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Determination of Crop Water Stress Index for Irrigation Scheduling of Bean (*Phaseolus vulgaris* L.)

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Abstract: This study was conducted to determine the relationship between the canopy-air temperature differential and the vapor pressure deficit (VPD), which can be used to quantify the crop water stress index (CWSI) under fully irrigated (100%) and maximum water stress (0%) conditions of trickle irrigated bean. The effects of 5 irrigation levels (100%, 75%, 50%, 25%, and 0% replenishment of soil water depleted when 50% of available soil moisture was consumed in the 0.60 m soil profile depth of fully irrigated treatment) on seed yields and resulting CWSIs calculated using the empirical approach were also investigated. The highest yield and water use were obtained with fully watered plants (100% replenishment of soil water depleted). The trends in CWSI values were consistent with the soil water content induced by deficit irrigation. CWSI increased with increased soil water deficit. The yield was directly correlated with seasonal mean CWSI values and the linear equation Y = 2.731 – 2.034 CWSI can be used for yield prediction. The CWSI value was useful for evaluating crop water stress in bean and should be useful for timing irrigation and predicting yield.

Key Words: Canopy temperature, vapor pressure deficit (VPD), irrigation, evapotranspiration, bean

Fasulyenin (*Phaseolus vulgaris* L.) Sulama Zamanı Planlamasında Bitki Su Stresi İndeksinin Değerlendirilmesi

Özet: Bu çalışma, damla sulama yöntemi ile sulanan fasulyenin, maksimum su stresi (%0) ve tam sulama koşullarında (%100), bitki su stresi indeks (CWSI) değerlerinin elde edilmesinde kullanılan bitki tacı-hava sıcaklığı farkı ile buhar basıncı açığı arasındaki ilişkileri belirlemek amacıyla yürütülmüştür. Çalışmada, beş farklı sulama konusunun (tam sulanan konuda 60 cm toprak derinliğinde kullanılabilir su tutma kapasitesinin yaklaşık % 50' si tüketildiğinde eksik nemin % 0, 25, 50, 75 ve 100' ünün karşılandığı) verim ve sayısal yaklaşım ile hesaplanan bitki su stresi indeksi değerlerine etkisi araştırılmıştır. En yüksek verim ve su kullanımı bitki su ihtiyacının tamamının karşılandığı konudan elde edilmiştir. CWSI değerlerinin değişimi, toprak nem eksikliğindeki değişimle benzer eğilim göstermiştir. Topraktaki nem eksikliği arttıkça, CWSI değerlerinde artış görülmüştür. Verim değerleri ile ortalama CWSI değerleri arasında verim tahmininde kullanılabilecek 'Y = 2.731 – 2.034 CWSI' doğrusal eşitliği elde edilmiştir. Sonuçta, bitki su stresi indeksi değerlerinden sulama zamanının planlanmasında ve fasulyenin verim tahmininde yararlanılabileceği belirlenmiştir.

Anahtar Sözcükler: Bitki tacı sıcaklığı, buhar basıncı açığı (VPD), sulama, bitki su tüketimi, fasulye

Introduction

Productivity response to water stress is different for each crop and is expected to vary with the climate. Many factors need to be accounted for in order to obtain a good measure of actual stress levels, but leaf temperature is the most important factor (Smith et al., 1985; Stockle and Dugas, 1992). Therefore, critical values of the crop water stress index (CWSI) should be determined for a particular crop in different climates and soils for use in yield prediction and irrigation management. Predicting yield response to crop water stress is important in both developing strategies and decision-making concerning irrigation management under limited water conditions by farmers and their advisors, as well as researchers. A range of empirical studies (Jackson, 1982; Stark and Wright, 1985; Fangmeir et al., 1989; Hutmacher et al., 1991; Ben-Asher et al., 1992; Stegman and Soderlund,

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1992; Nielsen, 1994; Gençoğlan and Yazar, 1999; Ödemiş and Baştuğ, 1999; Yazar et al., 1999; Irmak et al., 2000; Alderfasi and Nielsen, 2001; Orta et al., 2002; Colaizzi et al., 2003; Orta et al., 2003; Yuan et al., 2004) have shown that there may be different non-water stress baselines that can be used to quantify CWSI in the evaluation of plant water stress, and that ideally these need to be determined for each agro-climatic zone in which a particular crop is being grown.

The CWSI derived from canopy-air temperature differences (T_c-T_a) versus the air vapor pressure deficit (VPD) was found to be a promising tool for quantifying crop water stress (Jackson et al., 1981; Idso and Reginato, 1982; Jackson, 1982). The calculation of CWSI based on the Idso and Reginato definition relies on 2 baselines: the non-water-stressed baseline (lower limit), which represents a fully watered crop, and the maximum stressed baseline (upper limit), which corresponds to a non-transpiring crop (stomata fully closed) (Yuan et al., 2004). The lower limit in the CWSI will change as a function of vapor pressure because at lower VPDs moisture is removed from the crop at a lower rate; thus, the magnitude of cooling is decreased. Idso (1982) demonstrated that the lower limit of the CWSI is a linear function of VPD for a number of crops, as well as bean and location (http://www.uswcl.ars.ag.gov/epd).

The main objective of this study was to determine the canopy-air temperature differential for computing the CWSI of bean grown with different rates of trickle irrigation and to evaluate the relationships amongst CWSI, yield, water stress, and soil water content.

Materials and Methods

This experiment was conducted during the 2003 growing season at the research field of the Viticultural Research Institute of Tekirdağ in Turkey (lat 40°59`, long 27°29`; 4 m above sea level). The climate in this region is classified as semi-arid and the averages of annual temperature, relative humidity, wind speed, sunshine duration per day, and total annual precipitation are 13.8 °C, 76%, 3.1 m s^{-1}, 6.5 h, and 575.4 mm, respectively (http://www.meteor.gov.tr/2003/bilgiedinme/index.html). Additionally, some of the climatic factors of the 2003 growing season are summarized in Table 1. The soil type of the plot area was clay–loam and the available water holding capacity within 0.90 m of the soil is about 0.18 m. Some physical characteristics of the soil at the experimental site, such as field capacity, wilting point, and available water holding capacity, are presented in Table 2. The electrical conductivity (EC) of the irrigation water was 0.42 dS m-1.

Bean crops (*Phaseolus vulgaris* L., cv. *Şehirali* 90) were established on May 02, 2003 by direct seeding in rows that were 50 cm apart, and the crops were harvested on September 08, 2003. The experiment was arranged in a randomized block design with 3 replications. Each plot covered an area of 15.00 m^2 (3.00 x 5.00 m) and contained 120 plants with 0.50 x 0.25 m spacing. There was a gap of 3 m width between each plot. Five irrigation treatments, differing in irrigation quantity, were evaluated. The irrigation treatments were based on soil water depletion replenishments. Control treatment "T_1" was designated to receive 100% soil water depletion and irrigation was applied when ~ 50% of available soil moisture was consumed in the 0.60 m

Table 1. Some climatic data of the experimental field for 2003.

Month	Average temperature (ºC)	Average relative humidity (%)	Average wind speed (m s^{-1})	Average sunshine duration (h)	Rainfall (mm)
May	17.9	76	2.0	9.5	5.0
June	23.0	70	2.3	10.9	1.4
July	24.8	70	2.6	10.7	15.8
August	25.2	69	2.6	11.0	2.6
September	19.3	75	2.4	7.4	13.0

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

Soil depth (cm)	Volume weight (g cm^{-3})	Field capacity		Wilting point		Available water holding capacity	
		(%)	mm	%	mm	(%)	mm
0-30	1.46	28.69	125.66	15.90	69.64	12.79	56.02
30-60	1.53	28.88	132.56	15.63	71.74	13.25	60.82
60-90	1.58	26.97	127.84	14.74	69.87	12.23	57.97
0-60			258.22		141.38		116.84
0-90			386.06		211.25		174.81

root zone during the irrigation season. The other treatments were arranged to receive 75% (T_2), 50% (T_3), 25% (T_4), and 0% (T_5) of the soil water depletion measured in treatment T_1.

The soil water level was monitored daily in each plot by using a neutron probe (CPN, 503 DR Hydroprobe, CPN International, Inc., California, USA) for each 0.30 m soil layer during the entire growing season. The soil moisture content in the first 30 cm layer was measured by the gravimetric method since it was not possible to monitor it with the neutron probe method (Evett et al., 1993). The amount of soil water in the 0.60 m top layer was used to initiate irrigation. Evapotranspiration (ET) for 10-day periods was calculated applying the water balance method to the upper 0.90 m soil layer (Heerman, 1985). The equation can be written as:

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

where R is the amount of precipitation (mm), I is the irrigation water applied (mm), D is the drainage (mm), and ΔW is the 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, drainage was neglected.

The plots were irrigated by pressure compensating drippers. The dripper discharge rate was 4 l h^{-1}. Irrigation water was taken by a pump from a small reservoir near the experimental site. The control unit consisted of a screen filter with 10 l s^{-1} capacity, a pressure regulator to control and regulate the pressure in the system, and manometers mounted on the inlet and outlet of each unit. Polyethylene (PE) tube was used for the 63 mm (nominal diameter) main and 20 mm manifolds of the irrigation system. The diameters of the PE laterals were 20 mm and each lateral irrigated one plant row. Dripper and lateral spacing were 0.50 m, based on the soil characteristics. Thus, the percentage of wetted area (P) that related dripper spacing to lateral spacing was 100%, according to the principles of Keller and Bliesner (1990).

The canopy temperature (T_c) was determined 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 (IRT) was operated with the emissivity adjustment set at 0.95. The IRT data collection was initiated on July 01 (day of year (DOY) 182), when the percentage of plant cover was approximately 80%-85% and continued until the July 28 (DOY 209). The canopy temperature was measured on 4 plants from 4 directions (east, west, north, and south) when fully sunlit, at a distance of 0.50 m from the crop, with oblique measurements at 20°-30° from the horizon to minimize soil background in the field of view and then averaged. The T_c measurements were made from 1100 to 1400 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 as the average of the calculated instantaneous VPDs, using the corresponding instantaneous wet and dry bulb temperatures and the standard psychrometer equation (Allen et al., 1998) with a mean barometric pressure of 101.25 kPa.

The CWSI values were calculated using the procedures of Idso et al. (1981). 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 (T_1). The upper (fully stressed) baseline was computed according to the procedures explained by Idso et al. (1981). To verify the upper baseline, the canopy temperatures of the fully stressed plants (T_5 treatment) were determined several times from July 1 (DOY 182) to the July 28 (DOY 209).

Using the upper and lower limit estimates, a CWSI can be defined as (Idso et al., 1981):

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

where T_c is the canopy temperature (ºC), T_a the air temperature (ºC), ll is the non-water-stressed baseline (lower baseline), and ul is the non-transpiring upper baseline.

Results and Discussion

The seasonal totals for irrigation depths, evapotranspiration (ET), precipitation, and the total number of irrigations for each irrigation treatment are presented in Table 3. As expected, the control treatment (T_1), had both the highest ET (732 mm) and total irrigation water (596 mm), suggesting that the irrigation water applied was adequate to meet the full crop requirements. This treatment was used, therefore, to determine the non-stressed CWSI baseline. Other treatments underwent water deficits and resulted in lower seasonal ET. The lowest ET occurred in treatment T_5 because there was no irrigation, except for germination water (18 mm), and maximum water deficit in the root zone. This treatment was used, therefore, to determine the fully-stressed baseline.

The upper and lower baselines for the experimental year were obtained from the data taken between the beginning of flowering and the end of the yield, and are shown in Figure 1. The lower baseline was described by the linear equation, T_c-T_a = -2.6955 VPD + 3.5309, for the non-water-stressed treatment. The coefficient of determination (R^2) for the lower baseline was 0.81 ($P < 0.01$), and the standard errors of the estimate were 0.49 ºC. The lower baseline equation showed small

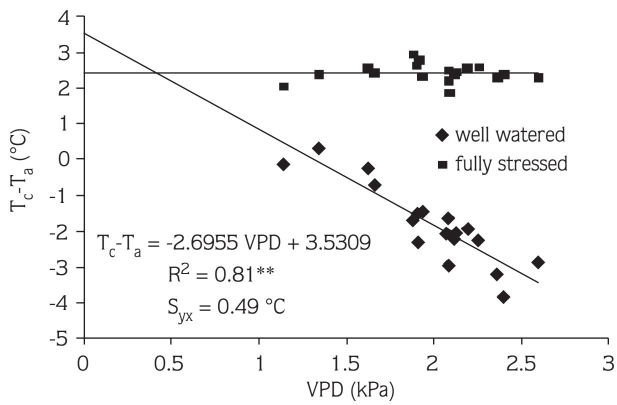

Figure 1. Canopy-air temperature differential (T_c – T_a) versus air VPD for well watered and fully stressed bean.

Table 3. Irrigation number, seasonal irrigation water, evapotranspiration and rainfall for treatments.

Treatment	Number of irrigation	Soil water depletion (mm)	Irrigation water applied (mm)	Seasonal evapotranspiration (mm)	Rainfall (mm)
T_1	10	98	596	732	38
T_2	10	107	453	598	38
T_3	10	91	308	437	38
T_4	10	111	164	313	38
T_5	-	130	18	186	38

differences from other results obtained by different researchers. For example, this equation was also determined for bean as T_c-T_a = -2.35 VPD + 2.91 by Idso (1982). Several factors, such as errors in determining relative humidity, IRT calibration, IRT aiming or field of view, and microclimate factors (like clouds or wind), can affect the baseline relationship. The upper limit that was determined for the fully-stressed treatment and used for calculation of CWSI was 2.4 °C in 2003.

Figure 2 shows the course of the CWSI on a time scale from DOY 182 to 209 for each irrigation treatment. Irrigations occurred on DOY 185, 190, 195, 201, and 209. During the measurement period, rain (16 mm) only occurred on DOY 186. Some days during the period were eliminated because of rain and an overcast sky. Moreover, Figure 2 shows that CWSI values were ranked accordingly to available water in the soil profiles. Following irrigation, water stress was usually relieved and CWSI declined accordingly, and then increased steadily to a maximum value just prior to the next irrigation application as the soil water in the crop root zone depleted. However, it was not clearly seen in T_1 treatment. This is because crops did not undergo as much stress in T_1 as in the other treatments, which led to less fluctuation in the CWSI curve. The CWSI values ranged from -0.07 to a maximum value of 0.18 in T_1, from -0.04 to 0.59 in T_2, from 0.19 to 0.87 in T_3, from 0.35 to 0.96 in T_4, and from 0.82 to 1.06 in T_5. Irrigations occurred when the CWSI on the previous day reached an average value of 0.07 in T_1, 0.35 in T_2, 0.61 in T_3, and 0.73 in T_4, respectively. This demonstrates that an average CWSI value of about 0.07 prior to irrigation will produce the maximum yield. This result is in agreement with the results from Albuquerque et al. (1998) for the same crop, as a CWSI limit before irrigation of about 0.15 for irrigation water management strategies will avoid significant yield loss. The seasonal CWSI values for each irrigation treatment calculated as the average for the entire measurement period was 0.10 in T_1, 0.35 in T_2, 0.76 in T_3, 0.86 in T_4, and 0.99 in T_5. The seasonal mean CWSI and mean CWSI values before irrigation in T_1 were lower than those for T_2, T_3, T_4, and T_5 because there was less stress in T_1 compared to the others.

The soil water content was consistent with the CWSI values in that the lowest irrigation level (T_5) had the largest soil water depletion levels and CWSI values, while the highest irrigation level (T_1) had the smallest soil water depletion levels and CWSI values (Figure 3).

The seasonal mean CWSI values for each treatment and seed yields for the experimental year are presented in Table 4. Seed yield was significantly increased by the irrigation amount ($P < 0.01$). As would be expected, the highest yield was measured as 2.38 t ha^{-1} for T_1 and seed yield for other treatments varied from 0.37 t ha^{-1} to 2.07 t ha^{-1}. The effect of irrigation treatments on bean yield was similar to previous investigations. These studies indicated that 1.2-3.03 t ha^{-1} yields were obtained in different locations (Günbatılı, 1993; Yıldırım et al., 1994; Albuquerque et al., 1998; Anlarsal et al., 2000, Medeiros

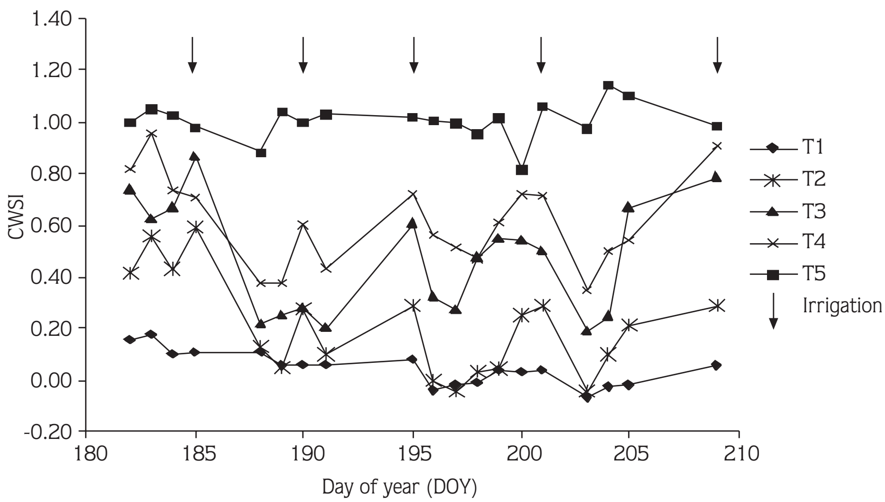

Figure 2. Variation of CWSI with time for each treatment.

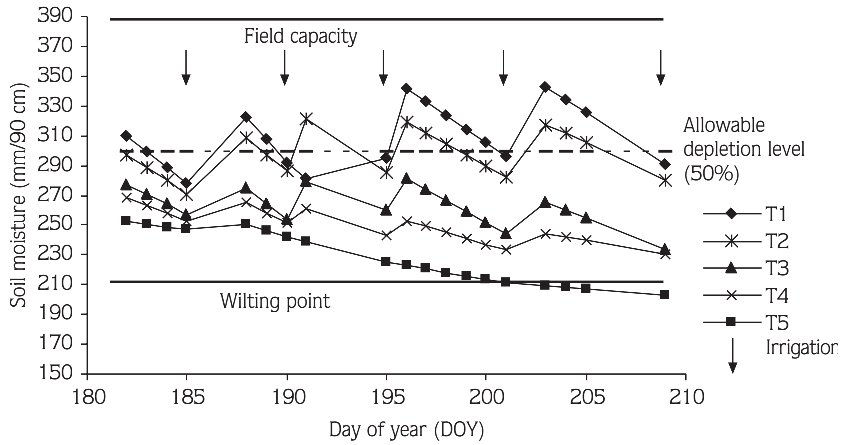

Figure 3. Variation of soil moisture with time for each treatment.

Table 4. Seed yield and seasonal mean CWSI values for treatments.

Treatment	Seed yield (t ha^{-1})	Seasonal CWSI
T_1	2.38a[a]	0.10
T_2	2.07ab	0.35
T_3	1.62b	0.76
T_4	1.00c	0.86
T_5	0.37d	0.99

[a] The letters indicate statistically significant differences at the level of 1% (LSD test)

et al., 2001). Results indicated that if the seasonal mean CWSI values were greater than the values mentioned above, seed yields would decrease. The relationship between yield and seasonal mean CWSI values was primarily linear, within the range of mean CWSI (Figure 4). As shown in Figure 4, the linear equation Y = -2.0344 CWSI + 2.7313 (R2 = 0.87, Syx = 0.33 t ha^{-1}, $P < 0.05$) can be used to predict the yield potential of bean. Predicting yield response to crop water stress is important to farmers and researchers for developing strategies and decision making concerning irrigation management under limited water conditions. The equation given above to predict the yield as a function of CWSI can be a useful tool for such goals. This result agrees with many other studies of different crops (Reginato, 1983; Howell et al., 1986; Glenn et al., 1989; Hutmacher et al., 1991; Ben-Asher et al., 1992; Stegman and Soderlund, 1992; Nielsen, 1994, Wanjura et al., 1995; Yazar et al., 1999).

Conclusion

In this research, the lower (non-stressed) and upper (stressed) baselines were determined empirically from measurements of T_c, T_a, and VPD values, and the CWSI was calculated for each irrigation treatment. The mean CWSI value before applying irrigation was 0.07 under non-water-stress conditions. This CWSI value was consistent with the highest yield for bean in our study. The average potential seed yield observed with this treatment averaged 2.38 t ha^{-1}. However, we cannot conclude that this CWSI value should be used for timing of irrigations for bean since we did not test irrigation scheduling using CWSI; further studies are needed to reach such a conclusion. A critical value of CWSI that a farmer can use to determine when to irrigate bean should be tested with long-term experiments. The yield was also

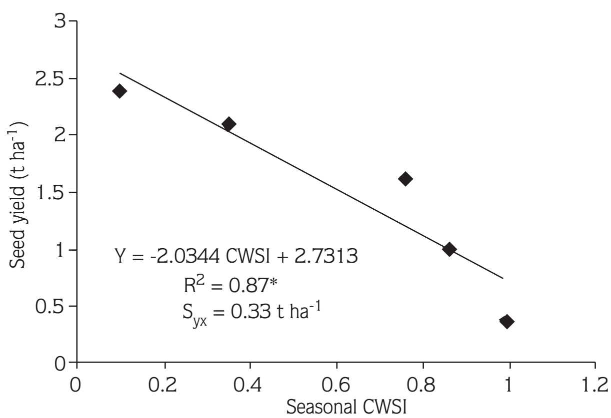

Figure 4. Seed yield as related to seasonal mean CWSI.

directly correlated with seasonal CWSI values and this linear equation, Y = -2.0344 CWSI + 2.7313, can be used for yield prediction. Predicting yield response to crop water stress is an important component of successful irrigation management.

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