farmers to develop their own strategies for their specific regions and conditions. Irrigation scheduling methods are based on 2 approaches: soil measurements, and crop monitoring. Methods based on plant measurements generally involve monitoring leaf water potential or canopy temperature (Hoffman et al., 1990).

Idso et al. (1981) developed empirical relationships for crop-air temperature difference in bright mid-day sunshine with soil water level sufficient to sustain energy-

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limited transpiration rates. Upper and lower limits (in bright sunshine) for crop-air temperature difference can be developed to quantify water stress. The upper limit $(T_c - T_a)_u$ represents the temperature difference occurring for severe stress when transpiration approaches zero (Jackson, 1982; Hatfield, 1990). The lower limit $(T_c - T_a)_l$ represents the temperature difference between the crop and the air when the crop is well watered. The lower limit has been found to depend on the vapor pressure deficit of the air. A crop water stress index (CWSI) varies from a value of zero for no water stress to a maximum value of one at severe stress (Hoffman et al., 1990).

Threshold CWSI values for irrigation timing are not well defined and further research is needed to define optimal CWSI values for irrigation timing (Hoffman et al., 1990). Nielsen and Gardner (1987), and Nielsen (1990) evaluated irrigation scheduling with different threshold CWSI values of corn and soybean, respectively. However, little research has been done to evaluate whether the CWSI can be used to schedule irrigation for different crops and locations. In earlier CWSI studies (Jackson, 1982; Stark and Wright, 1985; Fangmeir et al., 1989; Nielsen, 1990; Hutmacher et al., 1991; Ben-Asher et al., 1992; Stegman and Soderlund, 1992; Nielsen, 1994; Gençoğlan and Yazar, 1999; Ödemiş and Baştuğ, 1999; Yazar et al., 1999; Irmak et al., 2000; Alderfasi and Nielsen, 2001; Colaizzi et al., 2003; Orta et al., 2003; Yuan et al., 2004), baseline equations that can be used to calculate CWSI for monitoring water status and irrigation scheduling for various crops have been developed and correlations between computed mean CWSI values and the yield, water stress, water applied, stomatal resistance, leaf area index and the soil water content have been determined. All these researchers also reported that the CWSI values could be used to measure crop water status and to improve irrigation scheduling. Orta et al. (2002) also defined the non-water stressed baseline equation (T_c - T_a = -1.2069 VPD + 3.5945, Figure 1) and stressed baseline value (-1 °C) for sunflower in Tekirdağ conditions and they reported that, based on these results, an average CWSI of about 0.59 before irrigation will produce maximum yield. However, they suggest that this CWSI value should not be used unless irrigation scheduling using several threshold CWSI values for sunflower is tested.

The objectives of this study were to determine whether the CWSI can be used to schedule irrigations in

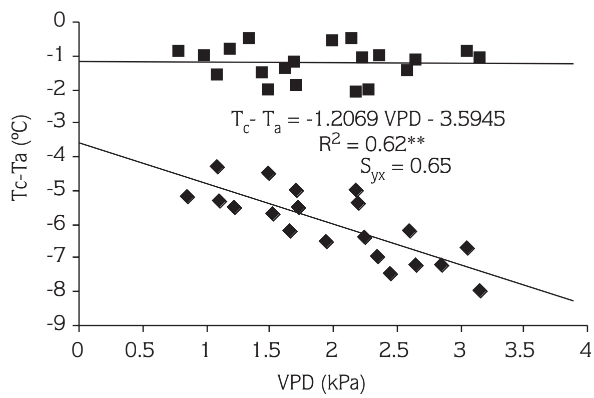

Figure 1. The upper and lower baselines for sunflower (Orta et al., 2002) (VPD: Vapor pressure deficit).

sunflower, to determine water application variations and seed yield with different threshold values of CWSI, to determine correlations between CWSI, available water in the active root zone and sunflower seed yield, and to evaluate water use and water use efficiency of sunflower in relation to the CWSI.

Materials and Methods

Growth conditions

The experiment was conducted during the summer of 2003 at the Viticultural Research Institute in Tekirdağ, Turkey (40º59´ N latitude, 27º29´ E longitude and 4 m altitude). The climate of this region is semi-arid with average annual precipitation of 575 mm and from April to October average precipitation is 180 mm. In addition, the averages of annual temperature, relative humidity, wind speed and sunshine duration per day are 13.8 °C, 76%, 3.1 m s^{-1} and 6.5 h, respectively (Meteoroloji Bülteni, 1974). Some climatic factors in 2003 during the growing season are listed in Table 1. The soil type in the plot area is clay–loam and is well drained. The gravimetric water content at the field capacity, wilting point and available water holding capacity of the soil are shown in Table 2. The electrical conductivity (EC) of the irrigation water is 0.42 dS m^{-1} and the sodium absorption ratio (SAR) is 2.7.

The Sunbro variety of sunflower was planted on May 2nd 1998 (DOY 122) in plots. Before planting, beds and furrows were formed with a disk bedder and trifluralin at a rate of 0.02 kg ha^{-1} was applied to control weeds. Fertilizer applications were based upon the soil test data

Table 1. Some climatic factors of the region in 2003 and the long term.

Month	Average temperature (°C)		Average relative humidity (%)		Average wind seed ($m\ s^{-1}$)		Average sunshine duration (h)	
	2003	Long term	2003	Long term	2003	Long term	2003	Long term
May	17.9	16.6	76	74	2	2.3	9.5	6.4
June	23	20.9	70	70	2.3	2.5	10.9	9.5
July	24.8	23.4	70	66	2.6	2.9	10.7	11.3
August	25.2	23.5	69	66	2.6	3.1	11	10.5
September	19.3	19.7	75	71	2.4	3.1	7.4	8.3

Table 2. Some physical characteristics of soil at the experimental site.

Soil depth (cm)	Bulk density ($g\ cm^{-3}$)	Field capacity (%)	Wilting point (%)	Available water holding capacity ($mm\ 30\ cm^{-1}$)
0-30	1.46	28.69	15.9	56
30-60	1.53	28.88	15.63	60.8
60-90	1.58	26.97	14.74	58
90-120	1.58	27.07	15.2	56.3
0-90				174.8
0-120				231.1

(Table 3) and a composed fertilizer including 50 kg ha^{-1} N and 50 kg ha^{-1} P_2O_5 was applied.

Experimental design

The experiment was designed as a randomized complete block design with 3 replications for each treatment. There were 50 plants (3.50 x 3.00 m) in each plot and plant spacing was 0.70 m between the rows and 0.30 m within each row. Irrigation water was applied by furrow irrigation and total water was measured with a flow meter. Soil moisture content in each plot was monitored by neutron probe (CPN, 503 DR Hydroprobe). To do this, aluminum access tubes were installed at 120 cm soil depth. The neutron probe was calibrated at the beginning of the growing season and the calibration equation was PV = 76.506 CR – 25.969, $R^2 = 0.85^{**}$ (PV: volumetric soil water content, CR: count ratio) (Evett et al., 1993). The amount of soil water in the 0.90 m depth was used to initiate irrigation; the values within the 1.20 m soil profile were used to obtain the evapotranspiration of the crop. Evapotranspiration for 10-day periods was calculated using the soil water balance equation (Heerman, 1985):

$$ET = R + I - Dp \pm \Delta W$$

where ET is the evapotranspiration (mm), R is the rainfall (mm), I is the depth of irrigation (mm), D is the depth of deep percolation (mm) and ΔW is the change in soil water storage in the measured soil depth. The 1.20 m soil depth

Table 3. Some chemical characteristics of soil at the experimental site.

Soil depth (cm)	Total salt (%)	pH	$CaCO_3$ (%)	P_2O_5 ($kg\ ha^{-1}$)	K_2O ($kg\ ha^{-1}$)	Organic matter (%)
0-20	0.071	7.8	2.82	64.9	820	1.87
20-40	0.077	7.8	3.35	47.4	515	1.24

was observed for determination of deep percolation while irrigation was applied to 0.90 m soil depth.

Leaf temperature measurements and CWSI calculations

In the experiment, there were 5 treatments and CWSI values were used to initiate irrigation. In the treatments $T_{0.2}$, $T_{0.4}$, $T_{0.6}$, $T_{0.8}$ and $T_{1.0}$, irrigation was approximately begun when CWSI values reached 0.2, 0.4, 0.6, 0.8 and 1.0 (non-irrigation), respectively, and ± 0.05 allowable error was also used. The CWSI values are only used for determining irrigation time, but how much irrigation water to apply is not calculated. For this reason, soil water contents for each treatment were observed for calculating irrigation water amount. When the CWSI value for each treatment reached the assigned CWSI value, soil water level was brought to field capacity at 0.90 m soil depth. The leaf temperature (T_c) was measured using a hand-held infrared thermometer (Raynger ST8 model, Raytek Corporation, Santa Cruz, CA, USA) with a 3° field view and equipped with a 7–18 μm spectral band-pass filter. The infrared thermometer was operated with the emissivity adjustment set at 0.95. The infrared thermometry (IRT) data collection was initiated on June 27th (DOY 178) when the plant completed vegetative growth and crop water stress treatments were observed. Before this date, irrigation was applied to irrigation treatments when approximately 50% of the available soil moisture was consumed in the 90 cm root zone. The leaf temperature was measured from 4 directions (east, west, north, south), 0.50 m away from the crop with oblique measurements at 20-30° from the horizon to minimize reflections coming from surface in the field of view and then the value were averaged. The T_c measurements were obtained from 11:00 to 14:00 at hourly intervals under clear skies. The dry and wet bulb temperatures were measured with an aspirated psychrometer at a height of 2.0 m in the open area adjacent to the experimental plots. The mean T_a was determined from the average of the dry-bulb temperature readings during the measurement period. The mean VPD was computed using the corresponding instantaneous wet and dry–bulb temperatures and the standard pyschrometer equation (Allen et al., 1998) using a mean barometric pressure of 101.25 kPa.

CWSI values were calculated using the procedures given by Idso et al. (1981). Using the upper and lower limit estimates, CWSI can be defined by the equation given below (Idso et al., 1981):

$$CWSI = \frac{[(T_c-T_a) - (T_c-T_a)_{ll}]}{[(T_c-T_a)_{ul} - (T_c-T_a)_{ll}]}$$

where T_c is the canopy temperature (°C), T_a is the air temperature (°C), ll is the non-water stressed baseline (lower baseline) and ul is the non-transpiring upper baseline. Orta et al. (2002) defined the baseline equations for sunflower in the same climatic and soil conditions as –1 °C upper limit and $T_c - T_a = -1.2069\ VPD – 3.5945$ ($R^2 = 0.62$, $S_{yx} = 0.65$ °C, $P < 0.01$, Figure 1) lower baseline equation, which were used for the determination of the CWSI for each treatment.

After physiological maturity, head samples for seed yield were harvested from 3 rows in each plot on September 8th 2003 (DOY 251). The seeds were separated from the heads, oven dried at 65 °C and adjusted to 9% moisture content (Unger, 1982). Treatment effects were analyzed using an F test in yield and the means were compared using Duncan's multiple range test (Yurtsever, 1982).

Water use efficiency (WUE) for each treatment was calculated as total yield divided by seasonal evapotranspiration (ET). Irrigation water use efficiency (IWUE) was determined as follows (Zhang et al., 1999):

$$IWUE = \frac{(Y_I-Y_{NI})}{I}$$

where Y_1 is the total yield of irrigation treatments (t ha^{-1}), Y_{NI} is the total yield of the non-irrigation treatment (t ha^{-1}) and I is the amount of irrigation water (mm).

Results and Discussion

The irrigation, rainfall dates and the amount of irrigation water for each treatment are listed in Table 4. The same irrigation water amount was applied to stress treatments (except the non-irrigation treatment) on DOY 165 since CWSI measurements were initiated on DOY 216. The irrigation application finished on August 4th (DOY 216), when the crop was in the ripening period. Irrigating with a higher CWSI resulted in lower seasonal irrigation and lower seasonal evapotranspiration (ET). The total irrigation numbers varied from 2 to 7, depending on the stress treatment (Table 4). The amount

Table 4. Applied irrigation water (mm) and dates.

Treatment	Irrigation dates (DOY)									
	165	178	185	196	197	201	203	209	216	Total
$T_{0.2}$	96	92	98	101	-	96	-	106	90	679
$T_{0.4}$	96	92	96	-	104	-	95	-	101	584
$T_{0.6}$	96	-	111	-	-	137	-	-	126	470
$T_{0.8}$	96	-	-	-	-	131	-	-	-	227
$T_{1.0}$	-	-	-	-	-	-	-	-	-	-

of total irrigation water was 679, 584, 470 and 227 mm for the $T_{0.2}$, $T_{0.4}$, $T_{0.6}$ and $T_{0.8}$ treatments, respectively. The highest total irrigation water was applied to the lowest CWSI value treatment ($T_{0.2}$) with 7 irrigation applications. During the growing period, only 37.8 mm of rainfall was received and the experimental year can be considered a drought year. The seasonal ET increased with the depth of irrigation water applied (Table 5). $T_{0.2}$ gave the highest total ET (809 mm) and in the other treatments ET decreased according to water deficit. The lowest ET occurred in $T_{1.0}$ (non-irrigation treatment). Erdem et al. (2001) measured the seasonal ET as 800 mm in 1998, 762 mm in 1999 and 852 mm in 2000 for sunflower in Tekirdağ. Furthermore, the seasonal ET is consistent with those obtained in the Kırklareli region: 845 mm (Yakan and Kamburoğlu, 1989) and 857 mm (Karaata, 1991).

The soil water content and CWSI values for each treatment are graphed in Figures 2–6. The CWSI values were calculated according to average T_c measurements while eliminating extreme values. Figures 2-6 show that CWSI values increased with decreasing soil water content and these values decreased after irrigation. For the non-irrigation treatment ($T_{1.0}$), the CWSI values ranged from 0.59 to 0.80 during the measurement period and did not reach 1.0. This result can be explained by the crop adapting to water stress early under non-irrigation conditions. The CWSI value in the $T_{0.8}$ treatment only increased to 0.79 on DOY 201 and ranged from 0.12 to 0.79 for the other measurement times. When a CWSI value of 0.6 was used ($T_{0.6}$), 3 irrigations were applied, i.e. 111 mm on DOY 185, 137 mm on DOY 201 and 126 mm on DOY 216 after CWSI measurements. For the $T_{0.4}$ treatment, the CWSI values dropped to approximately

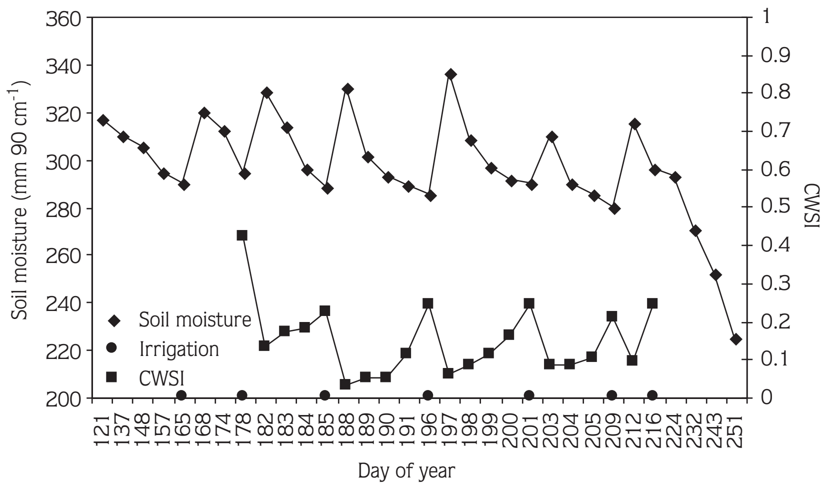

Figure 2. Seasonal trend of CWSI, soil moisture and times of irrigation for CWSI = 0.2 (CWSI: Crop water stress index).

Table 5. The total amount of irrigation water, seasonal evapotranspiration (ET), seed yield, irrigation water use efficiency (IWUE) and water use efficiency (WUE).

Treatment	Irrigation water applied (mm)	ET (mm)	Seed yield (t ha^{-1})	IWUE (kg m^{-3})	WUE (kg m^{-3})
$T_{0.2}$	679	809	4.38 a**	0.38 ns	0.54 b**
$T_{0.4}$	584	721	3.75 a	0.33	0.52 b
$T_{0.6}$	470	610	3.53 a	0.36	0.58 b
$T_{0.8}$	227	372	2.25 b	0.19	0.60 ab
$T_{1.0}$	-	197	1.83 b	-	0.93 a

**: Numbers followed by different letters indicate statistically significant differences between CWSI levels at $P \leq 0.01$
ns: Non-significant

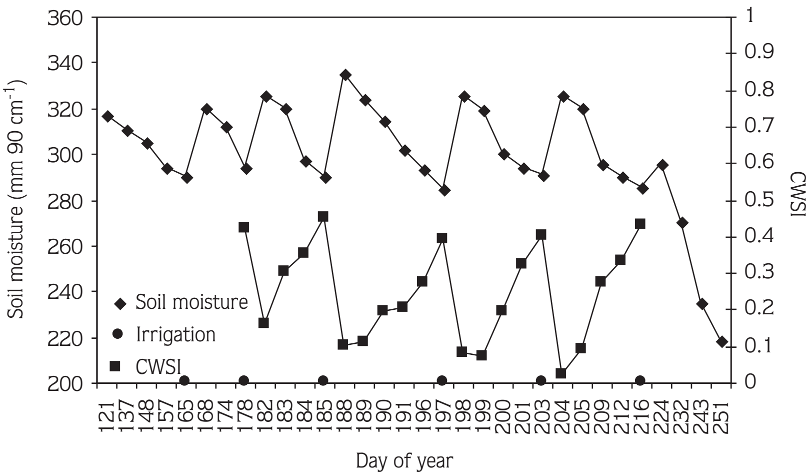

Figure 3. Seasonal trend of CWSI, soil moisture and times of irrigation for CWSI = 0.4 (CWSI: Crop water stress index).

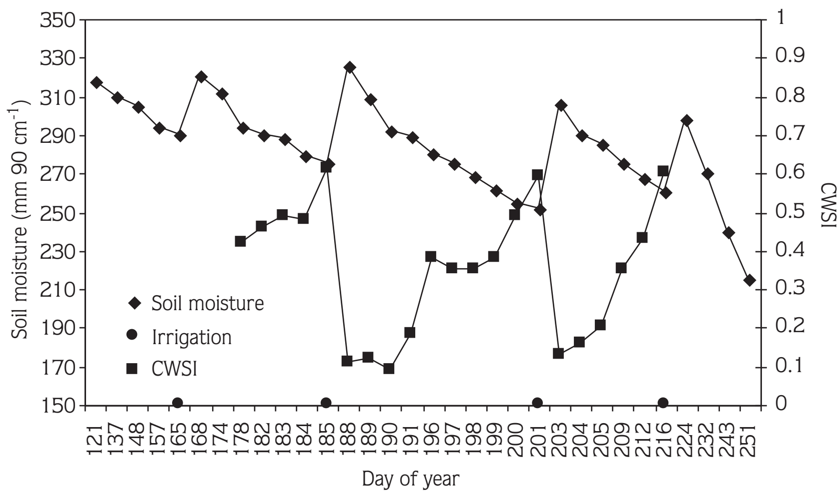

Figure 4. Seasonal trend of CWSI, soil moisture and times of irrigation for CWSI = 0.6 (CWSI: Crop water stress index).

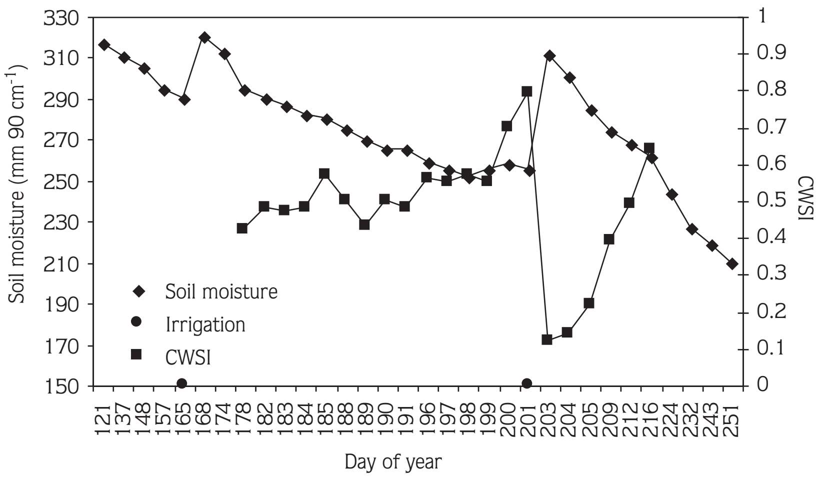

Figure 5. Seasonal trend of CWSI, soil moisture and times of irrigation for CWSI = 0.8 (CWSI: Crop water stress index).

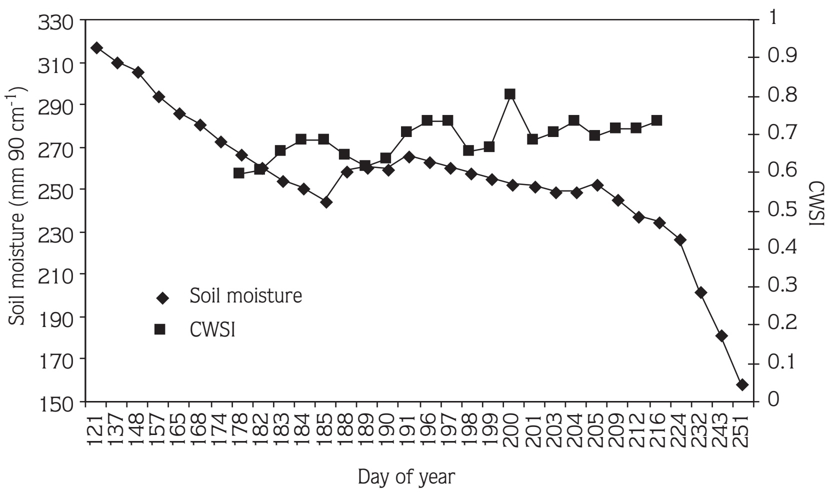

Figure 6. Seasonal trend of CWSI, soil moisture and times of irrigation for CWSI = 1.0 (non-irrigation treatment) (CWSI: Crop water stress index).

0.4 on DOY 178, 185, 197, 203 and 216, and the CWSI value generally ranged between 0.02 and 0.45. Six irrigations were applied when the CWSI value increased to 0.2 ($T_{0.2}$) and it decreased below this value. The soil water contents for each treatment were consistent with the CWSI values. The highest stress level (non-irrigation treatment) had the largest soil water depletions, while the lowest stress level ($T_{0.2}$) had the smallest soil water depletions. Soil water content within 90 cm depth gradually decreased towards the end of the growing season for each treatment. The higher stress treatments resulted in soil water contents near the wilting point towards the end of the growing season. Similar results on the CWSI for sunflower were reported by Nielsen and Anderson (1989), Nielsen (1994) and Orta et al. (2002).

Total seed yield, plant height, head diameter, stem diameter, seed weight, seed test weight, and total dry matter obtained from each treatment are summarized in Tables 5 and 6. The water stress level significantly affected seed yield at the $P \leq 0.01$ confidence level

Table 6. Yield and yield component parameters analysis for sunflower with irrigation scheduled by CWSI.

Treatment	Plant height (cm)	Head diameter (cm)	Stem diameter (cm)	Seed weight (g)	Seed test weight (kg 100 L^{-1})	Total dry matter (%)
$T_{0.2}$	173 ns	13.5 ns	1.6 ns	60.9 ns	43.2 ab*	92.1 ns
$T_{0.4}$	164	14.7	1.7	58.1	39.1 b	93.2
$T_{0.6}$	176	12.5	1.9	59.3	40.6 ab	92.8
$T_{0.8}$	154	12	1.8	61.7	44.8 a	93.3
$T_{1.0}$	142	12.2	1.4	57.3	44.4 a	93.5

*: Numbers followed by different letters indicate statistically significant differences between CWSI levels at $P \leq 0.01$
ns: Non-significant

according to an analysis of variance and the seed yield ranged from 1.83 to 4.38 t ha^{-1}. The highest seed yield was measured in $T_{0.2}$, while the lowest yield was obtained from $T_{1.0}$. However, the $T_{0.2}$, $T_{0.4}$ and $T_{0.6}$ treatments did not differ significantly from each other. As the amount of irrigation water decreased with increasing CWSI values, seed yield decreased. The seed yield decreased 14%, 19%, 49% and 58% for the $T_{0.4}$, $T_{0.6}$, $T_{0.8}$ and $T_{1.0}$ treatments according to $T_{0.2}$, respectively. It was observed that the ratio of decreases in seed yield per percent of crop water stress was not constant. Previous studies indicated that seed yield increased as the amount of water and the irrigation number increased (Unger, 1982; Rawson and Turner, 1983; Stone et al., 1996; Kadayıfçı and Yıldırım, 2000; Göksoy et al., 2004). Seed yield as a function of applied water and seasonal ET for the treatments is plotted in Figures 7 and 8, respectively. Based on the multiple regression analyses, seed yield was best correlated with applied irrigation water and ET. The vegetative growth and quality characteristics were not generally affected by water stress treatments, while the influence of water stress on seed test weight was significant at the $P \leq 0.05$ level (Table 6).

WUE and IWUE are listed in Table 5. Significant differences in WUE at the $P \leq 0.01$ level were observed between the treatments. The highest WUE (0.93 kg m^{-3}) was obtained from $T_{1.0}$ while the lowest WUE (0.52 kg m^{-3}) was obtained from 0.4 CWSI water stress treatment ($T_{0.4}$). Doorenbos and Kassam (1979) reported WUE values for sunflower of 0.3–0.5 kg m^{-3}. Göksoy et al. (2004) observed that the WUE value varied between 0.712 and 0.766 kg m^{-3} for rainfed and irrigated treatments, respectively. The effect of water stress on IWUE was not significantly different.

Conclusion

The CWSI is a valuable tool for monitoring and quantifying water stress and scheduling irrigations. Effective use of the CWSI is dependent on understanding the definition of the CWSI and proper determination and use of non-water stressed baselines (Gardner et al.,

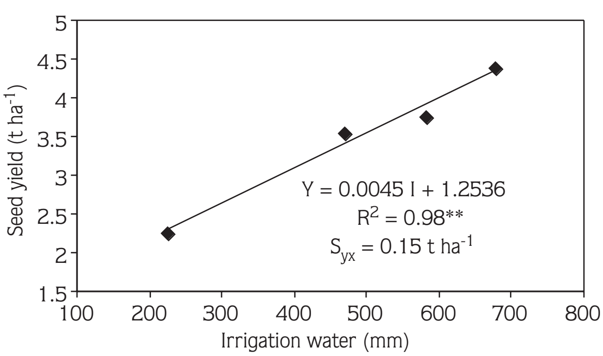

Figure 7. The relationship between seed yield and irrigation water.

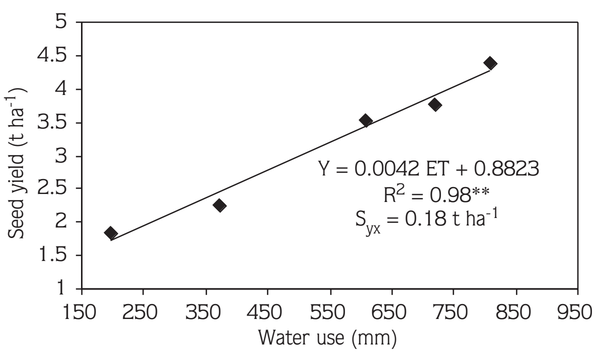

Figure 8. The relationship between seed yield and seasonal water use.

1992). In this research, the non-water stressed baseline determined by Orta et al. (2002), T_c-T_a = -1.2069 VPD – 3.5945, for the same region was used. Irrigations were applied when the CWSI reached threshold values of 0.2, 0.4, 0.6 and 0.8. Irrigation significantly increased crop water use and therefore seed yield. The seed yield was also directly correlated with CWSI values. The highest seed yield (4.38 t ha^{-1}) was obtained from the lowest CWSI values (0.2). However, the $T_{0.4}$ and $T_{0.6}$ treatments were not significantly different from $T_{0.2}$. Therefore, based on this research, a CWSI value of 0.6 should be used for the irrigation time of sunflower under Tekirdağ conditions. The vegetative growth and quality parameters were not highly affected by irrigation treatments. This study showed that the CWSI could be used to measure crop water status and to improve irrigation scheduling for sunflower.

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