Determination of water use and water stress of cherry trees based on canopy temperature, leaf water potential and resistance

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Abstract

This study was carried out in sub-humid climate conditions of Bursa, Turkey during the 21st–22nd of August, 2004. The main objectives were to develop baselines of graph, which is necessary for the calculation of crop water stress index (CWSI) and estimation of evaporation (E) from cherry trees to the air based on crop monitoring data. Two different irrigation water levels (T_1 water stressed and T_2 fully irrigated) were used. Besides canopy temperature, canopy resistance (r_c) and leaf water potential (LWP) were measured. Diurnal measurements were made from 6:50 a.m. (sunrise) to 7:40 p.m. (sunset). Experimental lower base lines and theoretical upper base lines of the basic graphic of CWSI were determined. Instantaneous E values were calculated and cumulative daily E (E_{cum}) and daily E (E_d) calculated by converting only one instantaneous E to the daily E were defined. Although CWSI values of T_1 were raised from sunrise to midday, CWSI values of T_2 were close to zero throughout the measurement days. E_{cum} and E_d values were very similar, thus converting instantaneous E values to daily basis could be used. Significant relationships were determined between CWSI – E and CWSI – LWP for T_1 treatments. Relationships of CWSI – E, and CWSI – LWP were non-significant or poor for T_2 treatment due to the non-fluctuated trend of CWSI. According to the statistical analysis, linear relationships between E and LWP were significant for both water stressed and fully irrigated conditions.

Key words: cherry, crop water stress index, leaf water potential, evapotranspiration, irrigation scheduling.

Introduction

Management of irrigation water with irrigation scheduling was subjected to some researches. Different irrigation scheduling techniques can be used to reduce irrigation water allocation to fruit orchards (Badal et al., 2010; Ben-Gal et al., 2010; Li et al., 2010; Marsal et al., 2010). Plant based water status monitoring (xylem flow, somatal conductance, photosynthesis, leaf temperature and leaf water potential) can improve the reliability of the scheduling (Naor, 2006; Jones, 2007; Ben-Gal et al., 2010). Currently, one of the most useful devices is infrared thermometer which can be used to define irrigation timing and water amount by measurement of canopy temperature.

The relationship between plant canopy temperature and water availability in the soil has been investigated by a suitable thermal index to establish the proper irrigation time (Idso et al., 1981; Jackson et al., 1981; Clawson, Blad, 1982). One of the first indices was the "stress-degree day", based on the

relationship between the difference of the canopy and air temperature (T_c–T_a) with the yield and water requirement of the crop (Jackson et al., 1977). Crop water stress index (CWSI), based on canopy-air temperature difference and vapor pressure deficit (VPD) of air, is the most known stress index (Idso et al., 1981). The authors established critical limits for the temperature difference between the canopy and the air temperature, especially when the canopy resistance to vapor transport assumed an infinite value (upper limit) and the zero value (lower limit). In this case, for well-watered crops under clear sky condition, a linear regression of T_c–T_a and VPD was obtained and used as a baseline to define CWSI. They showed that the CWSI is equal to one minus the ratio of actual to potential evapotranspiration ($1 − E_a/E_p$) obtained from the Penman-Monteith equation (Monteith, 1973).

Perrier (1975 a, b and c) explained surface temperature role in the evapotranspiration. Calculation of energy balance components based on surface temperature could be used to determine instantaneous evaporation (E) from the considered surface to the air. In this manner, surface temperature measured with hand held radiometers is useful to calculate real time sensible heat flux of energy balance. On the other hand, latent heat flux could be calculated based on some climatic variables and aerodynamic and canopy resistance (Glen et al., 1989). Converting instantaneous E to the daily E was subjected to some researches. The three best known methods of converting were developed by Jackson et al. (1983), Bastiaanssen et al. (1998) and Allen et al. (2005).

The aim of this study was to determine the base lines of basic calculation graph of CWSI for cherry trees, to evaluate the CWSI and LWP as irrigation timing indicator and to investigate E from cherry trees to the air estimated based on the measurement taken at one time of day as a tool to determine the required irrigation water amount.

Materials and methods

Experimental procedures. In this study, the data were measured from a field trial carried out on irrigation management of sweet cherry trees during the 21st and 22nd of August, 2004. The field was located in Bursa (western part of Turkey, 40º15′29″ N latitude, 28º53′39″ E longitude, and altitude of 100 m above mean sea level). The meteorological data were taken from Bursa central meteorological station which is 750 m away from the experimental site. According to the data, climate is sub-humid. Annual rainfall, temperature and relative humidity are 691.9 mm, +14.4ºC and 68.6%, respectively. Soil

texture is characterized as heavy and Total Available Moisture (TAM) was 136 mm m^{-1}. Plant material studied was sweet cherry trees (*Prunus cerasus* x *Prunus canescens,* variety Z-900) on 2-year old Gisela-5 dwarf rootstocks.

The trees were planted in 2002, 5 x 2.5 m apart. The experimental design was a completely randomized block design with three replications and each plot had nine cherry trees. The trees were subjected to two micro-sprinkler irrigation treatments (T_1 and T_2). T_1 and T_2 treatments were programmed using two reduction percentages of the US Weather Bureau Class A pan evaporation on weekly basis. The water applied in treatment T_2 was considered sufficient to fully satisfy the needs of the crop (100% of crop evapotranspiration, ET_c) and to allow good rooting and tree growth.

The total amount of irrigation water (TIW) applied was calculated based on the methodology given by Allen et al. (1998):

$$TIW = \frac{K_p \cdot K_c \cdot K_l}{E_a \cdot E_u} E_{pan} \qquad (1),$$

where K_p is the pan coefficient (0.70; Doorenbos, Pruitt, 1977), K_c is the crop coefficient (0.50 for June, 1.20 for July and August and 0.95 for September and October; Allen et al., 1998), K_l is the shade coefficient (0.61; Vermeiren, Jobling, 1986) taking into account that the estimated mean shade surface provided by the tree canopies was 46% of the total surface of the orchard, E_a is water application efficiency (0.90), E_u is the coefficient of uniformity of emitters (0.9; according to micro sprinkler producer). Irrigation water calculated for T_2 treatment was applied to both T_1 and T_2 treatments until DOY 171. Between DOY 172 and DOY 233, full and limited water were applied to trees of T_2 and T_1 treatments, respectively.

Applying the reduction percentage mentioned above to Eq. (1) gives the following total amounts of irrigation water (TIW) treatment:

$$TIW_{(T1)} = 0.32\ E_{pan} \qquad (2),$$

$$TIW_{(T2)} = 0.63\ E_{pan} \qquad (3).$$

Measurements. The diurnal measurements were carried out between 6:50 a.m. and 7:40 p.m. on the 21st and 22nd August, 2004. Since the application of irrigation water based on treatments was carried out between DOY 171 (19th of June) and DOY 233 (20th of August), measurements were made on these dates. To determine water stress clearly, and to investigate the use of one time of day measurements for evaporation estimation, diurnal change of

parameters related to leaf water status and canopy temperature were monitored. At the same time air wet and dry bulb temperatures were measured at the height of 1.5 m. Canopy temperatures were measured by an Everest Interscience Model 103 ZL infrared thermometer with a 4° field-of-view. The leaf resistance to water transport was measured with a Delta T Model AP4 porometer on one mid-shoot leaf for the same directions with infrared thermometer. The leaf water potential measurements were made with PMS Model 1000 pressure chamber utilizing compressed N gas.

Evapotranspiration. The energy balance for a crop was given by Monteith (1973) as:

$$R_n = G + H + \lambda E \qquad (4),$$

where R_n is the net radiant heat flux density, G is the soil heat flux density, H is the sensible heat flux density and λE is the latent heat flux density to the air (the product of evapotranspiration rate, E and the heat of vaporization, λ). All terms in the equation are in units of W m^{-2}. λE can be expressed as:

$$\lambda E = \rho\, C_p\, VPD\, /\, \gamma\, (r_a + r_c) \qquad (5),$$

where E is the evaporation rate (g s^{-1} m^{-2}), ρ is the density of the air (g m^{-3}), C_p is the specific heat of the air (J g^{-1} °K^{-1}), VPD is the vapor pressure deficit of the air (Pa), λ is the latent heat of vaporization (J g^{-1}), γ is the psychrometric constant (Pa °K^{-1}), r_a is the stability corrected aerodynamic resistance (s m^{-1}) and r_c is the canopy resistance (s m^{-1}) to water transport (Glen et al., 1989). According to Hatfield et al. (1983) stability corrected aerodynamic resistance can be expressed as:

$$r_a = \frac{\left[\ln\left[(z-d)/z_o\right]\right]^2}{\left(k^2 u\right)}\left[1 - \frac{n(z-d)g(T_c - T_a)}{\left(T_o u^2\right)}\right]$$
$$(6),$$

where z is the reference height of wind measurement (m), d is the zero plane displacement (m), z_o is the surface roughness height (m), k is Von Karman's constant (0.41, unitless), u is the wind speed at reference height (m s^{-1}), n is an empirical constant. Monteith (1973) suggested a value of 5, g is the acceleration due to gravity (9.8 m s^{-2}), $T_c - T_a$ (°K), canopy minus air temperature, T_o (°K), the average temperature (usually taken as the air temperature).

Hourly E was calculated based on instantaneous E (E_i) and cumulative E (E_{cum}) related to 6:50 a.m. to 7:40 p.m. time period was determined with the sum of hourly E values. Jackson et al. (1983) showed that the ratio of total daily irradiance (S_d) to the instantaneous irradiance (S_i) at any time equal to the ratio of total daily evapotranspiration (E_d) to the one time of day measurements of evapotranspiration (E_i):

$$J = S_d\,/\,S_i = E_d\,/\,E_i \qquad (7).$$

The time units will be mixed in J so that one time of day value of S_i and E_i can be determined in W m^{-2} and multiplied by J to give S_d or E_d in units of MJ m^{-2} day^{-1}. In this study, S_i values of 1:50 p.m. to 2:00 p.m. time period were used to calculate value of J. However, E_i value of the same time of day with S_i was used to calculate E_d.

Crop water stress index (CWSI). Some indexes are available which were developed for the quantification of plant water stress based on infrared temperature measurements such as crop water stress index (CWSI) (Idso et al., 1981; Jackson et al., 1981; 1986). The methodology of Jackson et al. (1981 and 1986) depends on energy balance. CWSI stated in Idso et al. (1981) is based on the vapor pressure deficit (VPD) of air and canopy and air temperature differences (T_c–T_a) relationship (Eq. 8). In order to use this methodology, at first it is necessary to define lower limit base line (non-water stressed condition) (Eq. 9) and upper limit base line (water stressed conditions) (Eq. 10) of the considered crop. One can define these lines based on the measurements of well watered and stressed crops. At the same time, upper limit base line can be determined according to Idso et al. (1981) based on vapor pressure gradient (VPG) for possible maximum temperature (Eq. 11).

$$CWSI = \frac{(T_c - T_a)_M - (T_c - T_a)_L}{(T_c - T_a)_U - (T_c - T_a)_L} \qquad (8),$$

$$(T_c - T_a)_L = a - b\,VPD \qquad (9),$$

$$(T_c - T_a)_U = a - b\,VPG \qquad (10),$$

$$VPG = es_{(Ta)} - es_{(Ta+a)} \qquad (11),$$

where: $(T_c$–$T_a)_M$ is the measured difference (ºC), $(T_c$–$T_a)_L$ is the lower limit (ºC), $(T_c$–$T_a)_U$ is the upper limit (ºC), a and b are the constant of relationship between T_c–T_a measurement related to well watered crop and VPD, $es_{(Ta)}$ and $es_{(Ta+a)}$ are the saturated vapor pressure (kPa) of air temperature and air temperature plus a constant respectively.

Results and discussion

During the 21st and 22nd of August, maximum air temperatures were 36.5 and 39.1°C, maximum VPD values were 4.05 and 5.20 kPa and aver-

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age wind speeds were 1.27 and 1.52 m s^{-1}, respectively. Based on the variation of temperature, VPD and wind speed between the study days, different E_{cum} and E_d values were calculated. However, E difference of T_1 and T_2 irrigation treatments was nearly 1 mm day^{-1} for each trial day (Fig. 1). On the 21st of August, distinction of E_{cum} and E_d values was 0.3 mm day^{-1} for both irrigation treatments and on the 22nd of August the difference was calculated 0.2 mm day^{-1} for T_2 irrigation treatment. There were no differences between the results of the two E calculation methods for T_1 treatment during the 22nd of August (Table 1).
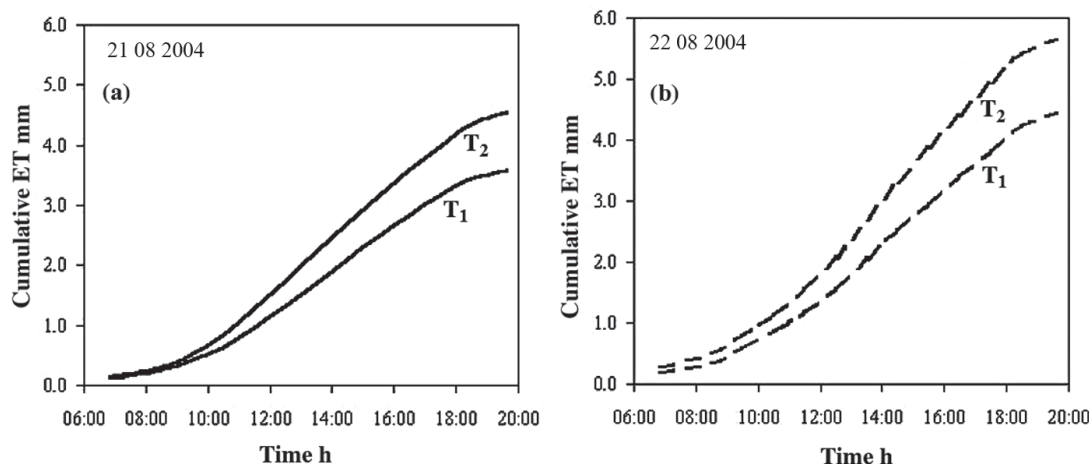

Figure 1. Cumulative daily evapotranspiration (E_{cum}) of T_1 and T_2 treatments of cherry trees during 21st (a) and 22nd (b) of August

Table 1. Evaporation from cherry trees to the air under different irrigation regimes and some climatic parameters for measurement days

Date	T$_1$		T$_2$		Maximum Ta (°C)	Maximum VPD (kPa)	Average u (m s^{-1})
	E_{cum}	E_d	E_{cum}	E_d			
21 08 2004	3.6	3.3	4.5	4.2	36.5	4.05	1.27
22 08 2004	4.5	4.5	5.7	5.5	39.1	5.20	1.52

The lower (non-water stressed) and upper (water stressed) baselines (Fig. 1) were defined for dwarf cherry trees and CWSI values were calculated using this diagram as the relative value between upper and lower baselines relating the T_c-T_a to the VPD as outlined by Idso et al. (1981). The differences between T_c and T_a were linearly correlated with VPD (Fig. 2). The resulting baseline for T_2 irrigation treatment described by the linear equation was $T_c-T_a = -1.1$ VPD $+ 0.3678$ ($r^2 = 0.996$) and $T_c-T_a = -1.1$ VPD $- 0.0583$ ($r^2 = 0.996$) for 21st and 22nd of August respectively. Lower limits for CWSI $(T_c-T_a)_L$ were calculated based on these relations separately for both study days. Accor-ding to Gardner et al. (1992) development of lower baseline for a single location is often limited by the VPD range, thereby limiting the baseline transportability to the other locations. In our study, the lower baseline was developed for relatively wide range of VPD (0.72–5.2 kPa) by means of diurnal measurements. Gardner and Shock (1989) suggested VPD range from 1 to 6 kPa to define a baseline that could be suitable to use in other locations for CWSI calculation. According to this, base lines given in Fig. 2 could be used for calculation of CWSI in another climatic region.

In order to calculate upper limit lines, maximum air temperature was assumed as 40°C for the experimental area (Eq. 10 and 11) (Fig. 2). According to results of these calculations, $(T_c-T_a)_U$ values were 0.02 and 0.53 for the 21st–22nd of August respectively. Based on Fig. 2, CWSI was calculated at hourly intervals (Fig. 3).

Canopy temperature depends on transpiration (Idso et al., 1981). If a crop is under the water stress, the transpiration is not at the potential rate so it causes the increase of the canopy temperature. CWSI values of T_1 irrigation treatment for both trial days were lower during two hours after sunrise and two hours before sunset and the highest values were calculated for solar noon times. The difference of diurnal variation between two experimental days
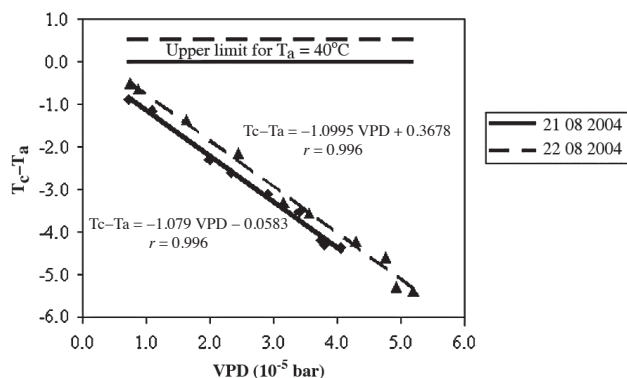
Figure 2. Crop-air temperature (T_c-T_a) differential vs. air vapor pressure deficit (VPD) for well-watered cherry trees

Figure 3. The crop water stress index of well watered and stressed cherry trees

can be seen clearly on Fig. 3. Maximum and minimum CWSI values for T_1 treatment were calculated as 0.68 and −0.052 for 21st of August and 0.51 and −0.01 for 22nd of August respectively. The difference of CWSI value between trial days may be attributed to the variation of Ta, VPD, lower and upper limits and E from cherry trees.

CWSI values of T_2 irrigation treatment varied between −0.05 and 0.06 for 21st of August and −0.06 and 0.06 for 22nd of August. Since the lower limit base lines were determined using the canopy temperature values of T_2, these values were found very close to zero. According to the results, one can assume that transpiration of the trees subjected to T_2 treatments was at the potential rate.

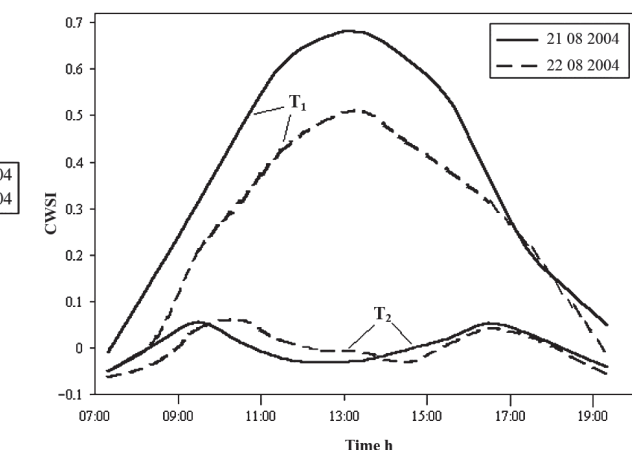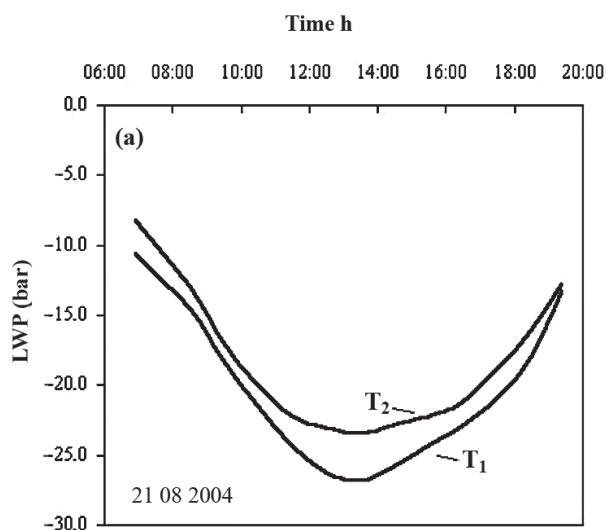LWP of both irrigation treatments was relatively changed with the E rate throughout the study days. Minimum LWP values were measured after sunrise and maximum values were measured at solar noon. There were no big differences between the LWP values of two measurement days. However, there were considerable differences between LWP values of T_1 and T_2 treatments in those days. During the 21st of August, maximum and minimum LWP values measured for T_2 and T_1 were −23.4 and −26.8 bar and −8.2 and −10.6 bar, respectively. Throughout the 22nd of August, maximum LWP values were −26.2 and −25.1 bar and minimum LWP values were −12.1 and −11.1 bar for T_1 and T_2 irrigation treatments, respectively (Fig. 4). For the second day, the difference between LWP of T_1 and T_2 treatments was not higher than the first day. In addition to this, LWP course of both treatments during the day time followed a parallel movement.
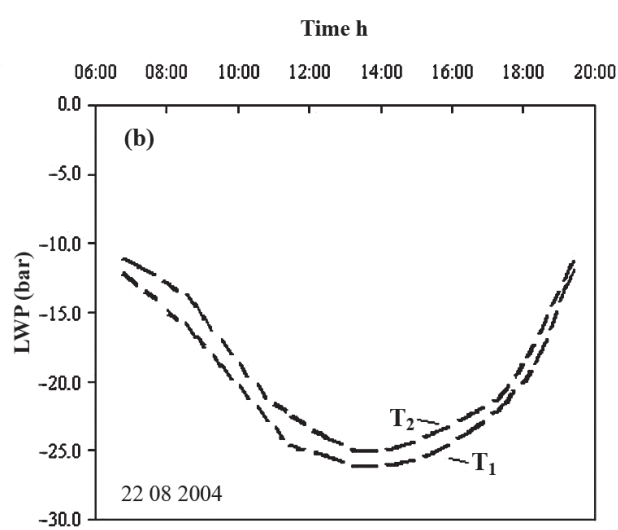

Figure 4. Course of leaf water potential throughout the measurement days

Comparisons between CWSI, E and LWP were made using linear regression analysis for T_1 and T_2 irrigation treatments separately. Fig. 5 shows the relationships between CWSI and cumulative E values. The results of T_1 and T_2 treatments were different due to the transpiration rate of water stressed and non-water stressed cherry trees. When E was at the potential rate, CWSI was close to zero. Under non-water stressed conditions while cumulative E increased from sunrise to sunset, CWSI did not change throughout the day. Thus no significant re-

lationship was found between E and CWSI for T_2 treatment (Fig. 5). Water stressed trees showed big CWSI difference, between midday and both early morning and decline of the day, in the similar direction with E (Fig. 3). Lower E values caused lower CWSI and higher E proved higher values of CWSI. Based on this interaction, the relationship between CWSI and E of water stressed T_1 treatment was statistically significant at $P < 0.01$ probability level.
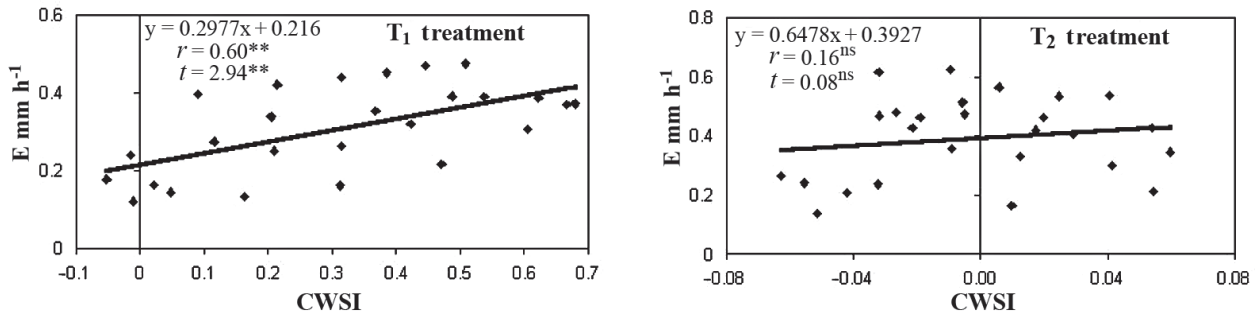

Figure 5. Relationship between CWSI and E of T_1 and T_2 treatments (** – $P < 0.01$, ns − non-significant)

Linear relationships between CWSI and measured LWP were investigated and results were given in Fig. 6. Although LWP of cherry trees of both T_1 and T_2 treatments varied during the study days and important amounts of decrease were monitored at mid time similar to CWSI of T_1 treatment. CWSI values of T_2 treatment were close to zero throughout

the study days. Because of this, significance level of relationship between CWSI and LWP of T_1 ($P < 0.01$) was higher than that of T_2 ($P < 0.05$). Fig. 6 shows that CWSI and LWP had a strong linear relationship under water stress conditions. CWSI which has an easy calculation procedure could be a useful tool for monitoring of water stress levels of cherry trees.
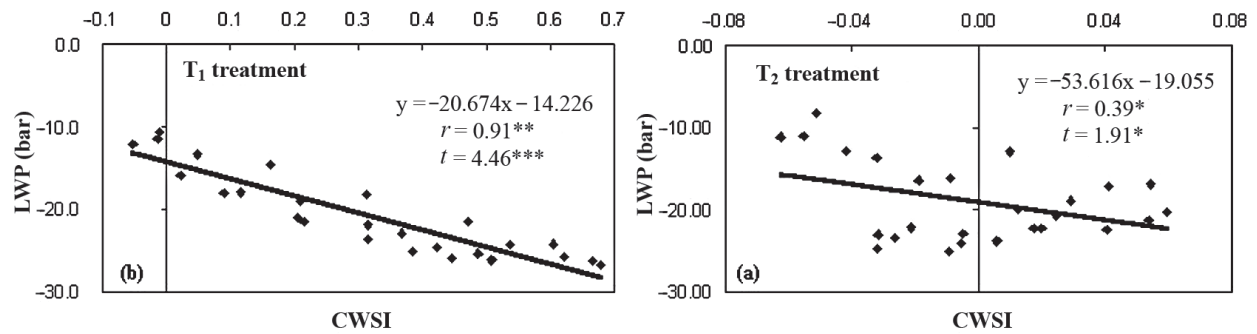

Figure 6. Comparison of CWSI and LWP of T_1 and T_2 treatments (* – $P < 0.05$, ** – $P < 0.01$, *** – $P < 0.001$)

Since LWP and E of water stressed and non-water stressed cherry trees showed similar variations, higher correlations were calculated between E and LWP of T_1 and T_2 treatments. Both LWP and E values increased from sunrise to solar noon and decreased from solar noon to sunset during the trial days. One can decide that change of LWP values was dependent on E rate for both water stressed and non-water stressed conditions (Fig. 7). In these relationships LWP was dependent and E was independent. In other words, leaf water content was de-

creased by the effect of higher E for either water stressed or non-water stressed cherry trees.

Consequently, CWSI shows the water stress difference more clearly and CWSI is more practical than LWP. As a result, it is possible to define irrigation time with CWSI and/or LWP and irrigation amount with the use of E derived from one time of day measurement for cherry trees. To achieve this, it is necessary to measure canopy temperature and canopy resistance simultaneously with some climatic parameters on a daily basis at a standard noontime.
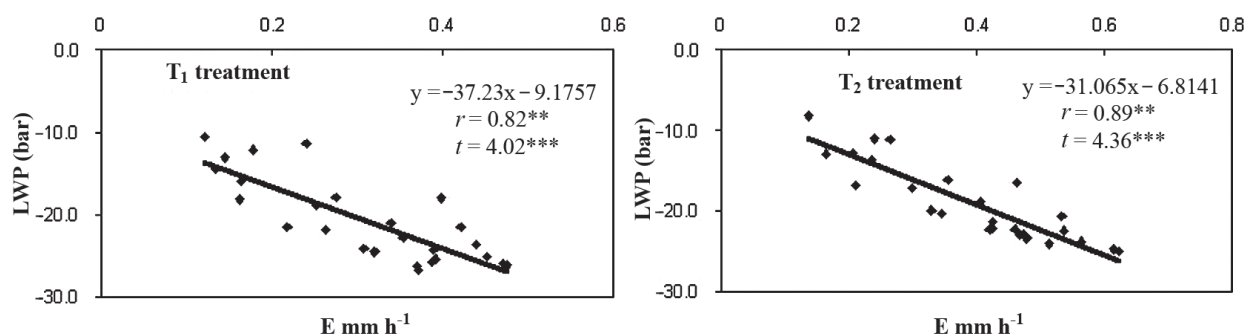
Figure 7. Correlation between E and LWP of T_1 and T_2 treatments (** – $P < 0.01$, *** – $P < 0.001$)

Conclusions

1. Crop water stress index (CWSI) could provide a useful tool for the evaluation of the water stress level of cherry trees in sub-humid climate conditions. According to results of this study CWSI is very sensitive to the applied amount of irrigation water for cherry trees.

2. Another important finding of this study was that converting instantaneous E to the daily E based on the assumption of Jackson et al. (1983) could give reliable results. This approach could be a practical way to estimate E of cherry trees.

3. Leaf water potential (LWP), which is affected by E, showed the water status of cherry leaves. However, CWSI could be offered instead of LWP for irrigation scheduling.

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Vyšnių vandens naudojimo ir vandens streso nustatymas remiantis lapų temperatūra, jų vandens potencialu ir atsparumu

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Santrauka

Tyrimai atlikti subtropinio klimato sąlygomis Bursoje, Turkijoje, 2004 m. rugpjūčio 21–22 dienomis. Tyrimų tikslas – remiantis augalų stebėjimo duomenimis sukurti grafikų išeities taškus, siekiant apskaičiuoti augalų vandens streso indeksą (CWSI) ir įvertinti evaporaciją (E) iš vyšnių lapų. Buvo naudoti du skirtingi vandens lietinimo lygiai: T_1 – vandens stresas ir T_2 – lietinimas pagal poreikį. Be lapų temperatūros, dar buvo matuota lapų pasipriešinimas (r_c) ir lapų vandens potencialas (LWP). Matavimai atlikti nuo 6:50 val. ryto (saulėtekio) iki 7:40 val. vakaro (saulėlydžio). Nustatytos CWSI tyrimo pagrindinio grafiko žemosios ir teorinės aukštosios bazinės linijos. Apskaičiuotos momentinės E vertės, o dienos suminė E (E_{cum}) ir dienos E (E_d) buvo skaičiuotos tik vieną momentinę E paverčiant į dienos E. Nors CWSI T_1 vertės didėjo nuo saulėtekio iki vidurdienio, matavimų dienomis CWSI T_2 vertės buvo artimos nuliui. E_{cum} ir E_d vertės buvo labai panašios, taigi galima taikyti momentinių E reikšmių verčių pavertimą į nustatytas dienos pagrindu. Nustatytas esminis ryšys tarp CWSI – E ir CWSI – LWP T_1 variante. T_2 variante ryšys tarp CWSI – E ir CWSI – LWP buvo neesminis arba silpnas, nes CWSI trendas nesvyravo. Statistinė analizė atskleidė, kad tiesinis ryšys tarp E ir LWP buvo esminis esant abiem lietinimo sąlygoms – vandens stresui ir lietinimui pagal poreikį.

Reikšminiai žodžiai: vyšnios, augalų vandens streso indeksas, lapų vandens potencialas, evapotranspiracija, lietinimo grafikas.