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

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ARTICLE INFO

Article history:
Received 15 December 2013
Accepted 21 April 2014
Available online 19 December 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 status, 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 (Tc) 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 (Tc – Ta) 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 formulation 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 greenhouse conditions 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 Badjagah (Fars province, Iran).

MATERIALS AND METHODS

Experimental procedure

The experiment was conducted on eggplant (Solanum melongena L.) crops in a 1500 m² field located in Badjagah (29°36’N, 52°32’E), College of Agriculture, Shiraz University, Shiraz, Iran, in a 120 m² 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 and the plastic pots, filled with the same ground soil from the same depth of soil surface, on the 5th 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 19th of May, 2012, when the plants had become established; before that, they were irrigated daily with tap water (also used as control treatment).

<table>
<thead>
<tr>
<th>Table 1. Some physical and chemical characteristics of the soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Depth (m)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>0 - 0.3</td>
</tr>
</tbody>
</table>

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): 

$$ET_c = \frac{\left[ \frac{(W_w - W_{w+1})}{\rho_w} \right] + (I - D_p)}{A} \quad (1)$$

where, $ET_c$ is the daily evapotranspiration (cm), $I$ and $D_p$ are the amount of applied and drainage water (cm³), $W_w$ and $W_{w+1}$ are pot weights in two consecutive days.
irrigated crop, Idso et al. (1981), derived the following equation:

\[
\text{CWSI}_\text{Idso} = \frac{(T_c - T_a)_m - (T_c - T_a)_LB}{(T_c - T_a)_UB - (T_c - T_a)_LB}
\]

(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:

\[
(T_c - T_a)_LB = a + bVPD
\]

(4)

\[
(T_c - T_a)_UB = a + bVPG
\]

(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 linear relationship between \( T_c - T_a \) and VPD based on the one-layer canopy energy balance model:

\[
\text{CWSI}_\text{Jackson} = \frac{\left(1 + \frac{r_c}{r_a}\right) - \left(1 + \frac{r_c}{r_a}\right)}{\Delta + \left(1 + \frac{r_c}{r_a}\right)}
\]

(6)

In which, \( \gamma \) is the psychometric coefficient (kPa°C⁻¹), \( r_s \) is the slope of the saturation vapor pressure-temperature curve (kPa°C⁻¹), \( r_c \) is the aerodynamic resistance (s m⁻¹), \( r_c \) and \( r_w \) are the water vapor diffusion resistance of the canopy under actual and potential evaporation states (s m⁻¹). The ratio of \( r_c \) to \( r_a \) is determined as follow:

\[
\frac{r_c}{r_a} = \frac{(T_c - T_a)_m + VPD}{(T_c - T_a)_m - \left(\frac{R_s}{\rho \cdot C_p} - (T_c - T_a)_m\right)} - 1
\]

(7)

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 dry crop, \( \text{CWSI}_\text{Idso} \) functions of the models. The method applied for this study is introduced as:

\[
\text{CWSI} = \frac{(T_c - T_a)_m - (T_c - T_a)_LB}{(T_c - T_a)_UB - (T_c - T_a)_LB}
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\]

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\[
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\]

(7)

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\[
\text{CWSI} = \frac{(T_c - T_a)_m - (T_c - T_a)_LB}{(T_c - T_a)_UB - (T_c - T_a)_LB}
\]
\[ r_a = 4.72 \left( \frac{\ln \left( \frac{z - d}{z_0} \right)}{1 + 0.54 u} \right)^2 \]  

(8)

where, \( R_n \) is the net radiation (MJ m\(^{-2}\) day\(^{-1}\)); \( \rho \) is the air density (kg m\(^{-3}\)); \( C_p \) is the specific heat of the air (MJ m\(^{-2}\) day\(^{-1}\)); \( u \) is wind speed (m s\(^{-1}\)); \( z \) 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):

\[ (T_a - T_o)_{UB} = \frac{r_a (R_n - G)}{\rho C_p} \left( \frac{1 + r_a}{r_a} \right) \frac{V P D}{\Delta + \gamma (1 + \frac{V P D}{r_a})} \]  

(9)

\[ (T_a - T_o)_{LB} = \frac{r_a (R_n - G)}{\rho C_p} \]  

(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](image-url)  

**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_1J1 and I_3J4 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 EC_e, I_t, total ET_c, mean yield and CWSI in the outdoor conditions

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Ec_e (ds/m)</th>
<th>ET_total (mm)</th>
<th>Y (gr/plant)</th>
<th>I_t (mm)</th>
<th>CWSI</th>
<th>Idso et al. Method</th>
<th>Jackson et al. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_1J1</td>
<td>2.7 c</td>
<td>846.6 a</td>
<td>2490.1 ab</td>
<td>924.3 a</td>
<td>0.04 h</td>
<td>0.00 h</td>
<td></td>
</tr>
<tr>
<td>I_1J2</td>
<td>8.5 d</td>
<td>680.9 b</td>
<td>1713.2 cd</td>
<td>758.6 b</td>
<td>0.39 f</td>
<td>0.32 f</td>
<td></td>
</tr>
<tr>
<td>I_1J3</td>
<td>10.6 cd</td>
<td>604.4 bc</td>
<td>1690.8 ed</td>
<td>682.1 bc</td>
<td>0.40 f</td>
<td>0.33 f</td>
<td></td>
</tr>
<tr>
<td>I_1J4</td>
<td>11.4 cd</td>
<td>532.7 ed</td>
<td>1536.4 cde</td>
<td>610.4 cd</td>
<td>0.41 f</td>
<td>0.34 f</td>
<td></td>
</tr>
<tr>
<td>I_2J1</td>
<td>3.17 e</td>
<td>604.7 bc</td>
<td>2720.3 a</td>
<td>662.8 bc</td>
<td>0.32 g</td>
<td>0.25 g</td>
<td></td>
</tr>
<tr>
<td>I_2J2</td>
<td>9.8 d</td>
<td>476.6 cde</td>
<td>1723.2 cd</td>
<td>539.1 cde</td>
<td>0.63 d</td>
<td>0.58 d</td>
<td></td>
</tr>
<tr>
<td>I_2J3</td>
<td>12.8 bc</td>
<td>417.9 def</td>
<td>1282.4 cdef</td>
<td>482.5 def</td>
<td>0.77 c</td>
<td>0.74 c</td>
<td></td>
</tr>
<tr>
<td>I_2J4</td>
<td>15.2 ab</td>
<td>380.3 efg</td>
<td>806.8 def</td>
<td>447.1 efg</td>
<td>0.80 c</td>
<td>0.78 c</td>
<td></td>
</tr>
<tr>
<td>I_3J1</td>
<td>4.3 e</td>
<td>439.2 de</td>
<td>1909.9 bc</td>
<td>481.5 de</td>
<td>0.54 e</td>
<td>0.48 e</td>
<td></td>
</tr>
<tr>
<td>I_3J2</td>
<td>9.9 c</td>
<td>299.6 fgh</td>
<td>1165.4 cdef</td>
<td>356.6 fgh</td>
<td>0.91 b</td>
<td>0.90 b</td>
<td></td>
</tr>
<tr>
<td>I_3J3</td>
<td>11.6 bc</td>
<td>275.9 ef</td>
<td>962.1 ef</td>
<td>308.8 gh</td>
<td>0.96 a</td>
<td>0.96 a</td>
<td></td>
</tr>
<tr>
<td>I_3J4</td>
<td>17.4 a</td>
<td>215.7 h</td>
<td>527.9 f</td>
<td>277.6 h</td>
<td>0.97 a</td>
<td>0.97 a</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Ec_e (ds/m)</th>
<th>ET_total (mm)</th>
<th>Y (gr/plant)</th>
<th>I_t (mm)</th>
<th>CWSI</th>
<th>Idso et al. Method</th>
<th>Jackson et al. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_1J1</td>
<td>1.6 d</td>
<td>598.5 a</td>
<td>2405.3 ab</td>
<td>676.2 a</td>
<td>0.02 h</td>
<td>0.00 h</td>
<td>g</td>
</tr>
<tr>
<td>I_1J2</td>
<td>9.9 c</td>
<td>495.9 bc</td>
<td>1849.7 c</td>
<td>573.7 b</td>
<td>0.16 g</td>
<td>0.04 g</td>
<td>g</td>
</tr>
<tr>
<td>I_1J3</td>
<td>11.6 bc</td>
<td>443.3 bc</td>
<td>1141.5 de</td>
<td>521.0 bc</td>
<td>0.39 f</td>
<td>0.28 f</td>
<td>g</td>
</tr>
<tr>
<td>I_1J4</td>
<td>13.9 ab</td>
<td>385.8 cd</td>
<td>1006.4 def</td>
<td>463.5 cd</td>
<td>0.49 e</td>
<td>0.39 e</td>
<td>g</td>
</tr>
<tr>
<td>I_2J1</td>
<td>2.1 d</td>
<td>394.2 cd</td>
<td>2679.0 a</td>
<td>460.8 cd</td>
<td>0.14 g</td>
<td>0.07 g</td>
<td>g</td>
</tr>
<tr>
<td>I_2J2</td>
<td>11.7 bc</td>
<td>294.3 de</td>
<td>1590.0 cd</td>
<td>363.7 de</td>
<td>0.40 f</td>
<td>0.31 f</td>
<td>g</td>
</tr>
<tr>
<td>I_2J3</td>
<td>11.6 bc</td>
<td>275.9 e</td>
<td>962.1 ef</td>
<td>345.7 e</td>
<td>0.52 d</td>
<td>0.45 d</td>
<td>g</td>
</tr>
<tr>
<td>I_2J4</td>
<td>14 ab</td>
<td>242.2 ef</td>
<td>779.3 ef</td>
<td>313.1 ef</td>
<td>0.61 c</td>
<td>0.54 c</td>
<td>g</td>
</tr>
<tr>
<td>I_3J1</td>
<td>2.7 d</td>
<td>233.4 ef</td>
<td>2080.6 bc</td>
<td>293.1 ef</td>
<td>0.40 f</td>
<td>0.31 f</td>
<td>g</td>
</tr>
<tr>
<td>I_3J2</td>
<td>11.9 bc</td>
<td>171.4 f</td>
<td>914.0 ef</td>
<td>236.2 f</td>
<td>0.73 b</td>
<td>0.67 b</td>
<td>g</td>
</tr>
<tr>
<td>I_3J3</td>
<td>12.5 bc</td>
<td>169.3 f</td>
<td>779.3 ef</td>
<td>235.4 f</td>
<td>0.71 b</td>
<td>0.66 b</td>
<td>g</td>
</tr>
<tr>
<td>I_3J4</td>
<td>16.4 a</td>
<td>145.3 f</td>
<td>497.9 f</td>
<td>213.8 f</td>
<td>0.88 a</td>
<td>0.85 a</td>
<td>g</td>
</tr>
</tbody>
</table>

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 were found in I_1J1, I_1J2, I_1J3 and I_1J4 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_2J3 and I_2J4 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_1J1 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 (J1) is around 1.5 to 1.6 times as much as CET in J4 treatments; while such ratio was between 1.6 and 1.8 in greenhouse treatments.

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 I1 to I3 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. The ECe values ranged from 1.6 (I1J1) to 13.9 (I3J4) ds/m in I1 treatment, while an increase from 2.7 (I1J1) to 16.4 (I3J4) 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 J1 to J4, 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 J1 to J4 treatments. In both environments, the limiting baselines of J3 treatments lied with a distance from J2, J3 and J4 treatments which were comparatively closer. The lower limiting baseline equations obtained from the theoretical Jackson et al. method were similar to those of empirical Idso et al. method for J1 treatments, in both environments (Tables 4 and 5) which indicates that despite its proper accuracy, the theoretical method is insensitive to the effect of water salinity.
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>
<thead>
<tr>
<th>Method</th>
<th>a</th>
<th>b</th>
<th>R²</th>
<th>(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idso et al. for J1</td>
<td>1.624</td>
<td>-0.134</td>
<td>0.79</td>
<td>2.04</td>
</tr>
<tr>
<td>Idso et al. for J2</td>
<td>2.640</td>
<td>-0.113</td>
<td>0.77</td>
<td>3.23</td>
</tr>
<tr>
<td>Idso et al. for J3</td>
<td>2.781</td>
<td>-0.108</td>
<td>0.73</td>
<td>3.38</td>
</tr>
<tr>
<td>Idso et al. for J4</td>
<td>2.685</td>
<td>-0.098</td>
<td>0.78</td>
<td>3.45</td>
</tr>
<tr>
<td>Jackson et al.</td>
<td>1.574</td>
<td>-0.155</td>
<td>0.92</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Obviously, the amplitude of the fluctuations increased from I1 to I3 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 I1 and higher in I3 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<sub>Idso</sub> were correlated with the corresponding values of CWSI<sub>Jackson</sub> 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<sub>c</sub> - T<sub>a</sub>) and CWSI consequently.

The average values of CWSI<sub>Idso</sub> and CWSI<sub>Jackson</sub> 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<sub>Idso</sub> and CWSI<sub>Jackson</sub> 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.

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) I1 and b) I3 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>
<thead>
<tr>
<th>Method</th>
<th>a</th>
<th>b</th>
<th>R²</th>
<th>(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idso et al. for J1</td>
<td>1.076</td>
<td>-0.195</td>
<td>0.82</td>
<td>1.49</td>
</tr>
<tr>
<td>Idso et al. for J2</td>
<td>1.963</td>
<td>-0.185</td>
<td>0.69</td>
<td>2.79</td>
</tr>
<tr>
<td>Idso et al. for J3</td>
<td>3.589</td>
<td>-0.167</td>
<td>0.80</td>
<td>4.78</td>
</tr>
<tr>
<td>Idso et al. for J4</td>
<td>4.000</td>
<td>-0.146</td>
<td>0.75</td>
<td>5.75</td>
</tr>
<tr>
<td>Jackson et al.</td>
<td>0.565</td>
<td>-0.204</td>
<td>0.93</td>
<td>1.62</td>
</tr>
</tbody>
</table>
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 ETc and CWSI at 5%, while their interactive effects were not significant on ETc. Neither the effect of the environment on Y and ECe nor its interactive effects with I and J was not significant.

Correlations of ETc, ECe, Y, and total irrigation water applied (I) with the CWSI

Simple correlation analysis showed that there were highly significant linear relationships between the CWSI values and ETc, ECe, Y, and I, (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 ETc in both environments, especially in those applying the CWSIdso.

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

<table>
<thead>
<tr>
<th>Source D</th>
<th>Greenhouse</th>
<th>Outdoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>D F</td>
<td>F Value</td>
<td>Pr &gt; F</td>
</tr>
<tr>
<td>Method</td>
<td>1</td>
<td>30.04</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>369.25</td>
</tr>
<tr>
<td>J</td>
<td>3</td>
<td>237.02</td>
</tr>
<tr>
<td>I*J</td>
<td>6</td>
<td>7.5</td>
</tr>
<tr>
<td>Method*I</td>
<td>3</td>
<td>0.26</td>
</tr>
<tr>
<td>Method<em>I</em>J</td>
<td>6</td>
<td>0.62</td>
</tr>
</tbody>
</table>

* 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 ETc, Y, ECe, CWSIdso, and CWSIJackson

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Total ETc</th>
<th>Mean Y</th>
<th>ECe</th>
<th>CWSIdso</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F Value</td>
<td>Pr &gt; F</td>
<td>F Value</td>
<td>Pr &gt; F</td>
</tr>
<tr>
<td>Environment</td>
<td>1</td>
<td>181.52</td>
<td>&lt;.0001*</td>
<td>6.04</td>
<td>0.0177</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>268.66</td>
<td>&lt;.0001*</td>
<td>36.17</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>Environment*I</td>
<td>2</td>
<td>54.83</td>
<td>&lt;.0001*</td>
<td>112.87</td>
<td>&lt;.0001*</td>
</tr>
<tr>
<td>J</td>
<td>3</td>
<td>1.39</td>
<td>0.2388</td>
<td>2.46</td>
<td>0.0372</td>
</tr>
<tr>
<td>I*J</td>
<td>6</td>
<td>3.93</td>
<td>0.0138</td>
<td>1.57</td>
<td>0.2083</td>
</tr>
<tr>
<td>Environment<em>I</em>J</td>
<td>6</td>
<td>0.14</td>
<td>0.991</td>
<td>1.01</td>
<td>0.429</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Environment</th>
<th>Variable</th>
<th>Idso et al. Method</th>
<th>Jackson et al. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>R²</td>
</tr>
<tr>
<td>Greenhouse</td>
<td>ETC (mm)</td>
<td>0.971</td>
<td>-0.002</td>
</tr>
<tr>
<td></td>
<td>Y (gr/plant)</td>
<td>0.904</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>1-ETc/ETm</td>
<td>0.005</td>
<td>0.965</td>
</tr>
<tr>
<td></td>
<td>1-Ya/Ym</td>
<td>0.091</td>
<td>0.839</td>
</tr>
<tr>
<td></td>
<td>ECe (ds/m)</td>
<td>0.052</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td>I (mm)</td>
<td>1.058</td>
<td>-0.002</td>
</tr>
<tr>
<td>Outdoor</td>
<td>ETC (mm)</td>
<td>1.333</td>
<td>-0.002</td>
</tr>
<tr>
<td></td>
<td>Y (gr/plant)</td>
<td>1.210</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>1-ETc/ETm</td>
<td>0.029</td>
<td>1.304</td>
</tr>
<tr>
<td></td>
<td>1-Ya/Ym</td>
<td>0.091</td>
<td>0.839</td>
</tr>
<tr>
<td></td>
<td>ECe (ds/m)</td>
<td>0.062</td>
<td>0.051</td>
</tr>
<tr>
<td></td>
<td>I (mm)</td>
<td>1.399</td>
<td>-0.002</td>
</tr>
</tbody>
</table>
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 ETa, ECe, Y and I, in both environments; however, better correlations were met between the outdoor CWSI and the aforementioned parameters.

REFERENCES


تحقیقات کشاورزی ایران (۱۳۹۴) (۲)۱۳۹۴-۰۹-۰۶

تغییر CWSI به منظور برآورد تبخیر-ترع و عملکرد باندجان

تحت شرایط گلخانه و مزرعه

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چکیده - شاخص نش آب‌کی (CWSI) یکی از متداول‌ترین شاخص‌های مبتکر بر دمای پوشش سبز برای پایش و تغییر نش آب‌کی گیاهان می‌باشد. برای محاسبه حذف مبنای بالایی و یا پایین منطق بر محیط یافته روند نازل می‌باشد. در این پژوهش، معادلات خطوط مبنای تجربی و نظری به منظور تغییر مقادیر CWSI گیاه باندجان در سطوح مختلف نش آب و شوری ارائه گردیده است. خطوط مبنای و CWSI باندجان تحت فاصله مختلف آب‌پذیری روانه، هفته‌ای و دو هفته‌ای سطح مختلف شوری آب (۲۰/۰، ۰/۲۰، ۰/۴۰ و ۰/۶۰ درصد زمستان بر متر) در شرایط گلخانه و مزرعه به دست آمد. نتایج سطوح مختلف نش آب و شوری بر تبخیر-ترع و عملکرد و نیز مورد مطالعه قرار گرفت. با افزایش شوری آب کاهشی در شیب خط مبنای پایینی (از CWSI نیز مورد مطالعه قرار گرفت. با افزایش شوری آب کاهشی در شیب خط مبنای پایینی (از ۱۹۸/۰ به ۱۴۶/۰ در گلخانه و از ۱۴۷/۰ به ۹۸/۰ مزرعه) نمای با صعود خط مبنای بالایی نش مشاهده گردید. افزایش سطح نش آب به نوسانات بیشتر در مقادیر CWSI در طول فصل رشد موجب گردید یا توجه به نتایج آزمون دانک مقادیر CWSI در هر دو محیط کشت به طور معنی‌داری تحت تأثیر کمبود آب و شوری می‌باشد.

اطلاعات مقاله

تأثیر CWSI
بر ابعاد، تبخیر-ترع و عملکرد باندجان

در سطوح مختلف نش آب و شوری

واژه‌های کلیدی:
CWSI
باندجان
تبخیر-ترع
گلخانه

خطوی مبنای نش