Iran Agricultural Research (2015) **34**(**2**) 49-60

Shiraz University

Determining cwsi to estimate eggplant evapotranspiration and yield under greenhouse and outdoor conditions

A. Ghaemi[*1], **H. Moazed**[2], **M. Rafie Rafiee**[3], **S. Broomand Nasab**[2]

[1]Department of Water Engineering, College of Agriculture, Shiraz University, Shiraz, I.R. Iran
[2] Department of water sciences Engineering, College of Agriculture Shahid Chamran University, Ahwaz, I. R. Iran
[3]Department of Irrigation, Jahrom Universtiy, Jahrom, I.R. Iran

* Corresponding Author: Ghaemi@shirazu.ac.ir -ghaemiali@yahoo.com

ARTICLE INFO

Article history:
Received **15 December 2013**
Accepted **21 April 2014**
Available online **19 Decembrt 2015**

Keywords:
CWSI
Eggplant
Evapotranspiration
Greenhouse
Limiting baselines

ABSTRACT-The crop water stress index (CWSI) is the most common index to monitor and assess crop water stress, based on canopy temperature. To calculate CWSI, upper and lower baselines adaptable to different environments are needed. In this study, empirical and theoretical limiting baseline equations were developed to determine eggplant CWSI values at different levels of water deficit and salinity stress. The limiting baseline and CWSI values of eggplant were obtained under different watering intervals (daily, weekly and every two weeks) and different irrigation water salinity levels (i.e. 0.8, 2.5, 5 and 7 dsm^{-1}) for greenhouse and outdoor conditions. The impact of various levels of water deficit and salinity on total evapotranspiration, yield and CWSI was also studied. With the increase of water salinity, a decrease in the slope of lower baseline was met (from 0.195 to 0.146 in the greenhouse and from 0.134 to 0.098 in the outdoor conditions) along with a rise in the upper baseline. Increase in the levels of water deficit led to greater fluctuations in CWSI variations during the growing season. According to the Duncan's test results, CWSI values were significantly affected by water deficit and salinity in both environments

INTRODUCTION

Assessing plant water status can be very useful in irrigation management and consequently in the attainment of sustained agriculture in arid and semi-arid regions. The behavior of the canopy temperature (T_c) under both stress and non-stress circumstances can provide indications for crop water status and yield performance during drought (Alderfasi and Nielsen, 2001). Regarding the rapid expansion of infrared technology, the use of infrared thermometers has become a rapid, reliable, non-contact and non-destructive practice in irrigation scheduling and measuring plant water stress (Irmak et al, 2000). Such a practice is based upon the presumption that water limitation leads to transpiration reduction and temperature increase in plant. Irrigation water salinity can also reveal similar results in agriculture. Based on canopy temperature, crop water stress index (CWSI) has been developed to quantify the level of water stress of crop canopies (Idso et al, 1981; Irmak et al, 2000). The CWSI essentially normalizes the stress degree parameter for environmental variability using the vapor pressure deficit of the air.

At potential evapotranspiration, a linear relationship has been observed between canopy-air temperature differences ($T_c - T_a$) and vapor pressure deficit (VPD) of the air (Idso et al., 1981). Such a relationship diverges from the linear line as transpiration decreases.

Two limiting baselines are needed to derive CWSI: a- the lower baseline indicating no water stress (fully watered crop) and b- the upper baseline representing no transpiration (fully closed stomata) (Yuan et al., 2004; Erdem et al., 2005). The CWSI values range between 0 (maximum transpiration) and 1 (no transpiration). The critical value signifying a reduction in transpiration of plants can be found between 0.25–0.35 (Roth and Goyne, 2004).

Several empirical and theoretical methods have been developed to quantify CWSI. Applying the theoretical methods is dependent on tools or methods determining net radiation and aerodynamic resistance, but enables the calculation of canopy conductance (Smith, 1988; Kjelgaard, et al., 1996; Leinonen et al., 2006). Empirical methods (Idso et al., 1981) surmount this problem by applying full and no-stressed references accounting for the CWSI upper and lower limits, respectively and therefore, the meteorological measurements are minimized (Jensen et al., 1990; Lhomme and Monteny, 2000; Cohen et al. 2005; Grant et al., 2007). However, to use such stress reference surfaces is an indisputable obstacle for such methods.

A comparison by Wanjura and Upchurch (2000) between the empirical and theoretical methods for corn and cotton on the High Plains of Texas showed that the empirical Idso method was rather more accurate than the theoretical approach of Jackson. Yuan et al. (1999) evaluated the application of the Idso and the Jackson forms of CWSI for winter wheat water stress monitoring in the North China Plain and showed the preference of the Jackson method in comparison with the Idso's definition. Ben-Gal et al. (2009) tested both the analytical and the empirical methods in an olive orchard with irrigation treatments, and found both methods to perform well, with no statistically significant difference between them.

The quantification and suitability of CWSI to program irrigation for various crops grown under different irrigation systems has been widely investigated by many researchers (Nakayama and Bucks, 1983; Smith, 1988; Yazar et al., 1999; Irmak et al., 2000; Alderfasi and Nielsen, 2001; Yuan et al., 2004; Gonza et al., 2005;, Möller et al., 2007).

Furthermore, incorporation of saline water, like drought stress, leads to a decrease in transpiration (Dudley et al., 2008), which subsequently increases CWSI. Despite considerable research on the relation of water deficit stresses with CWSI, few have spotted the effect of salinity or its combination with water stresses.

The expansion of greenhouse cultivation all over the world has led to the need for accurate formulization of water stress effect on crop evapotranspiration and canopy temperature in such environments to optimize irrigation programming and encounter better yield and crop quality. Nevertheless, the CWSI values and baselines calibrated for outdoor conditions are still applied to schedule irrigation in greenhouse conditions, while the applicability of such values under greenhouse conditions is a matter of uncertainty.

Eggplant is an economically important vegetable crop, produced as 35.3 million tones from 1.9 million ha worldwide. 93% of the eggplant production takes place in Asia, while 7% is produced in Africa, Europe and America (FAO, 2010). Plantation area of eggplant in greenhouses increases year by year with the application of improved agricultural technologies, and the eggplant is the fourth in rank within the greenhouse products, after tomato, pepper and cucumber (Boyaci, 2007).

The objective of this research is to develop baseline equations to calculate eggplant CWSI reflecting water deficit and salinity stresses, and also to study the effect of growth environment (field and greenhouse) on eggplant CWSI values and its relationship with the crop evapotranspiration and yield. It also compares the application of CWSI based on three different methods for detecting eggplant water stress in plastic greenhouses or climates similar to Badjgah (Fars province, Iran).

MATERIALS AND METHODS

Experimental procedure

The experiment was conducted on eggplant (*Solanum melongena L.*) crops in a 1500 m^2 field located in Badjgah (29°36'N, 52°32'E), College of Agriculture, Shiraz University, Shiraz, Iran, in a 120 m^2 area unheated plastic greenhouse. Greenhouse weather data including net radiation (R_n), air temperature (T_a), relative humidity (RH) and pan evaporation (E) were recorded using an automated weather station which was installed in the central part of the greenhouse. A similar system in the nearby college weather station was utilized for monitoring outdoor data.

Eggplant seeds of Anamur RZ cultivar which are commonly grown in either fields or greenhouses were sown on 18 March, germinated and raised under glasshouse conditions. Uniform seedlings (about 15 cm in height with four leaves) were transplanted to both field ground and the plastic pots, filled with the same ground soil from the same depth of soil surface, on the 5^{th} of May. Some physical and chemical soil characteristics are presented in Table 1. According to the chemical properties of the soil, 1 g mono ammonium phosphate was implemented for each soil pot before transplanting, and 2 g potassium nitrate was applied to each pot as 50%, 25% and 25% in three stages during the growth period (i.e. transplant, beginning flowering and start of harvest, respectively). Water stress and salinity treatments were initiated on the 19^{th} of May, 2012, when the plants had become established; before that, they were irrigated daily with tap water (also used as control treatment).

Table 1. Some physical and chemical characteristics of the soil

Soil Depth (m)	Field Capacity (Mass Percent)	Wilting Point (Mass Percent)	Bulk Density (gr cm^{-3})	pH	ECe (dSm^{-1})	N_{total} (%)	K ($mgkg^{-1}{}_{soil}$)	P ($mgkg^{-1}{}_{soil}$)
0 - 0.3	30.5	11	1.3	7.72	0.55	0.2	600	12.5

The experiment was undertaken according to the completely randomized design with three replicates per treatment. Irrigation frequency treatments consisted of: I_1, daily irrigation; I_2, irrigation at pot field capacity moisture level per every week interval; I_3, irrigation at pot filed capacity moisture level per two weeks interval. Salinity water treatments included irrigation water with electrical conductivities of J_1, 0.8 (tap water); J_2, 2.5; J_3, 5.0 and J_4, 7.0 $dS.m^{-1}$. 12 similar treatments were applied for greenhouse and outdoor experiments. Plastic pots with 35 cm diameter and 60 cm height were utilized for each treatment as microlysimeters in the greenhouse and the adjacent field. In outdoor cultivation, the plastic pots were installed into the ground in the center of each block allocated to each treatment, in which 9 crops were grown. Daily crop evapotranspiration (ET_c) values for each treatment were determined by diurnal weighting of each pot and by using equation 1 based on the water balance method (Jackson et al., 1981):

$$ET_c = \frac{\left[\dfrac{(W_n - W_{n+1})}{\rho_w} + (I - D_p)\right]}{A} \tag{1}$$

where, ET_c is the daily evapotranspiration (cm), I and D_p are the amount of applied and drainage water (cm^3), W_n and W_{n+1} are pot weights in two consecutive days (g), ρ_W is water bulk density (1 g cm^{-3}) and A is the top area of the cylindrical pots (cm^2). Due to the diurnal weighing of each pot, possible error due to the plant weight increase was indeed very little and negligible. Leachate (D_p) was collected and measured after irrigation using empty pots placed underneath of each cultivated pot. The irrigation water amount (I) needed to provide the field capacity moisture content of each pot was calculated as:

$$I = \frac{\frac{W_{FC} - W}{\rho W}}{1 - LF} \quad (2)$$

In which, W and W_{FC} are the pot weight (g) just before irrigation and at field capacity, respectively. LF is leaching fraction, set to a target of 0.15 as suggested by Ayers and Westcot (1985) for efficient irrigation. To obtain a specific level of water salinity for each treatment, the amount of Na (NaCl) applied was equal to Ca ($CaCl_2$) in order to prevent the destructive effect of SAR increase on soil structure and water gas movement.

Canopy temperature (T_c) of each treatment was measured using an Infratrance Model (Kane-May Limited Inc.), a portable hand-held infrared thermometer, and sensing radiation in the wavelength range of 7.5 to 14 μm. The instrument was held toward the green canopy at an angle of 45° below the horizon with a distance of 0.5 m. T_c measurements were taken every week at two consecutive days, so that for I_2 and I_3 treatments, T_c values were determined just before (1st day) and a day after (2nd day) irrigation; reminding that the I_3 treatments were irrigated every two weeks. The thermometer emissivity was calibrated with regard to the leaves color applying the Blad and Rosenberg (1976) method, at the days of measurements. For each crop, three canopy temperature readings were taken from the east and 3 from the west, and then, they were averaged. T_c values were measured from 11:00 to 14:00, when the temperature differences between stressed and non-stressed crops are at maximum. Weather data including, T_a, RH and R_n were determined using Max. and Min. thermometer, hydrograph, and Pergeometer, respectively and recorded at each measurement. Measured values were used to determine the limiting baseline equations for CWSI calculation in different methods.

Fruits were hand-harvested and weighted occasionally in August and September. Shoot and root dry weights were next determined. Finally, soil samples taken from each pot, were air dried and passed through a 2-mm screen. Saturated soil pastes were prepared, and saturation extracts were taken after 24h and their electrical conductivities (ECe) were measured.

Modeling crop water stress index (CWSI)

Considering the different definitions of lower limiting baseline, several methods have been developed to calculate the CWSI. Regarding the empirical linear relationship between $(T_c - T_a)$ and VPD for a fully irrigated crop, Idso et al. (1981), derived the following equation:

$$CWSI_{Idso} = \frac{(T_c - T_a)_m - (T_c - T_a)_{LB}}{(T_c - T_a)_{UB} - (T_c - T_a)_{LB}} \quad (3)$$

In which, $(T_c - T_a)_m$ refers to the difference for measured values of T_c and T_a; $(T_c - T_a)_{UB}$ is the maximum canopy-air temperature for a severely stressed crop (upper baseline) and $(T_c - T_a)_{LB}$ denotes the lower baseline as the difference between the two temperatures when evapotranspiration is not restricted by water availability, expressed as:

$$(T_c - T_a)_{LB} = a + b.VPD \quad (4)$$

$$(T_c - T_a)_{UB} = a + b.VPG \quad (5)$$

where, VPD is the saturated vapor pressure deficit for the maximum daily stress (kPa), a and b are the linear regression coefficients obtained for the lower baseline. VPG is the vapor pressure gradient, defined as the difference between the saturation vapor pressure evaluated at air temperature (T_a) and temperature equal to $T_a + a$.

The values of a and b have been developed for different crops (Idso, 1982; Glenn et al., 1989; Moriana et al., 2002; Orta et al., 2003; Roth and Goyne, 2004; Testi et al., 2008; Sneha et al., 2013) under a wide range of climatic conditions, from semi-arid (Wanjura and Upchurch, 2000) to sub-humid/sub-tropical regions (Jones et al., 2002). Furthermore, due to the change of weather data with location, time of day and year and its coincident effect on leaf temperature, it has been shown that the upper and lower baselines for the same crop may consequently differ with weather data conditions (James, 1988; Payero and Irmak, 2006; Zia et al., 2010). Jackson et al. (1981) derived another method to determine CWSI, viewed as a theoretical basis for the empirical relationship between $T_c - T_a$ and VPD based on the one-layer canopy energy balance model:

$$CWSI_{Jackson} = \frac{\gamma\left(1 + \frac{r_c}{r_a}\right) - \gamma\left(1 + \frac{r_{cp}}{r_a}\right)}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \quad (6)$$

In which, γ is the psychometric coefficient (kPa°C^{-1}), r_a is the slope of the saturation vapor pressure-temperature curve (kPa°C^{-1}), r_a is the aerodynamic resistance (sm^{-1}), r_c and r_{cp} are the water vapor diffusion resistance of the canopy under actual and potential evaporation states, respectively (sm^{-1}). The ratio of r_c to r_a is determined as follow:

$$\frac{r_c}{r_a} = \frac{\Delta (T_c - T_a)_m + VPD}{\gamma \left[\frac{r_a . R_n}{\rho . C_p} - (T_c - T_a)_m \right]} - 1 \quad (7)$$

$$r_a = 4.72 \frac{\left[\ln\left(\frac{z-d}{z_0}\right)\right]^2}{1+0.54u} \quad (8)$$

where, R_n is the net radiation ($MJm^{-2}day^{-1}$); ρ is the air density (kgm^{-3}), C_p is the specific heat of the air ($MJm^{-2}day^{-1}$); u is wind speed (ms^{-1}), z is the reference height of wind measurement (m); d, is the zero plane displacement height (m), z_0, is the roughness length (m). z_0 and d values are derived from field-measurement of plant height (h (m)) as z_0 = 0.13h and d=0.67h. The canopy resistance at potential transpiration (r_{cp}) was determined for each measuring day, modifying its value until the minimum CWSI value on that day was zero. This method was applied by Jackson et al. (1981) to determine the canopy resistance of a wheat crop after irrigation.

Regarding the upper and lower baselines, equation 6 has been derived as below (Yazar et al., 1999):

$$(T_c - T_a)_{LB} = \frac{r_a(R_n - G)}{\rho.c_p}\frac{\gamma(1+\frac{r_{cp}}{r_a})}{\Delta+\gamma(1+\frac{r_{cp}}{r_a})} - \frac{VPD}{\Delta+\gamma(1+\frac{r_{cp}}{r_a})} \quad (9)$$

$$(T_c - T_a)_{UB} = \frac{r_a(R_n - G)}{\rho.c_p} \quad (10)$$

In which G is the soil heat flux density ($MJ\ m^{-2}day^{-1}$). In this research, R_n values were measured by pergeometers and albidometers installed in the greenhouse and outdoor stations. The soil heat flux is ignored (G=0) in daily applications.

Statistical analysis

To assess the impact of various levels of water deficit and salinity on total evapotranspiration, yield and CWSI, a simple analysis of variance was used in each environment. A compound analysis of variance was also applied to the effect of each factor in greenhouse and outdoor environments. The data were analyzed applying the SAS statistical analysis software package. All statistical tests were performed at the 0.05 level of significance. Duncan's test was applied to determine the differences between the averages of the groups.

RESULTS AND DISCUSSION

Climatic data

The meteorological data of the outdoor and greenhouse stations covering the period of May, 19 to September, 5, 2012 were analyzed for the purposes of calculating evapotranspiration by the different methods. Fig. 1-a,b show daily variation of temperature, relative humidity and net radiation and pan evaporation data for greenhouse and outdoor conditions.

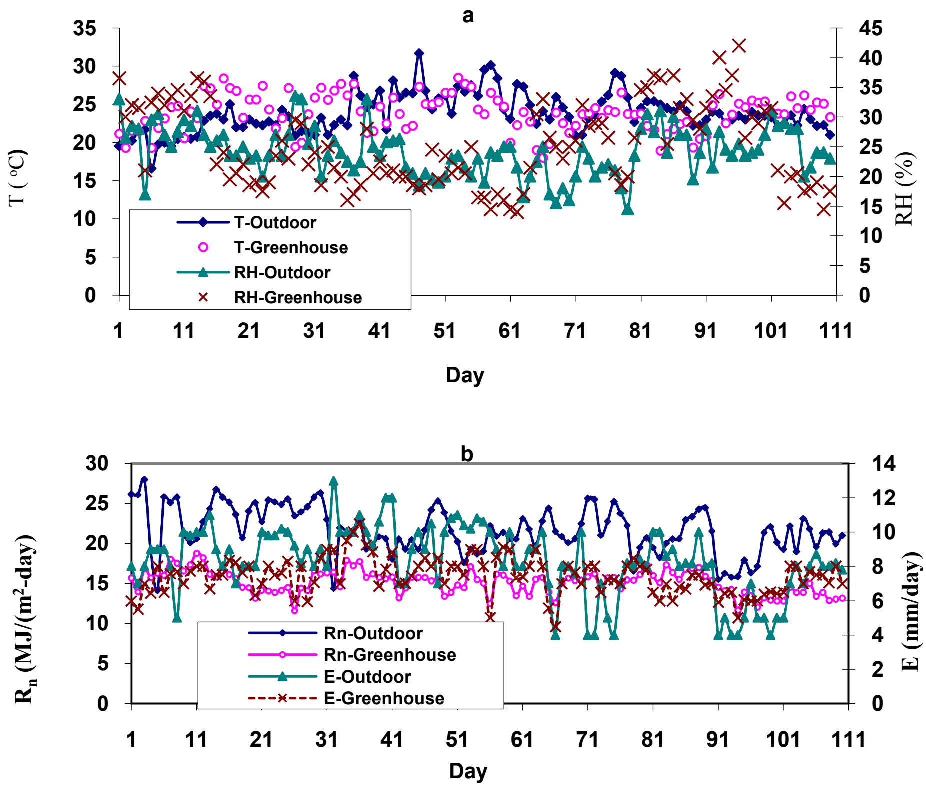

Fig. 1. Daily variations of a) temperature (T) and relative humidity (RH) and b) net radiation (R_n) and pan evaporation (E)

Irrigation

Irrigation was carried out in fixed intervals to provide field capacity moisture in the 0 to 30 cm soil depth of each pot. Throughout the growing season, 893 and 818 mm of evaporation was met in outdoor and greenhouse conditions, respectively. Total irrigation water amount (I_t) utilized in each treatment in outdoor and greenhouse cultivations is indicated in Tables 2 and 3. The lowest and highest amounts of total irrigation water were applied to I_1J_1 and I_3J_4 in both outdoor and greenhouse treatments. The total amount of irrigation water values ranged from 278 to 924 mm in the outdoor treatments while such values were between 214 to 676 mm in the greenhouse ones.

Table 2. The effect of different levels of water deficit and salinity on ECe, I_t, total ET_c, mean yield and CWSI in the outdoor conditions

Treatment	Ece (ds/m)		ET_{ctotal} (mm)		Y (gr/plant)		I_t (mm)		CWSI Idso et al.	Method	Jackson et al.	Method
I_1J_1	2.7	e	846.6	a	2490.1	ab	924.3	a	0.04	h	0.00	h
I_1J_2	8.5	d	680.9	b	1713.2	cd	758.6	b	0.39	f	0.32	f
I_1J_3	10.6	cd	604.4	bc	1690.8	cd	682.1	bc	0.40	f	0.33	f
I_1J_4	11.4	cd	532.7	cd	1536.4	cde	610.4	cd	0.41	f	0.34	f
I_2J_1	3.17	e	604.7	bc	2720.3	a	662.8	bc	0.32	g	0.25	g
I_2J_2	9.8	d	476.6	cde	1723.2	cd	539.1	cde	0.63	d	0.58	d
I_2J_3	12.8	bc	417.9	def	1282.4	cdef	482.5	def	0.77	c	0.74	c
I_2J_4	15.2	ab	380.3	efg	806.8	def	447.1	efg	0.80	c	0.78	c
I_3J_1	4.3	e	439.2	de	1909.9	bc	481.5	de	0.54	e	0.48	e
I_3J_2	14.4	b	299.6	fgh	1165.4	cdef	356.6	fgh	0.91	b	0.90	b
I_3J_3	14.4	b	251.4	gh	956.2	def	308.8	gh	0.96	a	0.96	a
I_3J_4	17.4	a	215.7	h	527.9	f	277.6	h	0.97	a	0.97	a

Table 3. The effect of different levels of water deficit and salinity on ECe, I_t, total ET_c, mean yield and CWSI in the greenhouse conditions

Treatment	Ece (ds/m)		ET_{ctotal} (mm)		Y (gr/plant)		I_t (mm)		CWSI Idso et al.	Method	Jackson et al.	Method
I_1J_1	1.6	d	598.5	a	2405.3	ab	676.2	a	0.02	h	0.00	g
I_1J_2	9.9	c	495.9	b	1849.7	c	573.7	b	0.16	g	0.04	g
I_1J_3	11.6	bc	443.3	bc	1141.5	de	521.0	bc	0.39	f	0.28	f
I_1J_4	13.9	ab	385.8	cd	1006.4	def	463.5	cd	0.49	e	0.39	e
I_2J_1	2.1	d	394.2	cd	2679.0	a	460.8	cd	0.14	g	0.07	g
I_2J_2	11.7	bc	294.3	de	1590.0	cd	363.7	de	0.40	f	0.31	f
I_2J_3	11.6	bc	275.9	e	962.1	ef	345.7	e	0.52	d	0.45	d
I_2J_4	14	ab	242.2	ef	779.3	ef	313.1	ef	0.61	c	0.54	c
I_3J_1	2.7	d	233.4	ef	2080.6	bc	293.1	ef	0.40	f	0.31	f
I_3J_2	11.9	bc	171.4	f	914.0	ef	236.2	f	0.73	b	0.67	b
I_3J_3	12.5	bc	169.3	f	779.3	ef	235.4	f	0.71	b	0.66	b
I_3J_4	16.4	a	145.3	f	497.9	f	213.8	f	0.88	a	0.85	a

Eggplant evapotranspiration and yield

Fig. 2 illustrates the outdoor and greenhouse eggplant cumulative evapotranspiration (CET) during the growing season under different treatments of water deficit and salinity. The highest values of CET_s were found in I_1J_1, I_1J_2, I_1J_3 and I_2J_1 treatments with the total values of 846.6, 680.9, 604.4 and 604.7 mm, respectively, while the lowest CETs were observed in I_3J_3 and I_3J_4 as 251.4 and 215.7 mm, respectively (Fig. 2-a).

Almost the same stepwise changes in the amplitude of the CET curve with increasing EC were observed in the greenhouse pots (Fig. 2-b), but the rate of CET increase observed was lower than that of outdoor treatments; in other words, the total CET in greenhouse ranged between 0.55 to 0.75 CET in outdoor conditions for different treatments.

The difference between the CET curves of I_1J_1 and other treatments was greater in outdoor condition compared to greenhouse, which shows outdoor eggplants evapotranspiration to be more sensitive to water deficit and salinity. Furthermore, a distinct CET decrease was met versus the increase of water salinity. The total ET demand under the greenhouse fresh water-irrigation conditions (J_1) is around 1.5 to 1.6 times as much as CET in J_4 treatments; while such ratio was between 1.6 and 1.8 in greenhouse treatments.

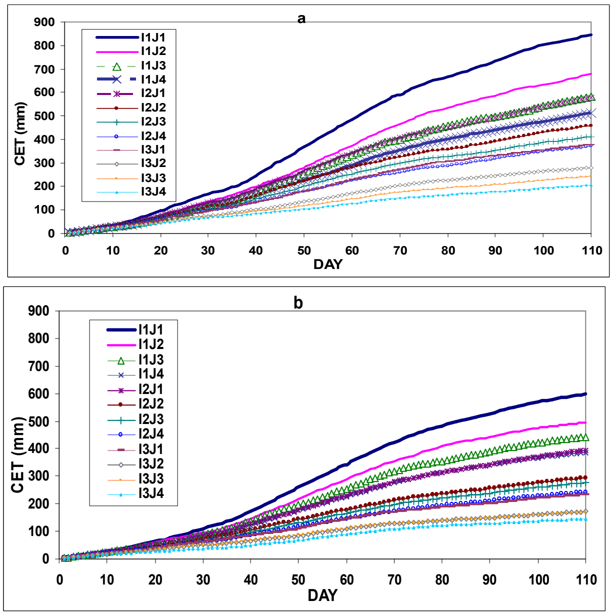

Fig. 2. Cumulative evapotranspiration throughout growing season in different water deficit and salinity levels in a) outdoor and b) greenhouse conditions

Total eggplant evapotranspiration (ET_c) and mean yields (Y) under greenhouse and outdoor conditions are given in Tables 2 and 3, respectively. The differences of the treatments are shown using Latin letters in the Duncan's test result. Based on the results of the Duncan's test, different watering regimes and salinity levels showed significant effects on ET_c values in both environments ($p<0.05$); however, no significant difference was observed between J_3 and J_4 treatments. Similarly, the interactive effects between irrigation and salinity treatments were not significant in both environments. It was shown that irrigation and salinity treatments had significant effects on eggplant yield (Y). However, no significant difference was met between I_1 and I_2 treatments neither in outdoor nor in greenhouse conditions ($p<0.05$).

ECe values

The values of measured soil extract salinity related to each level of water deficit and salinity are reported in Tables 2 and 3 for greenhouse and outdoor treatments, respectively. As indicated in the tables, the ECe values escalated with increasing salinity levels of irrigation water; meanwhile, water deficit intensified soil extract salinity from I_1 to I_3 treatments in both outdoor and greenhouse environments. Results of an ANOVA analysis showed significant effects of water deficit and salinity factors on ECe values in both environments. However, the interaction of these factors revealed no significant difference in ECe values. In outdoor conditions, the maximum ECe value measured in I_1 treatment was 11.4 ds/m while such value reached 17.4 ds/m in I_3 treatments. A similar trend was met in ECe variations in greenhouse, but the effect of irrigation water salinity was more evident in each treatment, while the intensity of water deficit was less effective in the ECe values. The ECe values ranged from 1.6 (I_1J_1) to 13.9 (I_1J_4) ds/m in I_1 treatment, while an increase from 2.7 (in I_3J_1) to 16.4 (in I_3J_4) ds/m was observed (please check the treatments I edited).

Limiting baselines

The limiting baselines were determined as linear relationships between (T_c-T_a) and VPD, obtained by empirical Idso et al. (1981) and theoretical Jackson et al. (1981) methods. Figs. 3 and 4 demonstrate the defined baselines for greenhouse and outdoor conditions, respectively. As shown in figs. 3-a and 4-a, the empirical method allows defining particular upper and lower baselines for each salinity treatment, through which the effect of water salinity on crop stress can be investigated distinctively. It can be concluded that with the increase of irrigation water salinity from J_1 to J_4, the slope of linear relationship between (T_c-T_a) and VPD (the lower baseline) declined from -0.195 to -0.146 in the greenhouse and from -0.134 to -0.098 in the outdoor conditions (Tables 4 and 5, respectively). Furthermore, as the salinity increased, the upper limiting baseline shifted from 1.49 to 5.75 in the greenhouse and from 2.04 to 3.45 in the outdoor at J_1 to J_4 treatments. In both environments, the limiting baselines of J_1 treatments lied with a distance from J_2, J_3 and J_4 treatments which were comparatively closer. The lower limiting baseline equations obtained from the theoretical Jackson et al. method were similar to those of empirical Isdo et al. method for J_1 treatments, in both environments (Tables 4 and 5) which indicates that despite its proper ccuracy, the theoretical method is insensitive to the effect of water salinity.

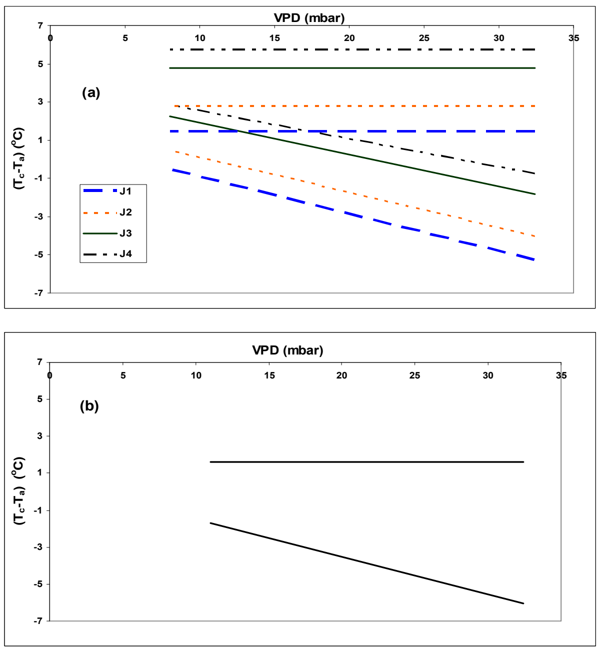

Fig. 3. Upper and lower baselines for greenhouse eggplant determined by a) Idso et al. method b) Jackson et al. method

The results indicate milder slopes of lower limiting baselines in greenhouse in comparison with those obtained in outdoor conditions. The slopes of the lowest baseline obtained in greenhouse were -0.134 and -0.155 for empirical and theoretical methods, respectively while such values were -0.195 and -0.204 in outdoor baselines.

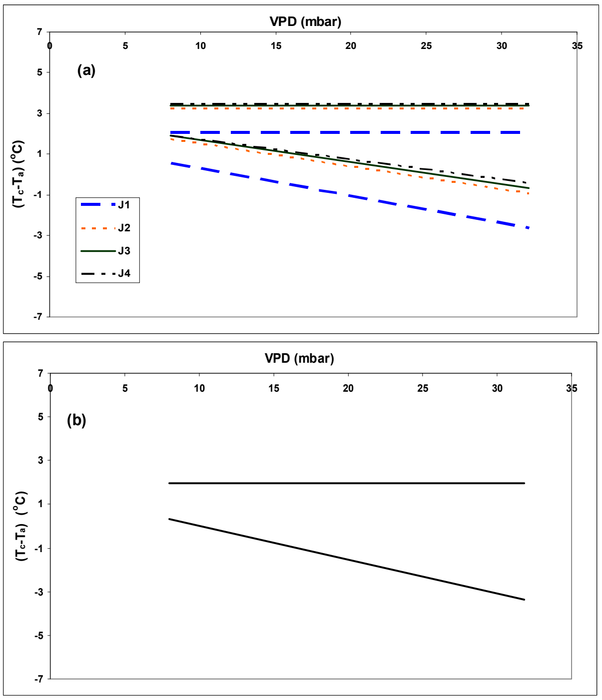

Fig. 4. Upper and lower baselines for outdoor eggplant determined by a) Idso et al. method b) Jackson et al. method

Table 4. Linear regression coefficients of lower baseline ($(T_C-T_a)_{LB}$ = a + b.VPD) and average values of $(T_C - T_a)_{UB}$ for greenhouse eggplants

	$(T_C - T_a)_{LB}$ = a + b.VPD			$(T_C - T_a)_{UB}$
	a	b	R^2	
Method	('C)	('C/mbar)		('C)
Idso et al. for J_1	1.076	-0.195	0.82	1.49
Idso et al. for J_2	1.963	-0.185	0.69	2.79
Idso et al. for J_3	3.589	-0.167	0.80	4.78
Idso et al. for J_4	4.000	-0.146	0.75	5.75
Jackson et al.	0.565	-0.204	0.93	1.62

CWSI values

The variations of CWSI during the eggplant growing season, calculated from the empirical Idso et al. and the theoretical Jackson et al. definitions are shown in Fig. 5 and 6 for greenhouse and outdoor plants, respectively.

Each Figure includes the CWSI changes in a) I_1 and b) I_3 treatments as the extreme treatments of irrigation frequency factor. Concurrent patterns with irrigation events were observed so that the CWSI values in irrigated pots generally fell very close to zero following each irrigation event, then rose steadily to a maximum value just before the next irrigation application as the soil water in the crop root zone was depleted.

Table 5. Linear regression coefficients of lower baseline($(T_C - T_a)_{LB}$ = a + b.VPD) and average values of $(T_C - T_a)_{UB}$ for outdoor eggplants

	$(T_C - T_a)_{LB}$ = a + b.VPD			$(T_C - T_a)_{UB}$
	a	b	R^2	
Method	('C)	('C/mbar)		('C)
Idso et al. for J_1	1.624	-0.134	0.79	2.04
Idso et al. for J_2	2.640	-0.113	0.77	3.23
Idso et al. for J_3	2.781	-0.108	0.73	3.38
Idso et al. for J_4	2.685	-0.098	0.78	3.45
Jackson et al.	1.574	-0.155	0.92	1.95

Obviously, the amplitude of the fluctuations increased from I_1 to I_3 treatments, with the intensity of water deficit imposed. In both environments, increase in water stress and salinity led to the trends of increase in empirical and theoretical CWSI values; yet, day-to-day variations were obtained frequently. The variations were lower in I_1 and higher in I_3 treatments. The results indicate that the empirically based CWSI values would exceed the range of 0-1 while the theoretically based values were commonly in that range. However, the values beyond 0-1 range were set to 0 or 1 in the final demonstration. The Jackson et al. CWSI values were somewhat smaller than those of the Idso et al. ones. However, similar trends in their day-to-day variations were met in both environments. The values of $CWSI_{Jackson}$ were correlated with the corresponding values of $CWSI_{Idso}$ with a correlation coefficient of 0.987 and 0.997, respectively for greenhouse and outdoor conditions (Fig. 7).

As shown in Figs. 5 and 6, variations and fluctuations of the greenhouse CWSI values were much greater than those of the outdoor CWSI. This might be a result of relatively higher air humidity in the greenhouse area leading to lower values of VPD and greater slopes of lower baselines at which small changes of VPD caused large variations in $(T_c - T_a)$ and CWSI consequently.

The average values of $CWSI_{Idso}$ and $CWSI_{Jackson}$ for the water deficit and salinity treatments are shown in Tables 2 and 3 for the greenhouse and outdoor conditions, respectively. According to the Duncan's test result, water deficit and salinity showed significant effects on $CWSI_{Idso}$ and $CWSI_{Jackson}$ values in both environments ($p<0.05$). A compound analysis of variance was also applied for a statistical comparison of different CWSI definition methods. As indicated in Table 6, the CWSI values obtained by Idso et al. and Jackson et al. were significantly different in either environment.

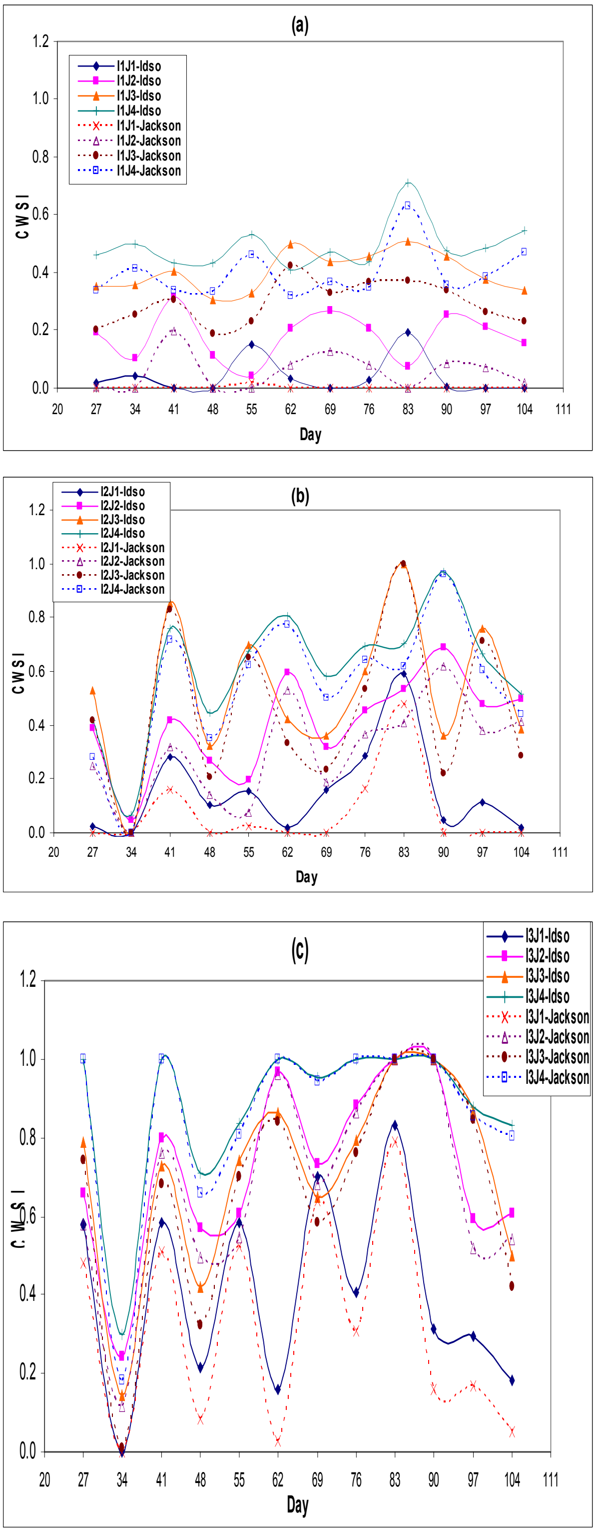

Fig. 5. Variations in the greenhouse $CWSI_{Idso}$ and $CWSI_{Jackson}$ values for a)I_1 b)I_2 and c)I_3 treatments during the growing season

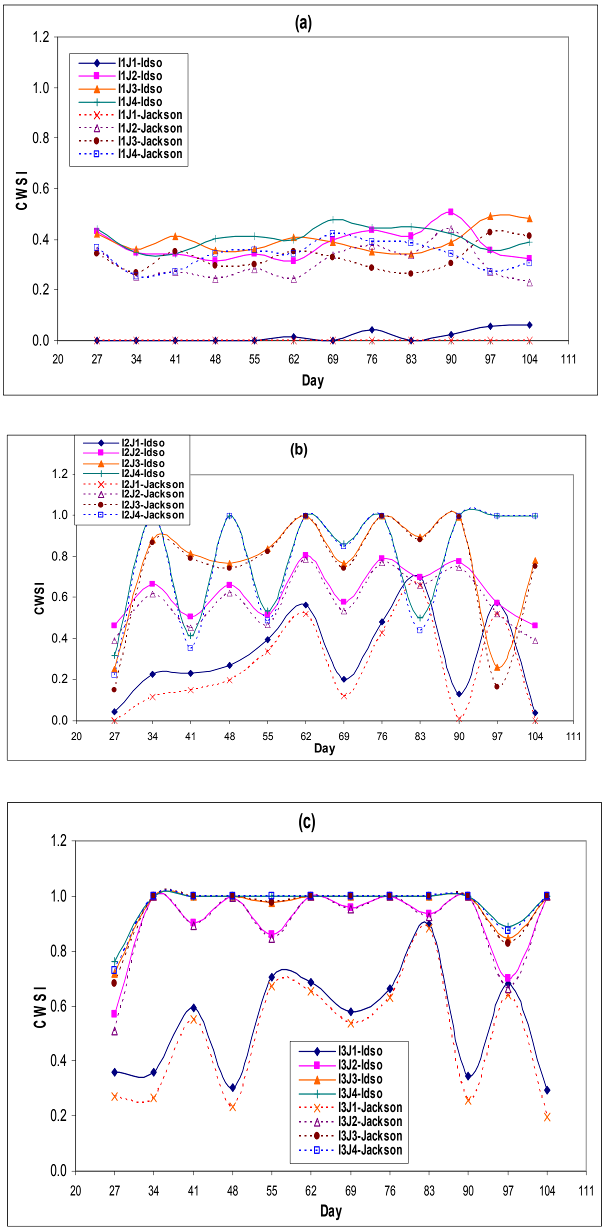

Fig. 6. Variations in the outdoor $CWSI_{Idso}$ and $CWSI_{Jackson}$ values for a) I_1 b) I_2 and c) I_3 treatments during the growing season

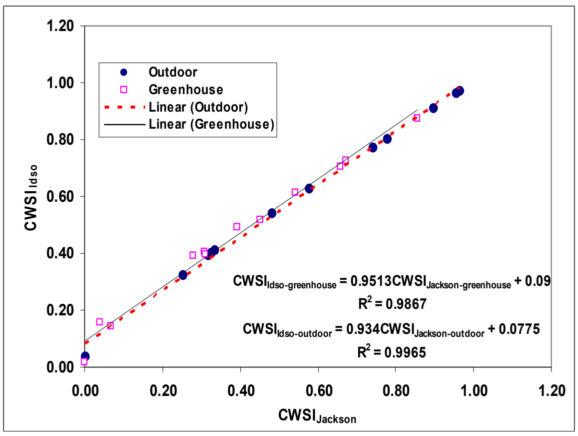

Fig. 7. The correlations of the CWSI values obtained from Idso et al. and Jackson et al. methods in greenhouse and outdoor conditions

Compound analysis of variance

The results of a compound analysis of variance applied for a statistical comparison of I and J effects in greenhouse with outdoor conditions are presented in Table 7. In different environments, I and J showed a significant effect on ET_c and CWSI at 5%, while their interactive effects were not significant on ET_c. Neither the effect of the environment on Y and ECe nor its interactive effects with I and J was not significant.

Correlations of ET_c, ECe, Y and total irrigation water applied (I_t) with the CWSI

Simple correlation analysis showed that there were highly significant linear relationships between the CWSI values and ET_c, ECe, Y and I_t ($P<0.05$). The parameters of the linear regression equations obtained as *CWSI=A+B.X* for each variable are presented in Table 8 for greenhouse and outdoor conditions. As which can be related to the greater fluctuations of the indicated in Table 8, better correlations were observed in the outdoor treatments than the greenhouse ones, greenhouse CWSI values obtained in the greenhouse plants. The best correlations were obtained between CWSI and ET_c in both environments, especially in those applying the $CWSI_{Idso}$.

Table 6. The effect of different calculation methods on the CWSI values in greenhouse and outdoor conditions according to compound ANOVA results

Source	DF	Greenhouse		Outdoor	
		F Value	Pr > F	F Value	Pr > F
Method	1	30.04	<.0001*	17.71	0.0001*
I	2	369.25	<.0001*	1092.52	<.0001*
Method*I[a]	2	0.6	0.5521	1.71	0.1923
J	3	237.02	<.0001*	438.6	<.0001*
I*J	6	7.5	<.0001*	7.31	<.0001*
Method*J	3	0.26	0.8513	0.18	0.9069
Method*I*J	6	0.62	0.7137	0.53	0.7821

* Values are significant at 5%

[a] interaction of each CWSI definition method (Idso and Jackson) with water stress levels (I)

Table 7. Source of variation, related F-ratios and Pr-values calculated from compound ANOVA from SAS software for the ET_c, Y, ECe, $CWSI_{Idso}$ and $CWSI_{Jackson}$

Source	DF	Total ETc		Mean Y		ECe		$CWSI_{Idso}$	
		F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Environment	1	181.52	<.0001*	6.04	0.0177	1.82	0.1837	199.21	<.0001*
I	2	268.66	<.0001*	36.17	<.0001*	34.22	<.0001*	741.07	<.0001*
Environment*I	2	2.62	0.0835	0.77	0.47	7	0.0022	23.68	<.0001*
J	3	54.83	<.0001*	112.87	<.0001*	310.06	<.0001*	390.92	<.0001*
I*J	6	1.39	0.2388	2.46	0.0372	1.79	0.1209	2.91	0.0168
Environment*J	3	3.93	0.0138	1.57	0.2083	1.43	0.246	10.31	<.0001*
Environment*I*J	6	0.14	0.991	1.01	0.429	1.65	0.1548	4.68	0.0008

Table 8. Parameters of linear correlations of the CWSI values with ET_c, ECe, Y, relative decrease in yield (1- Y/Ym), relative decrease in evapotranspiration (1- ET_c /ETm) and I_t in greenhouse and outdoor conditions

Environment	Variable	Idso et al. Method			Jackson et al. Method		
		A	B	R^2	A	B	R^2
Greenhouse							
	ETc (mm)	0.971	-0.002	0.8	0.918	-0.002	0.79
	Y (gr/plant)	0.904	0.000	0.8	0.842	0.000	0.77
	1-ETc/ETm	0.005	0.965	0.8	-0.082	0.999	0.79
	1-Ya/Ym	0.091	0.839	0.82	0.012	0.857	0.79
	ECe (ds/m)	0.052	0.040	0.61	-0.016	0.040	0.55
	I_t (mm)	1.058	-0.002	0.78	1.009	-0.002	0.77
Outdoor							
	ETc (mm)	1.333	-0.002	0.94	1.339	-0.002	0.93
	Y (gr/plant)	1.210	0.000	0.77	1.210	0.000	0.77
	1-ETc/ETm	0.029	1.304	0.94	-0.048	1.388	0.93
	1-Ya/Ym	0.091	0.839	0.82	0.012	0.857	0.79
	ECe (ds/m)	0.062	0.051	0.73	-0.014	0.055	0.72
	I_t (mm)	1.399	-0.002	0.93	1.410	-0.002	0.92

CONCLUSIONS

Empirical and theoretical limiting baseline equations were developed to determine eggplant CWSI values at different levels of water deficit and salinity. Individual baselines were obtained for each level of salinity, using the empirical Idso et al. (1981) method. It was concluded that with the increase of salinity, the slope of lower baseline decreased while the upper baseline shifted higher in both greenhouse and outdoor conditions. However, milder slopes were obtained for greenhouse lower baselines.

The variations in the calculated CWSI values during the growing season revealed concurrent patterns with irrigation events, falling close to zero after each irrigation event and rising to a maximum value just before the next irrigation. The amplitude fluctuations increased by increasing levels of water deficit. The greenhouse values of CWSI were significantly greater than those of the outdoor, which could be related to air humidity in the greenhouse area leading to lower values of VPD and greater slopes of lower baselines. According to the Duncan's test results, CWSI values were significantly affected by water deficit and salinity in both environments. Highly significant linear relationships were obtained between the CWSI values and ET_c, ECe, Y and I_t in both environments; however, better correlations were met between the outdoor CWSI and the aforementioned parameters.

REFERENCES

Alderfasi, A.A., & Nielsen, D.C. (2001). Use of crop water stress index for monitoring water status and scheduling irrigation in wheat. *Agricultural Water Management*, 47, 69-75.

Ayers, R.S., & Westcot, D.W. (1985). Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29, Rev. 1, Rome.

BenGal, A., Agam, N., Alchanatis, V., Cohen, Y., Yermiyahu, U., Zipori, I., Presnov, E., Sprintsin, M., & Dag, A., (2009). Evaluating water stress in irrigated olives: correlation of soil water status, tree water status, and thermal imagery. *Irrigation Science*, 27, 367–376.

Blad, B.L., & Rosenberg. N.J. (1976). Measurement of crop temperature by leaf thermocouple, infrared thermometry and remotely sensed thermal imagery. *Agronomy Journal*, 68, 635–641.

Boyaci, H.F. (2007). Resistance resources and its inheritance against to fusarium wilt in eggplants, CukurovaUniversity, Ph D Thesis, Natural and Applied Sciences. 108 p.

Cohen, Y., Alchanatis, V., Meron, M., Saranga, Y., & Tsipris, J. (2005). Estimation of leafwater potential by thermal imagery and spatial analysis. *Journal of Experimental Botany*, 56, 1843−1852.

Dudley, L.M., BenGal, A., & Shani, U. (2008). Influence of plant, soil and water on the leaching fraction. *Vadose Zone Journal*, 7, 420–425.

Erdem, Y., Erdem, T., Orta, A. & Okursoy, H. (2005). Irrigation scheduling for watermelon with crop water stress index (CWSI). Journal Central European Agricultural, Vol.6,No.4, pp.449-460.

FAO, (2010). Food and Agriculture Organization of The United Nations. http://www.fao.org.

Glenn, D., Worthington, J., Welker, W., & McFarland, M. (1989). Estimation of peachtree water-use using infrared thermometry. *Journal of the American Society for Horticultural Science*, 114: 737−741.

GonzalezDugo M.P., Moran, M. S., Mateos, L., & Bryant. R. (2005). Irrigation Science, DOI 10.1007/s00271-005-0023-7.

Grant, O.M., Tronina, L., Jones, H.G., & Chaves, M.M. (2007). Exploring thermal imaging variables for the detection of stress responses in grapevine under different irrigation regimes. *Journal of Experimental Botany*, 58, 815−825.

Idso, S.B. (1982). Non-water-stressed baselines: A key to measuring and interpreting plant water stress. *Agricultural Meteology*, 27, 59−70.

Idso, S.B., Jackson, R.D., Pinter, P.J., JrReginato, R.J., & Hatfield, J.L. (1981). Normalizing the stress-degree-day parameter for environmental variability. *Agricultural Meteology*, 24, 45–55.

Irmak, S., Haman, D.Z., & Bastug, R. (2000). Determination of crop water stress index for irrigation timing and yield estimation of corn. *Agronomy Journal*, 92(6), 1221–1227.

Jackson, R.D., Idso, S.B., & Reginato, R.J. (1981). Canopy temperature as a crop water stress indicator. *Water Resours Reserch*, 17, 1133–1138.

James, L.G., (1988). Principles of farm irrigation system design. John Wiley and Sons. Inc., New York. 543 p.

Jensen, H.E., Svendsen, H., Jensen, S.E., & Mogensen, V.O. (1990). Canopyair temperature of crops grown under different irrigation regimes in a temperate humid climate. *Irrigation Science*, 11, 181–188.

Jones, H.G., Stoll, M., Santos, T., Sousa, C.D., Chaves, M. M., & Grant, O.M. (2002). Use of infrared thermography for monitoring stomatal closure in the field: application to grapevine. *Journal of Experimental Botany*, 53, 2249−2260.

Kar, G., & Kumar, A. (2010). Energy balance and crop water stress in winter maize under phenology-based irrigation scheduling. *Irrigation Science*, 28, 211–220.

Kjelgaard, J.F., Stockle, C.O., & Evans, R.G. (1996). Accuracy of canopy temperature energy balance for determining daily evapotranspiration. *Irrigation Science*, 16, 149-157.

Leinonen, I., Grant, O.M., Tagliavia, C.P.P., Chaves, M.M., & Jones, H.G. (2006). Estimating stomatal conductance with thermal imagery. *Plant, Cell and Environment*, 29, 1508−1518.

Lhomme, J.P., & Monteny, B. (2000). Theoretical relationship between stomatal resistance and surface temperatures in sparse vegetation. *Agricultural and Forest Meteorology*, 104, 119−131.

Möller, M., Alchanatis, V., Cohen, Y., Meron, M., Tsipris, J., & Ostrovsky, V., (2007). Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. *Journal of Experimental Botany*, 58, 827−838.

Moriana A., Villalobos, F.J., & Fereres, E. (2002). Stomatal and photosynthetic responses of olive (Olea europaea L.) leaves to water deficit. *Plant Cell Environment*, 25.

Nakayama, F.S., & Bucks, D.A. (1983). Application of a foliage temperature based crop water stress index to guayule (Parthenium argentatum). *Journal of Arid Environments*, 6, 269−276.

Orta, A.H., Erdem, Y., & Erdem, T. (2003). Crop water stress index for watermelon. *Scientia Horticulturae*, 98, 121-130.

Payero, J.O., & Irmak, S. (2006). Variable upper and lower crop water stress index baselines for corn and soybean. *Irrigation Science*, 25, 21–32.

Payero, J.O., Neale, C.M.U., & Wright. J.L. (2005). Non-water-stressed baselines for calculating crop water stress index (CWSI) for alfalfa and tall fescue grass. *Translation ASAE*, 48(2), 653–661.

Roth, G. & Goyne, P., (2004). Measuring plant water status. In WATERpak, Australian Cotton CRC/CRDC (http://www.cotton.crc.org.au), p. 157-164.

Sepaskhah, A.R., & Kashefipour, S.M. (1994). Relationships between leaf water potential, CWSI, yield and fruit quality of sweet lime under drip irrigation. *Agricultural Water Management*, 25, 13−22.

Smith, R.C.G. (1988). Inferring stomatal resistance of sparse crops from infrared measurements of foliage temperature. *Agricultural and Forest Meteorology*, 42, 183−198.

Sneha, C., Santhoshkumar, A.V., & Sunil. K.M. (2013). Quantifying water stress using crop water stress index in mahogany (Swietenia macrophylla King) seedlings. CURRENT SCIENCE. 104, NO. 3.

Testi, L., Goldhamer, D.A., Iniesta, F., & Salinas. M. (2008). Crop water stress index is a sensitive water stress indicator in pistachio trees. *Irrigation Science*, 26, 395−405.

Wanjura, D.F., Hatfield, J.L., & Upchurch, D.R. (1990). Crop water stress index relationships with crop productivity. *Irrigation Science*, 11, 93−99.

Wanjura, D.F., & Upchurch, D.R. (2000). Canopy temperature characterizations of corn and cotton water status. *Translation ASAE*, 43, 867–875.

Yazar, A., Howell, T.A., Dusek, D.A., & Copeland, K.S. (1999). Evaluation of crop water stress index for LEPA irrigated corn. *Irrigation Science*, 18, 171–180.

Yuan, G.F., Luo, Y., Sun, X., & Tang, D. (2004). Evaluation of a crop water stress index for detecting water stress in winter wheat in the North China Plain. *Agricultural Water Management*, 64, 29–40.

Zia, S., Spohrer, K., Du, W., Spreer, W., He, X., & Muller, J. (2010). Conference on International Research on Food Security, Natural Resource Management and Rural Development. ETH Zurich, September, 14 – 16.

Zolnier, S., Gates, R.S., Anderson, R.G., Nokes, S.E., & Duncan, G.A. (2001). Non-water-stressed baseline as a tool for dynamic control of misting system for propagation of poinsettias. *Translation ASAE*, 44(1), 137–147.

تحقیقات کشاورزی ایران (۱۳۹۴) ۳۴(۲) ۴۹-۶۰

تعیین CWSI به منظور برآورد تبخیر-تعرق و عملکرد بادنجان تحت شرایط گلخانه و مزرعه

علی اصغر قائمی*[1]، هادی معاضد[2]، محمدرفیع رفیعی[3]، سعید برومند نسب[2]

[1]بخش آبیاری، دانشکده کشاورزی، دانشگاه شیراز، شیراز، ج. ا. ایران
[2]گروه مهندسی آب، دانشکده مهندسی علوم آب، ، دانشگاه شهید چمران اهواز، اهواز، ج. ا. ایران
[3]گروه مهندسی آب کشاورزی، دانشگاه جهرم ، جهرم، ج. ا. ایران

*نویسنده مسئول

اطلاعات مقاله

تاریخچه مقاله:
تاریخ دریافت: ۱۳۹۲/۹/۲۴
تاریخ پذیرش: ۱۳۹۳/۲/۱
تاریخ دسترسی: ۱۳۹۴/۹/۲۸

واژه های کلیدی:
CWSI
بادنجان
تبخیر-تعرق
گلخانه
خطوط مبنای تنش

چکیده- شاخص تنش آبی گیاه (CWSI) یکی از متداول‌ترین شاخص‌های مبتنی بر دمای پوشش سبز، برای پایش و تعیین تنش آبی گیاهان می‌باشد. برای محاسبه CWSI حدود مبنای بالایی و پایینی منطبق بر محیط های مختلف مورد نیاز می‌باشد. در این پژوهش، معادلات خطوط مبنای تجربی و نظری به منظور تعیین مقادیر CWSI گیاه بادنجان در سطوح مختلف تنش آبی و شوری ارائه گردیده است. خطوط مبنا و CWSI بادنجان تحت فواصل مختلف آبیاری (روزانه، هفتگی و دو هفته‌ای) سطوح مختلف شوری آب (یعنی ۰/۸ ، ۲/۵، ۵/۰ و ۷/۰ دسی زیمنس بر متر) در شرایط گلخانه و مزرعه به دست آمد. تاثیر سطوح مختلف تنش آبی و شوری بر تبخیر-تعرق کلی، عملکرد و CWSI نیز مورد مطالعه قرار گرفت. با افزایش شوری آب، کاهشی در شیب خط مبنای پایینی (از ۰/۱۹۵ به ۰/۱۴۶ در گلخانه و از ۰/۱۳۴ به ۰/۰۹۸ مزرعه) توام با صعود خط مبنای بالایی تنش مشاهده گردید.افزایش سطوح تنش آبی به نوسانات بیشتر در مقادیر CWSI در طول فصل رشد منجر گردید. با توجه به نتایج آزمون دانکن مقادیر CWSI در هر دو محیط کشت به طور معنی داری تحت تاثیر کمبود آب و شوری می‌باشند.
.