

# Chlorophyll Response to Water Stress and the Potential of Using Crop Water Stress Index in Sugar Beet Farming

Ali Kaan Yetik<sup>1</sup>  · Burak Nazmi Candoğan<sup>2</sup> 

Received: 28 January 2022 / Accepted: 15 June 2022 / Published online: 4 August 2022  
© The Author(s), under exclusive licence to Society for Sugar Research & Promotion 2022

**Abstract** Field experiments were conducted in 2019 and 2021 growing seasons to evaluate the chlorophyll readings and crop water stress index (CWSI) response to full and deficit irrigation for drip-irrigated sugar beet (*Beta vulgaris* L.) under sub-humid climate of Bursa, Turkey. In addition, the changes of soil water content under different irrigation treatments and statistical relationships between chlorophyll and CWSI values and  $ET_c$ , root yield and sugar yield were investigated. Experiments were carried out in a completely randomized blocks design with three replications. Irrigations were scheduled based on the replenishment of 100 (S1), 66 (S2), 33 (S3), and 0% (S4) of soil water depletion within the soil profile of 0–90 cm using 7 day irrigation intervals. Lower and upper baselines obtained by measurements based on the canopy temperature from the treatments full irrigated and non-irrigated were used to calculate CWSI. The variations in CWSI values were consistent with the variations of seasonal soil water contents induced by the different irrigation practices. CWSI values generally varied between 0 and 1 throughout the experimental periods. In 2019, seasonal mean chlorophyll readings varied between 203.3 and 249.1, and mean CWSI values varied between 0.12 and 0.85. In 2021, seasonal mean chlorophyll readings varied between 232.7 and 259.3 and mean CWSI values between 0.19 and 0.89. Unlike chlorophyll values, CWSI decreased with increased irrigation water amount. In both years, statistically significant relationships were determined

between chlorophyll readings and CWSI and  $ET_c$ , root yield and sugar yield. The greatest root yield was achieved with a seasonal mean CWSI value of 0.12. An exponential equation determined as “Root Yield =  $10.804e^{-1.55CWSI}$ ” between seasonal average CWSI values and root yield can be used for estimation of root yield in sugar beet farming. The mean CWSI values determined by infrared thermometer technique can be used in determination of crop water stress and irrigation scheduling of sugar beet cultivation under sub-humid climatic conditions.

**Keywords** Sugar beet · Deficit irrigation · Crop water stress index · Chlorophyll readings

## Introduction

The world population of 7.8 billion is expected to reach over 9 billion by 2050, and to peak at around 11 billion at the end of the twenty-first century (Bonaccorsi et al. 2020). Problems in the food supply chain will grow even more as this expected population increase further increases the already high demand for food (Smith and Archer 2020). Another situation threatened by the rapid increase in population is natural water resources (Howard et al. 2016). When the increased use of water resources due to population growth is combined with the degradation of precipitation regimes due to climate change, hydrology is expected to be entirely affected, and groundwater consumption will increase significantly (Bates et al. 2008; Arnell and Gosling 2013; Taylor et al. 2013). Water is a renewable resource, but its availability is limited and variable (Pimentel et al. 1997). Approximately 70% of the current water consumption in the world belongs to agricultural use (Siebert et al. 2010; Grafton et al. 2018). Therefore, the application of sufficient irrigation water at the

✉ Ali Kaan Yetik  
alikaanyetik@ohu.edu.tr

<sup>1</sup> Department of Biosystems Engineering, Faculty of Agricultural Sciences and Technologies, Nigde Ömer Halisdemir University, Niğde, Turkey

<sup>2</sup> Department of Biosystems Engineering, Faculty of Agriculture, Bursa Uludağ University, Bursa, Turkey

appropriate time is important in terms of saving the water resources and reducing the negative environmental effects of irrigation (Calzadilla et al. 2010). Modern water management strategies should be used to deal with the threat of population growth and climate change to water resources.

Sugar beet (*Beta vulgaris* L.) is one of the important plants in sugar production in the world, and the irrigation water requirement is higher than many plants (Köksal and Yıldırım 2011). Irrigation applications should be planned to increase yield and product quality per unit irrigation water amount applied to plants with high irrigation water needs such as sugar beet. The methods used for this purpose include monitoring soil water content, measuring physiological responses of plants and collecting climatic data.

The amount of irrigation water should be reduced gradually while scheduling irrigation by observing the plant's responses because water stress experienced by sugar beet could be negative effects on physiological parameters such as chlorophyll values (Moosavi et al. 2017). Pigment concentration affected by chlorophyll changes of plants provides crucial information for leaf development. Chlorophylls tend to decline rapidly when plants are under stress or during leaf senescence (Merzlyak et al. 1999). Since physiological measurement of plant responses to water stress is more reliable than soil or atmospheric-based measurements (Reginato 1983), the importance of using plant-based measurements in irrigation scheduling has increased. One of the methods based on plant-based measurements is the plant canopy temperature. This method is based on the principle that water evaporated from the leaf surfaces by transpiration cools the plant canopy. Under deficit irrigation conditions, transpiration decreases, and leaf temperatures increase. If transpiration decreases, leaf temperature will show higher values than the surrounding atmosphere due to the absorbed radiation (Jackson 1982). Determining crop water stress by measuring canopy temperature has been investigated since a study conducted by Ehrler et al. (1978).

The crop water stress index (CWSI) method has been used successfully for several crops and climate conditions. In this method, canopy temperatures can be measured by remote sensing systems, and determine if the plant is under water stress. Infrared thermometers are used for remote sensing of leaf or canopy temperature without destroying the plant surface (Jackson and Idso 1969). Many studies have been done so far on the use of infrared thermometers to measure plant canopy temperature (Akkuzu et al. 2013; Candogan et al. 2013; Bellvert et al. 2014; Veysi et al. 2018; Kirnak et al. 2019). CWSI is commonly determined by an empirical approach proposed by Idso et al. (1981). The approach utilizes relationships between the canopy temperature minus air temperature value ( $T_c - T_a$ ) and vapor pressure deficit (VPD) of the air under water-stressed and non-water-stressed conditions. The linear relation between  $T_c - T_a$  and VPD values

for well-irrigated plants creates the lower limit baseline, and  $T_c - T_a$  values of water-stressed plants at the given VPD create the upper baseline. In the previous studies carried out was reported CWSI values give crucial information about the water stress experienced by plants. It has been pointed out that with irrigation schedules to be determined by taking these outcomes into account, it is possible to increase the yield, quality and water saving (Idso et al. 1981; Reginato 1983; Sepaskhah and Kashefipour 1994; Olufayo et al. 1996; Cárcova et al. 1998; Alderfasi and Nielsen 2001; Cremona et al. 2004; Yuan et al. 2004). Köksal and Yıldırım (2011) stated that the CWSI can be used effectively in the irrigation scheduling of sugar beet, under semi-arid conditions. Kovár and Cerny (2016) investigated the effects of different irrigation regimes on two different sugar beet varieties with an infrared thermometer and determined CWSI, in the Czech Republic. Authors reported CWSI values varied between 0 and 1 during the research, but during the season CWSI averages exceed 1 on the days there was no precipitation and water stress increased. Bahmani et al. (2017) reported that seasonal CWSI values changed between 0.08 and 0.42 in the first year of the study and between 0.1 and 0.44 in the second year, and recommended threshold CWSI values for irrigation time of sugar beet were 0.3, under Iran conditions. While it has been reported in previous studies that CWSI threshold values can be used in irrigation scheduling of sugar beet, no study came across conducted in sub-humid climatic conditions.

The main intends of this study are: (i) to determine upper and lower baselines of sugar beet; (ii) to investigate the potential use of CWSI for irrigation scheduling of sugar beet; (iii) to examine the effects of deficit irrigation on seasonal mean chlorophyll and CWSI values; and (iv) to determine the relations between  $ET_c$ , root yield and sugar yield and chlorophyll and CWSI values in sub-humid climatic conditions.

## Material and Methods

The experiment was conducted at the Research and Training Centre of the Faculty of Agriculture, Bursa Uludağ University located in the Bursa, Turkey (latitude 40°13'33" N, 28°51'34" E; altitude 112 m) for two years (2019 and 2021). Climatically, the region is situated in the sub-humid climate zone with an average annual rainfall of 708.7 mm. During the growing period for sugar beet, the average precipitation for many years was 170.5 mm. Meteorological data of the research area for 2019 and 2021 were provided from the Nilüfer Meteorology Station affiliated to the General Directorate of State Meteorology Affairs which is located 150 m away from the trial area. The meteorological data of the experimental years (2019 and 2021) and the long-term

(1928–2020) averages taken from the Bursa Province central meteorological station are summarized in Table 1.

Textural classification content of the soil of the experimental field was an average of 22.8% sand, 28.7% loam and 45.8% clay. It is in clay soil class for a depth of 0–120 cm. Considering 30 cm soil layers, bulk density is 1.35–1.38 g cm<sup>-3</sup>; field capacity ranged from 38.17 to 43.01% in terms of dry weight and wilting point ranged from 23.18 to 27.07%. The water holding capacity for effective rooting depth of sugar beet (90 cm) is 163.3 mm. The irrigation water requirement for the trial was met from an irrigation pond. The water sample used for irrigation was examined in a laboratory, and as a result of the analysis, pH value, electrical conductivity value and sodium adsorption rate (SAR) of the water were determined as 7.12, 310 micromhos cm<sup>-1</sup> [(ECx10) 25 °C] and 0.23, respectively.

The sugar beet cultivar Akazia provided by KWS Turkish Agricultural Company was used as plant material. Seeds were hand sown on May 1, 2019, and May 3, 2021; row spacing was 0.45 m, and on-row spacing was 0.2 m. In 2018, a study was conducted based on the irrigation of maize in the experimental area, and no research was conducted in 2020 due to COVID-19 pandemic. The experiment consisted of a completely randomized block design with three replications. The plot area was 13.5 m<sup>2</sup> and consisted of five rows of 6 m in length. Four different irrigation treatments based on replenishment of soil water depletion (SWD) were created in the study. Experimental plots were irrigated at 7-day intervals (Candoğan et. al. 2013; Kuscu et. al. 2013; Kuscu and Demir 2013; Candogan and Yazgan 2016). Irrigation treatments were based on the application of 100% (S1), 67% (S2), 33% (S3) and 0% (S4) of water consumed in 0–90 cm

soil layer of full irrigated treatment. After sowing in both years, total amount of 55 mm of irrigation water was applied to the plots for two weeks with a sprinkler irrigation system for emergence and germination. After, drip irrigation system was used for irrigation. Application of different irrigation water quantities to treatments was started on 26 June for the first year and 23 June for the second year. Experimental plots were immediately fertilized after sowing with NPK compound fertilizer (50 kg ha<sup>-1</sup>) and when plants reached 15 cm height, 70 kg ha<sup>-1</sup> additional urea fertilizer was applied for both years. Irrigation water was supplied through 16-mm lateral pipes (polyethylene) with pressure-regulated in-line emitters of 2 L h<sup>-1</sup> under 1 atm pressure. A lateral line was placed in each row (0.45 m), and emitter spacing was 20 cm.

Soil water content was monitored by gravimetric method. Soil samples were taken from 0 to 30, 30 to 60, 60 to 90 and 90 to 120 cm soil profiles with a soil auger at 7-day intervals in order to determine crop evapotranspiration (ET<sub>c</sub>). ET<sub>c</sub> values for different treatments given in Table 2 were calculated by the following equation (Montoya et al. 2017).

$$ET_c = I + P \pm \Delta S - D - R \tag{1}$$

where I is the irrigation water depth (mm), P is the rainfall (mm), ΔS is the change in soil water storage between different measurements (mm 90 cm<sup>-1</sup>), D is the deep percolation (mm), and R is the runoff (mm). Since irrigation applications were based on the principle of completing the deficient moisture within the root zone to the field capacity and the irrigation water was applied in a controlled manner by drip irrigation method, runoff (R) was neglected because the trial plots were surrounded by earthen embankments. Based on

**Table 1** Meteorological parameters of the long term and experimental period in 2019 and 2021

Year	Month	Air temperature (°C)	Relative Humidity (%)	Wind Speed <sup>a</sup> (m s <sup>-1</sup> )	Rainfall (mm)
2019	May	19.6	67.3	2.3	40.4
	June	23.7	68.6	2.9	51.2
	July	23.6	64.6	2.8	37.9
	August	24.5	64.3	3.2	39.1
	September	21.3	63.5	2.9	11.3
2021	May	18.6	67.1	1.8	14.5
	June	20.9	73.0	1.7	61.7
	July	25.5	66.1	2.2	32.8
	August	25.9	60.6	2.1	0.1
	September	20.3	64.5	2.2	10.9
Long Term (1928–2020)	May	17.7	68.1	2.0	51.1
	June	22.0	62.3	2.0	34.4
	July	24.5	59.6	2.3	22.3
	August	24.3	61.5	2.3	18.6
	September	20.3	66.8	1.9	44.1

<sup>a</sup>Average wind speed (at 2 m height)

**Table 2** Crop evapotranspiration ( $ET_c$ ) values, total precipitation ( $P$ ) and yields of treatments

Treatments	$ET_c$ (mm)		P (mm)		Root Yield (t da <sup>-1</sup> )		Sugar Yield (t da <sup>-1</sup> )	
	2019	2021	2019	2021	2019	2021	2019	2021
S1	896.9	830.0	166.6	120.0	8.6	7.5	1.4	1.3
S2	751.2	705.0			7.6	6.4	1.2	1.1
S3	558.7	547.0			5.0	4.2	1.2	1.0
S4	362.3	387.3			2.9	2.6	0.7	0.7

soil water content measurements at 90–120 cm soil profile, deep percolation was neglected.

The amount of applied irrigation water for the effective rooting depth of 90 cm is calculated with Eq. 2.

$$I = (FC - AW/100) * \gamma_t * D * PWA \quad (2)$$

where  $I$ , irrigation water depth (mm);  $FC$ , field capacity (%);  $AW$ , available water in the soil (mm);  $\gamma_3$ , bulk density (g cm<sup>-3</sup>);  $D$ , effective rooting depth (mm);  $PWA$ , percentage of the wetted area.

Sugar beet plants from each treatment were harvested by hand on the 1st of October for both years. In previous studies conducted, irrigation applications were ended approximately 2–3 weeks before the harvest (Topak et al. 2016; Uygan et al. 2021). Two rows of each plot and 0.5 m at the beginning and end of each row were removed to avoid the side effect. Roots and leaves of sugar beets were separated to determine root yield (t da<sup>-1</sup>). The remaining samples were frozen and sent to the Central Research Institute of Food and Feed Control, Bursa, Turkey. In laboratory, sugar ratio (%) was determined by Lane–Eynon method (Rajakylä and Paloposki 1983), and sugar yield (t da<sup>-1</sup>) was calculated by multiplying the determined sugar ratio (%) with root yield (Table 2).

A chlorophyll meter (FieldScout CM 1000, Spectrum Technologies, Inc., Aurora, IL, USA) was used to take chlorophyll readings. The device is portable and can measure without damaging the plant. Measurements were made before and after each irrigation, three times on two leaves of three plants in each plot, between 13:00 and 14:00. The chlorophyll reading measurements were made according to principles stated by Mahdavi et al. (2016) and Hughes et al. (2017). The chlorophyll meter was manually controlled by holding at a 40–45° vertical angle around 40 cm from the sugar beet canopy. Measurements were carried out on the dates between 25 June and 13 September in 2019 and 22 June and 17 September in 2021.

An infrared thermometer (Testo 845, Testo AG, Germany) was used to determine canopy temperature ( $T_c$ ). This device has a spectral band gap of 8–14  $\mu$ m, and the light reflection coefficient can be adjusted between 0.10 and 1.00. Infrared thermometer measurements were carried out for each plot twice a week (before and after irrigation) between

13:00 and 14:00 local time, under completely open weather conditions and at four different angles: 0° (solar azimuth angle), 90°, 180° and 270°. Canopy temperature measurements were collected from 25th June (55 days after sowing) to 13th September (135 days after sowing) in the first year, and from 22nd June (49 days after sowing) to 17th September (136 days after sowing) in the second year in order to determine the CWSI values of sugar beet. Dry and wet-bulb temperature values were measured using an aspirated psychrometer placed under an agricultural visor at the experimental area (at 1.5 m height) on the measurement days. Air vapor pressure deficit (VPD) was computed using the standard psychrometer equation determined by Allen et al. (1988).

A method known as the experimental approach exhibited by Idso et al. (1981) was used to determine crop water stress index (CWSI). According to this approach, lower limit was linear regression of  $T_c - T_a$  and VPD values determined from measurements made in the full irrigated S1 treatments, upper limit line was obtained by using the data measured on the non-irrigated S4 treatment. To determine the lower and upper limit lines, canopy temperature measurements were carried out for two days (after irrigation) in 2019 and 2021 on full irrigated S1 and non-irrigated S4 treatments. Measurements were carried out on 2nd August and 9th August for 2019, and on 13th August and 20th August for 2020, between 09:00 and 20:00 at 1 h intervals. Crop water stress index values were determined by lower and upper baselines. CWSI is calculated by using Eq. 3 (Idso et al. 1981).

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}} \quad (3)$$

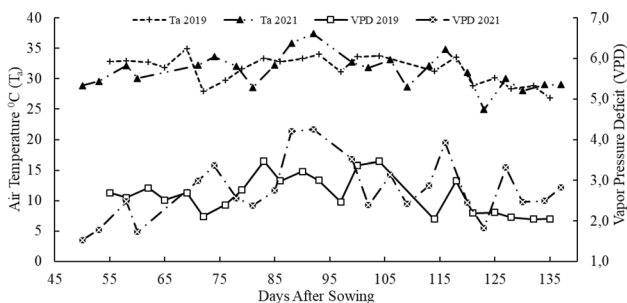
where  $(T_c - T_a)_{ll}$  is the difference between canopy temperature of full irrigated treatments and the air temperature (lower limit), and  $(T_c - T_a)_{ul}$  is the difference between canopy temperature of non-irrigated treatments and the air temperature (upper limit).

Chlorophyll readings and CWSI data obtained as a result of the study were subjected to analysis of variance according to at 0.01 and 0.05 probability levels to three replicated completely randomized block design. The least significant test (LSD) at a significance level of 0.05 was used to determine statistically different groups. Relationships between

chlorophyll readings and CWSI versus  $ET_c$ , root yield and sugar yield were determined by regression analysis.

### Results and Discussion

The  $T_c$  and VPD changes for the sugar beet growing periods of 2019 and 2021 are given in Fig. 1. As shown in Fig. 1, an increase was observed in VPD values on the days where air temperature increased. Previous studies showed that higher air temperatures cause VPD to increase (Yuan et al. 2019; Madani et al. 2020; Jain et al. 2021).

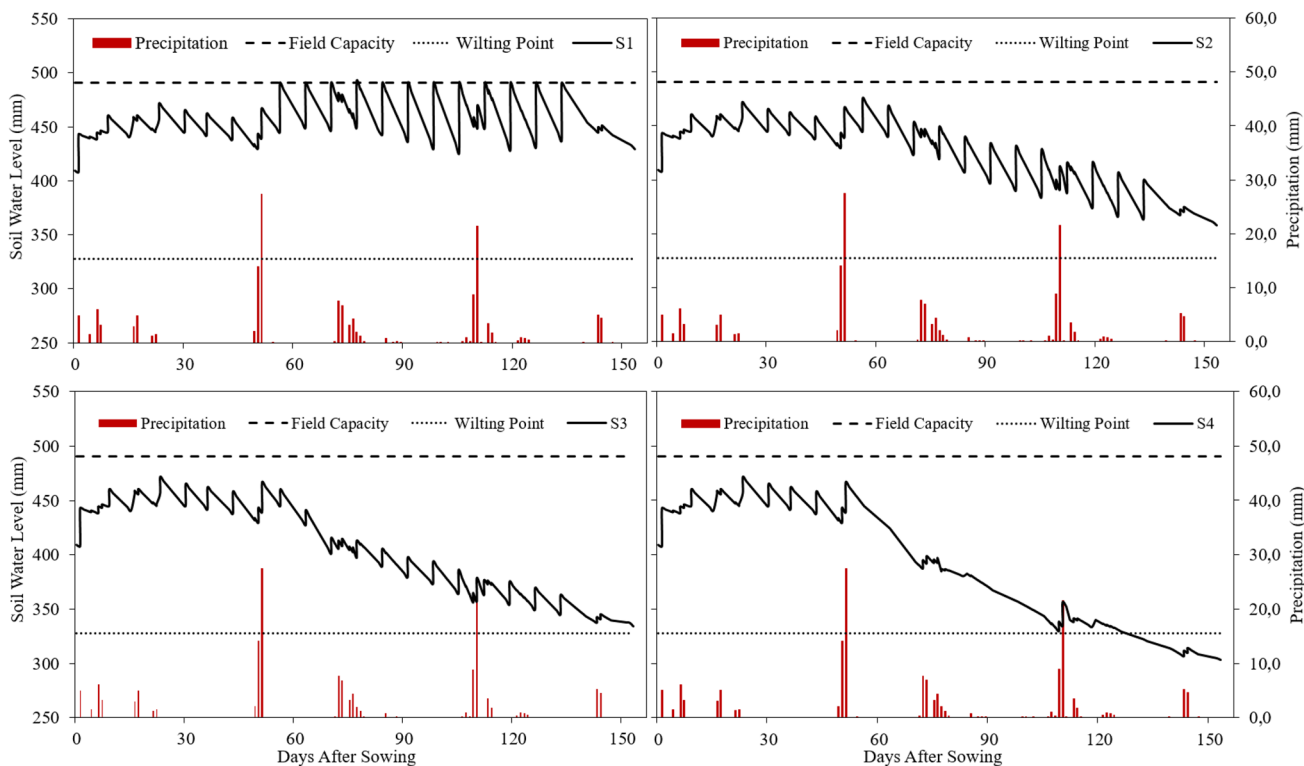


**Fig. 1** Daily air temperatures and VPD changes for research years

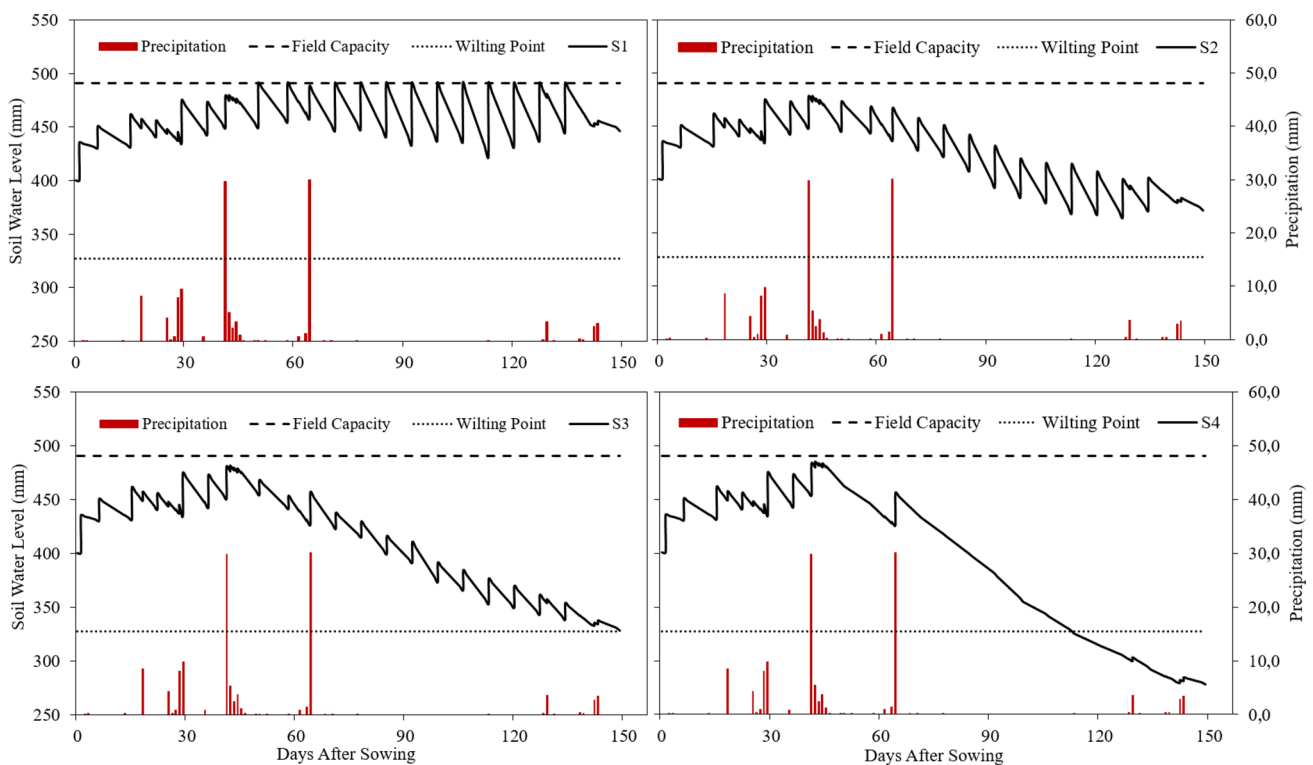
The changes in soil water content as a result of irrigation practices and precipitation during the growing seasons of 2019 and 2021 are shown in Fig. 2 and Fig. 3, respectively. Soil water content reached the field capacity level in each irrigation in the S1 treatment and remained below field capacity throughout the seasons in S2 and S3 treatments. In the rain-fed S4 treatment, soil water content increased only with precipitation and decreased below wilting point level at 128th day after sowing for the first year and 113th day after sowing for the second year.

Seasonal variations of the chlorophyll reading values for 2019 and 2021 are shown in Fig. 4. While the minimum and maximum values of chlorophyll readings of the first year of the study varied between 187 and 295, this range was determined as 121–286 in the second year. According to the seasonal changes of chlorophyll readings, it was concluded that there will be decrease in chlorophyll values due to the water deficit applied in sugar beet cultivation in sub-humid climatic conditions. Water stress generally induces a decline in chlorophyll content (El Jaouhari et al. 2018). Mahmoud et al. (2018) reported that chlorophyll values would decrease as water stress increased in the sugar beet plant. According to Baigy et al. (2012), water stress caused an increase in chlorophyll values.

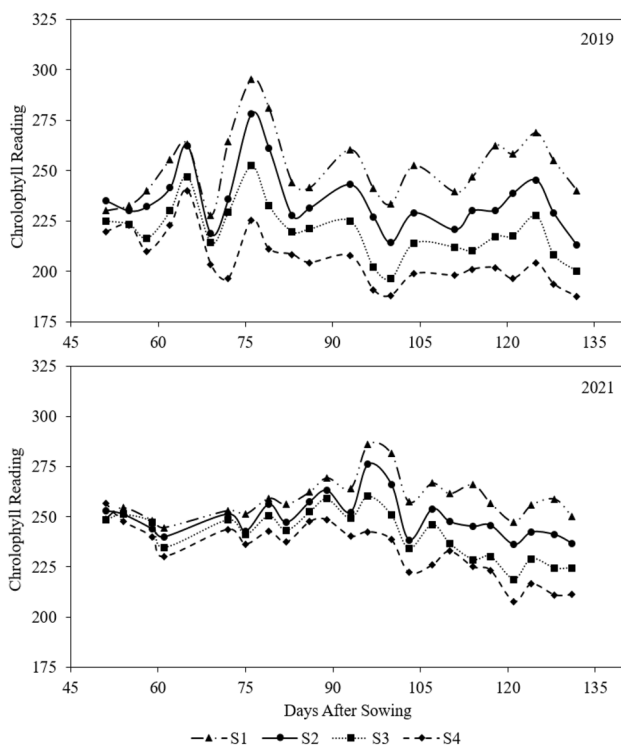
The effect of different irrigation treatments on chlorophyll readings in sugar beet plants was significant at the  $p < 0.01$



**Fig. 2** Changes in soil water content during the growing season of 2019



**Fig. 3** Changes in soil water content during the growing season of 2021



**Fig. 4** Chlorophyll readings changes of irrigation treatments for growing seasons

level, and seasonal chlorophyll reading averages were determined in four different statistical groups (Table 3). Chlorophyll readings of S1, S2, S3 and S4 treatments were 249.1, 233.0, 217.6, and 203.3, respectively, in 2019, whereas they were 259.3, 249.3, 241.0, and 232.7, respectively, in 2020. In previous studies carried out on different crops, Mäkelä et al. (2000) for tomato, Bousba et al. (2009) for durum wheat, Inalpulat et al. (2014) for eggplant, Chéour et al. (2014) for barley, Luo et al. (2016) for cotton and Vijay Kumar et al. (2019) for industrial hemp, they concluded that as irrigation water increases, chlorophyll values will also increase.

Root yields of different irrigation treatments varied between  $2.9 \text{ t da}^{-1}$  and  $8.6 \text{ t da}^{-1}$  in 2019 and between  $2.6 \text{ t da}^{-1}$  and  $7.5 \text{ t da}^{-1}$  in 2021. Lowest and greatest sugar yields were determined as  $0.7 \text{ t da}^{-1}$  and  $1.4 \text{ t da}^{-1}$ , respectively, for the first year, and  $0.7 \text{ t da}^{-1}$  and  $1.3 \text{ t da}^{-1}$ , respectively, for the second year (Table 2). Linear, logarithmic, polynomial, and exponential regression analyses were used to determine the greatest determination coefficient of the relationships between chlorophyll reading values and  $\text{ET}_c$ , root yield and sugar yield. The relation between chlorophyll reading and  $\text{ET}_c$  ( $R^2=0.6847$ ) was determined at the  $p < 0.05$  significance level, the relations between chlorophyll reading and root yield ( $R^2=0.7756$ ) and sugar yield ( $R^2=0.6976$ ) were found at the  $p < 0.01$  significance level, and all relations were with polynomial function (Fig. 5). The chlorophyll content is

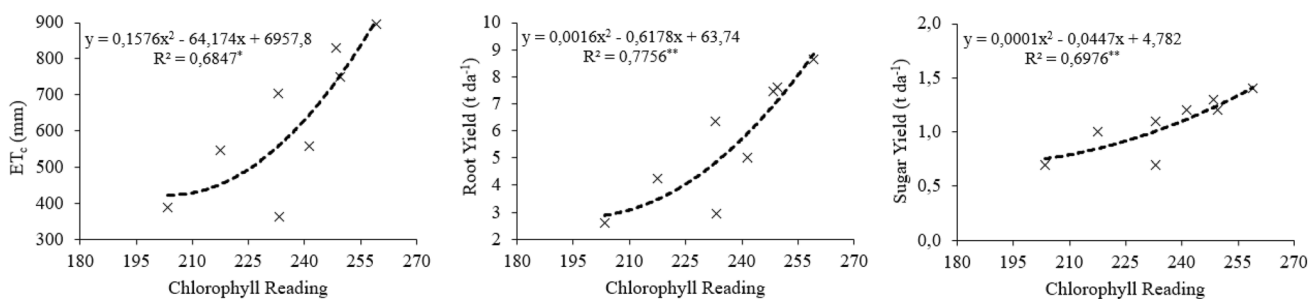
**Table 3** Results of variance analysis and seasonal averages of chlorophyll readings

Year	Source	df	Chlorophyll Reading					
			Sum of Squares	Mean Square	S1	S2	S3	S4
2019	Blocks	2	168.5110	84.2557 <sup>ns</sup>	249.1 a <sup>1</sup>	233.0 b	217.6 c	203.3 d
	Treatments	3	4190.2500	1396.7500**		LSD <sub>0.05</sub>	14.850	
	Error	6	331.5030					
2021	Blocks	2	18.1667	9.08335 <sup>ns</sup>	259.3 a	249.3 b	241.0 c	232.7 d
	Treatments	3	1172.917	390.9722**		LSD <sub>0.05</sub>	11.702	
	Error	6	205.8333					

<sup>ns</sup>Non-significant

\*\*Significant at the 1% probability level ( $P < 0.01$ )

<sup>1</sup>Indicate significant differences at  $P < 0.05$  using least significant difference (LSD) test

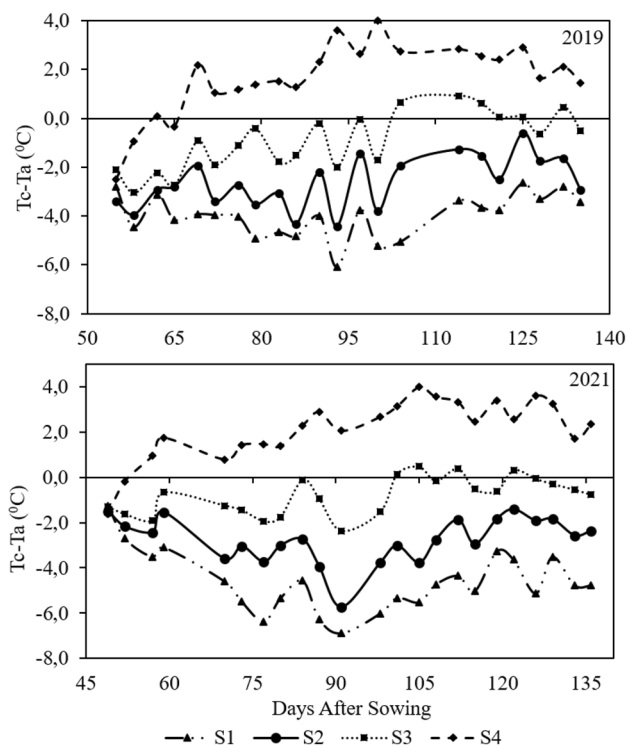


**Fig. 5** Relationships between chlorophyll readings and ET<sub>c</sub>, root yield and sugar yield

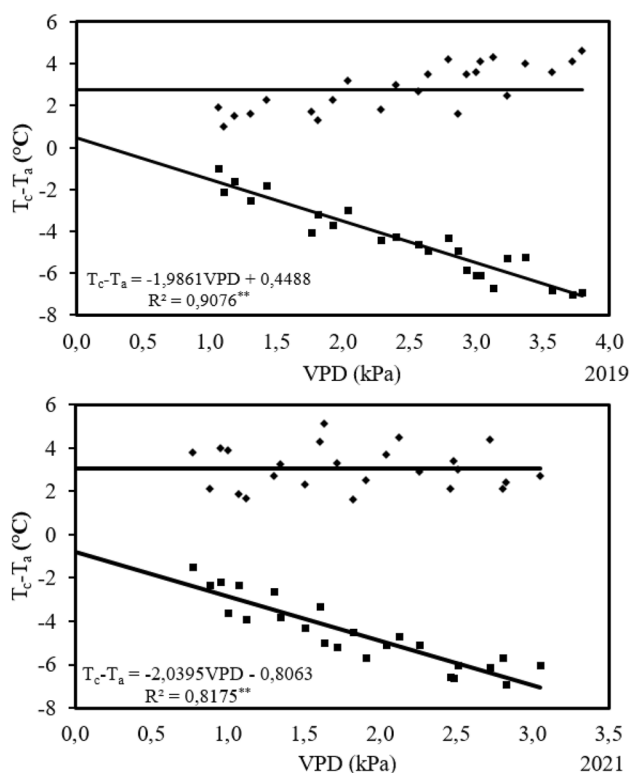
positively correlated with water usage (Fotovat et al. 2007). Köksal (2006) indicated root and sugar yield of sugar beet plants could be estimated through chlorophyll measurements and reported relationships between chlorophyll values and root ( $r = 0.77$ ) and sugar ( $r = 0.82$ ) yields were significant at the 1% probability level.

$T_c - T_a$  values were affected by the air temperature, the vapor pressure deficit, and the different irrigation treatments encountered throughout the study (Fig. 6). The highest values of the  $T_c - T_a$  were determined at S4 treatment for both years as 4.0 °C, and the lowest values were observed at S1 treatment as -6.1 °C (2019) and -6.9 (2021). Canopy temperature ( $T_c$ ) increased from the full irrigated S1 treatment to the non-irrigated S4 treatment. Similar results were reported in a study conducted on irrigation of sugar beet by Köksal and Yıldırım (2011). Pinter et al. (1979) indicated that the canopy temperatures increased as a result of the stress experienced by plants and information about plant stress could be obtained by  $T_c$  measurements.

Upper and lower limit baselines were determined to calculate CWSI values. Upper limit of  $T_c - T_a$  was found as 2.73 and 3.06 °C for the first and second year, respectively. Lower limit baselines were defined with a linear equation as  $T_c - T_a = -1,9861VPD + 0,4488$  ( $R^2 = 0.9076$ ) and  $T_c - T_a = -2,0395VPD - 0,8063$  ( $R^2 = 0.8175$ ), respectively, for experimental years (Fig. 7). The equation of



**Fig. 6**  $T_c - T_a$  changes of irrigation treatments for growing seasons

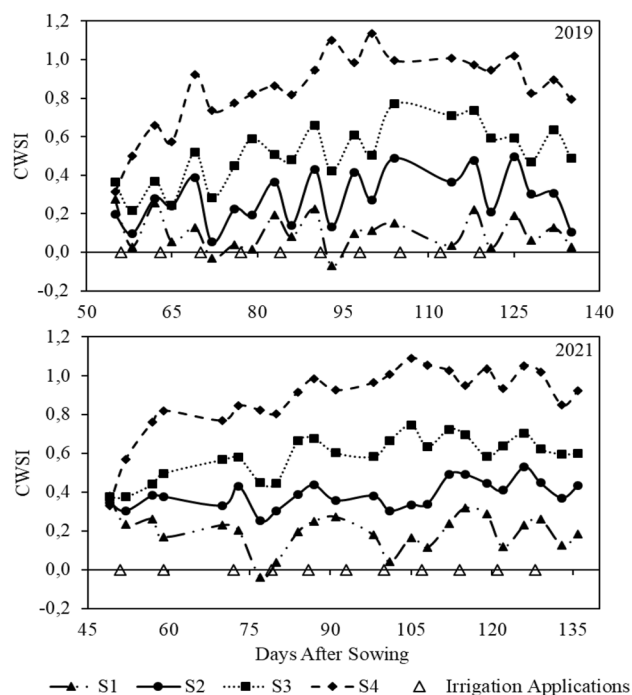


**Fig. 7** The  $T_c-T_a$  versus the air vapor pressure deficit (VPD) for non-water stressed and maximally stressed sugar beet

lower limit baseline was determined by Idso (1982) as  $T_c-T_a = -1,92VPD + 2,50$  ( $r = 0,898$ ). Köksal and Yıldırım (2011) reported the upper limits of sugar beet as 3.20 °C and 3.47 °C, respectively, and lower limit baselines with linear equations as  $T_c - T_a = -2,17VPD + 0,95$  ( $r = 0,82$ ) and  $T_c-T_a = -2,75 VPD + 3,17$  ( $r = 0,87$ ), respectively, for the study years. Bahmani et al. (2017) reported the upper and lower limits as 5.3 °C and  $T_c-T_a = 0,832VPD + 2,1811$  ( $R^2 = 0,6508$ ). Changes in climatic factors, crop cultivars or irrigation schedules could be because of the differences in the upper and lower limits.

Seasonal variation ranges of CWSI values were determined as  $-0,07-1,14$  and  $-0,04-1,09$ , respectively, for the research years (Fig. 8). CWSI values of sugar beet can be lower than zero under excessive irrigation conditions and as high as 1 in a dry season (Köksal and Yıldırım 2011; Kovár and Cerny 2016; Quebrajo et al. 2018; King et al. 2020). Sepaskhah et al. (1987) reported that the range of seasonal CWSI was  $-0,05-1,19$ , in Iran. Bahmani et al. (2017) reported the ranges of CWSI values of full irrigation and 30% water deficit treatments as  $-0,12-0,48$  and  $-0,09-0,49$ , respectively, for two years under semi-arid conditions.

Variance analysis results of the effects of different irrigation treatments on seasonal CWSI averages and seasonal mean CWSI values of the treatments are given in Table 4.



**Fig. 8** CWSI changes of irrigation treatments for growing seasons

Differences between irrigation treatments were statistically significant at  $p < 0,01$  level for determined mean CWSI values. The determined CWSI values for S1, S2, S3 and S4 treatments were 0.12 and 0.19, 0.28 and 0.38, 0.51 and 0.59 and 0.85 and 0.89 for both years, respectively. Bahmani et al. (2017) reported the mean CWSI of 0.1 and 0.8 for full irrigated treatments and 0.44 and 0.42 for the 30% water deficit.

Relationships between mean CWSI values and  $ET_c$ , root yield and sugar yield were significant at  $p < 0,01$  level (Fig. 9). The relationships with the highest coefficient of determination between  $ET_c$  and sugar yield and mean CWSI were polynomial. According to the regression analyzes conducted between root yield and mean CWSI, the relationship with the highest coefficient of determination was found in the exponential regression. The determination coefficient of the relationship between  $ET_c$  and CWSI was  $R^2 = 0,9902$ . A decrease in crop evapotranspiration caused a decrease in transpiration values, resulting in temperature increases on the plant canopy, and this increased CWSI values. An inverse correlation was found between root yield and mean CWSI values ( $R^2 = 0,9847$ ). Bahmani et al. (2017) reported a significant relationship at the  $p < 0,01$  level between sugar beet root yield and CWSI with a similar coefficient of determination ( $R^2 = 0,9888$ ). The relationships with high correlations between yield and CWSI values for alfalfa, sweet lime, corn, cucumber, black cumin and soybean were also reported by Abdul-Jabbar et al. (1985), Sepaskhah and Kashefipour (1994), Irmak et al. (2000), Şimşek et al. (2005), Al-Kayssi



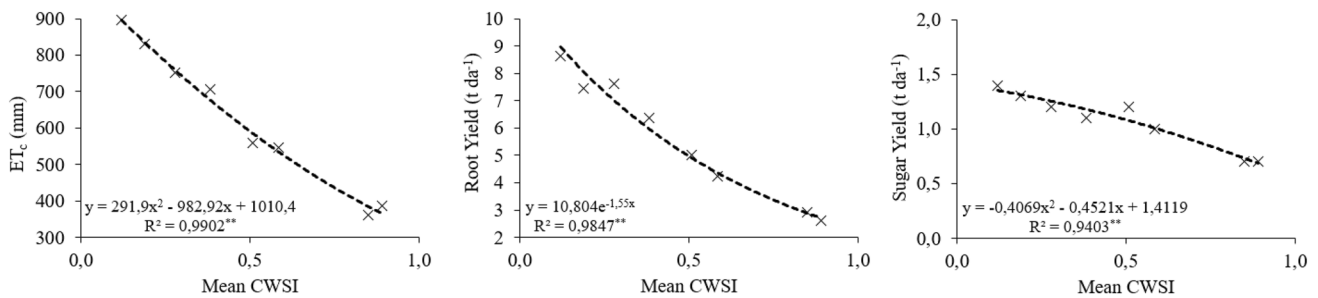
**Table 4** Results of variance analysis and seasonal averages of CWSI values

Year	Source	df	Seasonal CWSI					
			Sum of Squares	Mean Square	S1	S2	S3	S4
2019	Blocks	2	0.004867	0.002433 <sup>ns</sup>	0.12 a <sup>1</sup>	0.28 b	0.51 c	0.85 d
	Treatments	3	0.893092	0.297697 <sup>**</sup>		LSD <sub>0,05</sub>	0.071	
	Error	6	0.007533					
2021	Blocks	2	0.03185	0.015925 <sup>ns</sup>	0.19 a	0.38 b	0.59 c	0.89 d
	Treatments	3	0.8147	0.271567 <sup>**</sup>		LSD <sub>0,05</sub>	0.118	
	Error	6	0.02095					

<sup>ns</sup> Non-significant

<sup>\*\*</sup> Significant at the 1% probability level ( $P < 0.01$ )

<sup>1</sup> Indicate significant differences at  $P < 0.05$  using least significant difference (LSD) test



**Fig. 9** Relationships between chlorophyll readings and ET<sub>c</sub>, root yield and sugar yield

et al. (2011) and Candogan et al. (2013), respectively. According to the determined relationship between sugar yield and CWSI ( $p < 0.01$ ,  $R^2 = 0.9403$ ), increases in the CWSI values would cause a significant decrease in the sugar yield to be obtained from sugar beet. In a previous study with the parallel findings, Bahmani et al. (2017) indicated that the relationship between sugar yield of sugar beet and mean CWSI values was inverse ( $p < 0.01$ ,  $R^2 = 0.9362$ ).

### Conclusions

In present study, the effect of different irrigation levels on seasonal chlorophyll readings was significant at the  $p < 0.01$  level. Greatest average chlorophyll values were obtained from S1 treatment with 249.1 and 259.3, while the lowest chlorophyll values were obtained from rain-fed S4 treatment with 203.3 and 232.7 for experimental years, respectively. Decreases in chlorophyll reading values were observed as a result of water deficits applied in sugar beet cultivation under sub-humid climatic conditions. The relations between chlorophyll reading and ET<sub>c</sub> ( $p < 0.05$ ), root yield ( $p < 0.01$ ) and sugar yield ( $p < 0.01$ ) were with polynomial functions.

The effect of four irrigation treatments on seasonal CWSI values was found to be significant at the  $p < 0.01$  level. Lowest CWSI values for 2019 and 2021 were 0.12 and 0.19 (S1), while the greatest CWSI values were 0.85 and 0.89 (S4),

respectively. CWSI values calculated by the upper and lower baselines encountered in the study generally varied between 0 and 1 throughout the experimental periods. The relations between ET<sub>c</sub> (polynomial), root yield (exponential) and sugar yield (polynomial) and mean CWSI values were significant at the  $p < 0.01$  level. A CWSI value of 0.12 can be recommended as the threshold value for determination of the irrigation time to get the greatest root and sugar yield.

As a result, mean CWSI values determined by the infrared thermometer technique can be used in irrigation scheduling of sugar beet cultivation under sub-humid climatic conditions. Moreover, the regression equations of ET<sub>c</sub>, root yield and sugar yield versus mean chlorophyll reading and mean CWSI can be used to predict ET<sub>c</sub>, root yield and sugar yield.

**Acknowledgements** This study contains partial findings of the MSC dissertation of Ali Kaan Yetik. Many thanks to Prof. Dr. Mehmet Sinik from Bursa Uludağ University in Bursa, Turkey, for conveyance of the knowledge and experiences about sugar beet cultivation throughout the study.

**Author Contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by AKY and BNC. The first draft of the manuscript was written by AKY and BNC, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** This work did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

## Declarations

**Conflict of Interest** The authors declare that they have no conflict of interest.

## References

- Abdul-Jabbar, A.S., D.G. Lugg, T.W. Sammis, and L.W. Gay. 1985. Relationships between crop water stress index and alfalfa yield and evapotranspiration. *Transactions of the ASAE* 28 (2): 454–0461. <https://doi.org/10.13031/2013.32278>.
- Akkuzu, E., Ü. Kaya, G. Çamoğlu, G.P. Mengü, and Ş Aşık. 2013. Determination of crop water stress index and irrigation timing on olive trees using a handheld infrared thermometer. *Journal of Irrigation and Drainage Engineering* 139 (9): 728–737. [https://doi.org/10.1061/\(asce\)ir.1943-4774.0000623](https://doi.org/10.1061/(asce)ir.1943-4774.0000623).
- Alderfasi, A.A., and D.C. Nielsen. 2001. Use of crop water stress index for monitoring water status and scheduling irrigation in wheat. *Agricultural Water Management* 47 (1): 69–75. [https://doi.org/10.1016/S0378-3774\(00\)00096-2](https://doi.org/10.1016/S0378-3774(00)00096-2).
- Al-Kayssi, A.W., R.M. Shihab, and S.H. Mustafa. 2011. Impact of soil water stress on nigellone oil content of black cumin seeds grown in calcareous-gypsiferous soils. *Agricultural Water Management* 100 (1): 46–57. <https://doi.org/10.1016/J.AGWAT.2011.08.007>.
- Allen, R.G., L.S. Pereira, D. Raes, and M Smith. 1998. Crop evapotranspiration-guidelines for computing crop water requirements. In: *Irrigation and drainage paper 56*. Rome: FAO.
- Arnell, N.W., and S.N. Gosling. 2013. The impacts of climate change on river flow regimes at the global scale. *Journal of Hydrology* 486: 351–364. <https://doi.org/10.1016/j.jhydrol.2013.02.010>.
- Bahmani, O., A.A. Sabziparvar, and R. Khosravi. 2017. Evaluation of yield, quality and crop water stress index of sugar beet under different irrigation regimes. *Water Science and Technology: Water Supply* 17 (2): 571–578. <https://doi.org/10.2166/ws.2016.163>.
- Baigy, M.J., F.G. Sahebi, E. Purkhiz, F. Ejlali, and A. Asgari. 2012. Effect of water stress on sugar beet product in the tape drip irrigation. *International Journal of Agriculture: Research and Review* 2: 1032–1036.
- Bellvert, J., P.J. Zarco-Tejada, J. Girona, and E. Fereres. 2014. Mapping crop water stress index in a ‘Pinot-noir’ vineyard: Comparing ground measurements with thermal remote sensing imagery from an unmanned aerial vehicle. *Precision Agriculture* 15 (4): 361–376. <https://doi.org/10.1007/s11119-013-9334-5>.
- Bonaccorsi, G., G. Garamell, G. Cavallo, and C. Lorini. 2020. A systematic review of risk assessment associated with jellyfish consumption as a potential novel food. *Foods* 9 (7): 935. <https://doi.org/10.3390/foods9070935>.
- Bousba, R., N. Ykhlef, and A. Djekoun. 2009. Water use efficiency and flat leaf photosynthetic in response to water deficit of durum wheat (*Triticum durum* Desf). *World Journal of Agricultural Sciences* 5: 609–616.
- Calzadilla, A., and K., Rehdanz, and R.S.J. Tol. 2010. The economic impact of more sustainable water use in agriculture: a computable general equilibrium analysis. *Journal of Hydrology* 384 (3–4): 292–305. <https://doi.org/10.1016/J.JHYDROL.2009.12.012>.
- Candogan, B.N., M. Sincik, H. Buyukcangaz, C. Demirtas, A.T. Goksoy, and S. Yazgan. 2013. Yield, quality and crop water stress index relationships for deficit-irrigated soybean [*Glycine max* (L.) Merr.] in sub-humid climatic conditions. *Agricultural Water Management* 118: 113–121. <https://doi.org/10.1016/j.agwat.2012.11.021>.
- Candogan, B.N., and S. Yazgan. 2016. Yield and quality response of soybean to full and deficit irrigation at different growth stages under sub-humid climatic conditions. *Journal of Agricultural Sciences* 22: 129–144. [https://doi.org/10.1501/tarimbil\\_000001375](https://doi.org/10.1501/tarimbil_000001375).
- Cárcova, J., G.A. Maddonni, and C.M. Ghersa. 1998. Crop water stress index of three maize hybrids grown in soils with different quality. *Field Crops Research* 55 (1–2): 165–174. [https://doi.org/10.1016/S0378-4290\(97\)00076-2](https://doi.org/10.1016/S0378-4290(97)00076-2).
- Chéour, F., I. Kaddachi, D. Achouri, S. Bannour, and L. Zorgui. 2014. Effects of water stress on relative water, chlorophylls and proline contents in barley (*Hordeum vulgare* L.) leaves. *IOSR Journal of Agriculture and Veterinary Science* 7: 13–16. <https://doi.org/10.9790/2380-07611316>.
- Cremona, M.V., H. Stützel, and H. Kage. 2004. Irrigation scheduling of kohlrabi (*Brassica oleracea* var *gongylodes*) using crop water stress index. *Hort Science* 39 (2): 276–279. <https://doi.org/10.21273/hortsci.39.2.276>.
- Ehrler, W.L., S.B. Idso, R.D. Jackson, and R.J. Reginato. 1978. Wheat canopy temperature: Relation to plant water potential. *Agronomy Journal* 70 (2): 251–256. <https://doi.org/10.2134/AGRONJ1978.00021962007000020010X>.
- El Jaouhari, N., A. Abouabdillah, R. Bouabid, M. Bouriou, L. Aleya, and M. Chaoui. 2018. Assessment of sustainable deficit irrigation in a Moroccan apple orchard as a climate change adaptation strategy. *Science of the Total Environment* 642: 574–581. <https://doi.org/10.1016/J.SCITOTENV.2018.06.108>.
- Fotovat, R., M. Valizadeh, and M. Toorchi. 2007. Association between water-use efficiency components and total chlorophyll content (SPAD) in wheat (*Triticum aestivum* L.) under well-watered and drought stress conditions. *Journal of Food, Agriculture & Environment* 5: 225–227.
- Grafton, R.Q., J. Williams, C.J. Perry, F. Molle, C. Ringler, P. Steduto, B. Udall, et al. 2018. The paradox of irrigation efficiency. *Science* 361 (6404): 748–750. <https://doi.org/10.1126/science.aat9314>.
- Howard, G., R. Calow, A. Macdonald, and J. Bartram. 2016. Climate change and water and sanitation: Likely impacts and emerging trends for action. *Annual Review of Environment and Resources* 41: 253–276. <https://doi.org/10.1146/ANNUREV-ENVIRON-110615-085856>.
- Hughes, M.P., C.H.O. Lallo, V. Mlambo, and P.G.A. Jennings. 2017. Calibration and validation of optical chlorophyll-measuring devices for use in predicting crude protein concentration in tropical grass herbage. *Grass and Forage Science* 72: 118–136. <https://doi.org/10.1111/gfs.12219>.
- Idso, S.B. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. *Agricultural Meteorology* 27 (1–2): 59–70. [https://doi.org/10.1016/0002-1571\(82\)90020-6](https://doi.org/10.1016/0002-1571(82)90020-6).
- Idso, S.B., R.D. Jackson, P.J. Pinter, R.J. Reginato, and J.L. Hatfield. 1981. Normalizing the stress-degree-day parameter for environmental variability. *Agricultural Meteorology* 24: 45–55. [https://doi.org/10.1016/0002-1571\(81\)90032-7](https://doi.org/10.1016/0002-1571(81)90032-7).
- Inalpulat, M., L. Genc, U. Kizil, and S. Aksu. 2014. Responses of eggplant to pruning under irrigation deficiency. In *International Conference on Biological, Civil and Environmental Engineering* 1: 17–18. <https://doi.org/10.15242/iicbe.c0314149>.
- Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Mitigation of Climate Change*. Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9780511546013>.
- Irmak, S., D.Z. Haman, and R. Bastug. 2000. Determination of crop water stress index for irrigation timing and yield estimation of corn. *Agronomy Journal* 92 (6): 1221–1227. <https://doi.org/10.2134/AGRONJ2000.9261221X>.

- Jackson, R.D. 1982. Canopy temperature and crop water stress. In *Advances in Irrigation* 1: 43–85. <https://doi.org/10.1016/b978-0-12-024301-3.50009-5>.
- Jackson, R.D., and S.B. Idso. 1969. Ambient temperature effects in infrared thermometry. *Agronomy Journal* 61 (2): 324–325. <https://doi.org/10.2134/agronj1969.00021962006100020044x>.
- Jain, P., D. Castellanos-Acuna, S.C.P. Coogan, J.T. Abatzoglou, and M.D. Flannigan. 2021. Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nature Climate Change* 12 (1): 63–70. <https://doi.org/10.1038/s41558-021-01224-1>.
- King, B.A., K.C. Shellee, D.D. Tarkalson, A.D. Levin, V. Sharma, and D.L. Bjorneberg. 2020. Data-driven models for canopy temperature-based irrigation scheduling. *Transactions of the ASABE* 63 (5): 1579–1592. <https://doi.org/10.13031/TRAN.13901>.
- Kirnak, H., H.A. Irik, and A. Unlukara. 2019. Potential use of crop water stress index (CWSI) in irrigation scheduling of drip-irrigated seed pumpkin plants with different irrigation levels. *Scientia Horticulturae*. 256: 108608. <https://doi.org/10.1016/j.scienta.2019.108608>.
- Köksal, E.S., and Y.E. Yıldırım. 2011. Using crop water stress index for determination of sugar beet irrigation time. *Anadolu Journal of Agricultural Sciences* 26: 57–62.
- Köksal, E.S. 2006. Sulama suyu düzeylerinin şekerpancarının verim, kalite ve fizyolojik özellikleri üzerindeki etkisinin, infrared termometre ve spektroskopiyometre ile belirlenmesi. *PhD Thesis Ankara University, Institute of Science, Agricultural Structures and Irrigation*.
- Kovár, M., and I. Černý. 2016. Evaluation of water regime in sugar beet plants by infrared thermography. *Listy Cukrovarnické a Řepářské* 132: 54–59.
- Kuscu, H., and A.O. Demir. 2013. Yield and water use efficiency of maize under deficit irrigation regimes in a sub-humid climate. *Philippine Agricultural Scientist* 96: 32–41.
- Kuscu, H., A. Karasu, M. Oz, A.O. Demir, and I. Turgut. 2013. Effect of irrigation amounts applied with drip irrigation on maize evapotranspiration, yield, water use efficiency, and net return in a sub-humid climate. *Turkish Journal of Field Crops* 18: 13–19.
- Luo, H.H., T.M. Merope, Y.L. Zhang, and W.F. Zhang. 2016. Combining gas exchange and chlorophyll a fluorescence measurements to analyze the photosynthetic activity of drip-irrigated cotton under different soil water deficits. *Journal of Integrative Agriculture* 15 (6): 1256–1266. [https://doi.org/10.1016/S2095-3119\(15\)61270-9](https://doi.org/10.1016/S2095-3119(15)61270-9).
- Madani, N., N.C. Parazoo, J.S. Kimball, A.P. Ballantyne, R.H. Reichle, M. Maneta, S. Saatchi, P.I. Palmer, Z. Liu, and T. Tagesson. 2020. Recent amplified global gross primary productivity due to temperature increase is offset by reduced productivity due to water constraints. *AGU Advances*. 1 (4): e2020AV000180. <https://doi.org/10.1029/2020av000180>.
- Mahdavi, S., M. Kafi, E. Fallahi, M. Shokrpour, and L. Tabrizi. 2016. Water stress, nano silica, and digoxin effects on minerals, chlorophyll index, and growth in ryegrass. *International Journal of Plant Production* 10: 251–264.
- Mahmoud, E.S.A., M.A. Hassanin, T.I. Borham, and E.I.R. Emar. 2018. Tolerance of some sugar beet varieties to water stress. *Agricultural Water Management* 201: 144–151. <https://doi.org/10.1016/j.agwat.2018.01.024>.
- Mäkelä, P., J. Kärkkäinen, and S. Somersalo. 2000. Effect of glycinebetaine on chloroplast ultrastructure, chlorophyll and protein content, and RuBPCO activities in tomato grown under drought or salinity. *Biologia Plantarum* 201: 144–151. <https://doi.org/10.1023/A:1026712426180>.
- Merzlyak, M.N., A.A. Gitelson, O.B. Chivkunova, and V.Y. Rakitin. 1999. Non-destructive optical detection of pigment changes during leaf senescence and fruit ripening. *Physiologia Plantarum* 106: 135–141. <https://doi.org/10.1034/j.1399-3054.1999.106119.x>.
- Montoya, F., C. García, F. Pintos, and A. Otero. 2017. Effects of irrigation regime on the growth and yield of irrigated soybean in temperate humid climatic conditions. *Agricultural Water Management* 193: 30–45. <https://doi.org/10.1016/j.agwat.2017.08.001>.
- Moosavi, S.G.R., S.H.R. Ramazani, S.S. Hemayati, and H. Gholizade. 2017. Effect of drought stress on root yield and some morphophysiological traits in different genotypes of sugar beet (*Beta vulgaris* L.). *Journal of Crop Science and Biotechnology*. 20 (3): 167–174. <https://doi.org/10.1007/s12892-017-0009-0>.
- Olufayo, A., C. Baldy, and P. Ruelle. 1996. Sorghum yield, water use and canopy temperatures under different levels of irrigation. *Agricultural Water Management* 30 (1): 77–90. [https://doi.org/10.1016/0378-3774\(95\)01205-2](https://doi.org/10.1016/0378-3774(95)01205-2).
- Pimentel, D., J. Houser, E. Preiss, O. White, H. Fang, L. Mesnick, T. Barsky, S. Tariche, J. Schreck, and S. Alpert. 1997. Water resources: Agriculture, the environment, and society: an assessment of the status of water resources. *BioScience* 47 (2): 97–106. <https://doi.org/10.2307/1313020>.
- Pinter, P.J., M.E. Stanghellini, R.J. Reginato, S.B. Idso, A.D. Jenkins, and R.D. Jackson. 1979. Remote detection of biological stresses in plants with infrared thermometry. *Science* 205 (4406): 585–587. <https://doi.org/10.1126/science.205.4406.585>.
- Quebrajo, L., M. Perez-Ruiz, L. Pérez-Urrestarazu, G. Martínez, and G. Egea. 2018. Linking thermal imaging and soil remote sensing to enhance irrigation management of sugar beet. *Biosystems Engineering* 165: 77–87. <https://doi.org/10.1016/j.biosystemseng.2017.08.013>.
- Rajakylä, E., and M. Paloposki. 1983. Determination of sugars (and betaine) in molasses by high-performance liquid chromatography. Comparison of the results with those obtained by the classical lane-eynon method. *Journal of Chromatography A* 282: 595–602. [https://doi.org/10.1016/S0021-9673\(00\)91636-4](https://doi.org/10.1016/S0021-9673(00)91636-4).
- Reginato, R.J. 1983. Field qualification of crop water stress. In *Paper - American Society of Agricultural Engineers*. 26 (3): 772–0775. <https://doi.org/10.13031/2013.34021>.
- Sepaskhah, A.R., and S.M. Kashfipour. 1994. Relationships between leaf water potential, CWSI, yield and fruit quality of sweet lime under drip irrigation. *Agricultural Water Management* 25 (1): 13–21. [https://doi.org/10.1016/0378-3774\(94\)90049-3](https://doi.org/10.1016/0378-3774(94)90049-3).
- Sepaskhah, A.R., M. Nzemsadat, and A. Kamgarhaghghi. 1987. Water stress of sugar beet as related to leaf and canopy temperatures and to leaf water content. *Iran Agricultural Research* 6: 29–43.
- Siebert, S., J. Burke, J.M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F.T. Portmann. 2010. Groundwater use for irrigation - A global inventory. *Hydrology and Earth System Sciences* 14 (10): 1863–1880. <https://doi.org/10.5194/HESS-14-1863-2010>.
- Şimşek, M., T. Tonkaz, M. Kaçira, N. Çömlekçiöglü, and Z. Doğan. 2005. The effects of different irrigation regimes on cucumber (*Cucumis sativus* L.) yield and yield characteristics under open field conditions. *Agricultural Water Management*. 73 (3): 173–191. <https://doi.org/10.1016/j.agwat.2004.10.013>.
- Smith, G.R., and R. Archer. 2020. Climate, population, food security: Adapting and evolving in times of global change. *International Journal of Sustainable Development and World Ecology* 27 (5): 419–423. <https://doi.org/10.1080/13504509.2020.1712558>.
- Taylor, R.G., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, et al. 2013. Ground water and climate change. *Nature Climate Change* 3: 322–329. <https://doi.org/10.1038/nclimate1744>.
- Topak, R., B. Acar, R. Uyanöz, and E. Ceyhan. 2016. Performance of partial root-zone drip irrigation for sugar beet production in a semi-arid area. *Agricultural Water Management* 176: 180–190. <https://doi.org/10.1016/j.agwat.2016.06.004>.

- Uygan, D., O. Cetin, V. Alveroglu, and A. Sofuoglu. 2021. Improvement of water saving and economic productivity based on quotation with sugar content of sugar beet using linear move sprinkler irrigation. *Agricultural Water Management* 255: 106989. <https://doi.org/10.1016/j.agwat.2021.106989>.
- Veysi, A., A. Naseri, and S. Hamzeh. 2018. Relationship between leaf sheath moisture and crop water stress index (CWSI) using infrared thermometer. *Irrigation Science and Engineering*. 40 (4): 77–90. <https://doi.org/10.22055/IISE.2017.13287>.
- Vijay Kumar, I., T.B. Acuna, S. Lisson, and M. Hardie. 2019. Growth and development of industrial hemp (*Cannabis sativa* L) in response to irrigation treatments. In: 19th Australian Society of Agronomy Conference. 1: 1–4.
- Yuan, G., Y. Luo, X. Sun, and D. Tang. 2004. Evaluation of a crop water stress index for detecting water stress in winter wheat in the North China Plain. *Agricultural Water Management* 64 (1): 29–40. [https://doi.org/10.1016/S0378-3774\(03\)00193-8](https://doi.org/10.1016/S0378-3774(03)00193-8).
- Yuan, W., Y. Zheng, S. Piao, P. Ciais, D. Lombardozzi, Y. Wang, Y. Ryu, et al. 2019. Increased atmospheric vapor pressure deficit reduces global vegetation growth. *Science Advances*. 5 (8): 139. <https://doi.org/10.1126/sciadv.aax1396>.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.