

Daylight crop water stress index for continuous monitoring of water status in apple trees

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Abstract We studied the suitability of empirical crop water stress index (CWSI) averaged over daylight hours (CWSI_d) for continuous monitoring of water status in apple trees. The relationships between a midday CWSI (CWSI_m) and the CWSI_d and stem water potential (ψ_{stem}), and soil water deficit (SWD) were investigated. The treatments were: (1) non-stressed where the soil water was close to field capacity and (2) mildly stressed where SWD fluctuated between 0 and a maximum allowable depletion (MAD of 50 %). The linear relationship between canopy and air temperature difference (ΔT) and air vapor pressure deficit (VPD) averaged over daylight hours resulted in a non-water-stressed baseline (NWSBL) with higher correlation ($\Delta T = -0.97 \text{ VPD} - 0.46$, $R^2 = 0.78$, $p < 0.001$) compared with the conventional midday approach ($\Delta T = -0.59 \text{ VPD} - 0.67$, $R^2 = 0.51$, $p < 0.001$). Wind speed and solar radiation showed no significant effect on the daylight NWSBL. There was no statistically meaningful relationship between midday ψ_{stem} and CWSI_m. The CWSI_d agreed well with SWD ($R^2 = 0.70$, $p < 0.001$), while the correlation between SWD and CWSI_m was substantially weaker ($R^2 = 0.38$, $p = 0.033$). The CWSI_d exhibited high sensitivity to mild variations in the soil water content, suggesting it as a promising indicator of water availability in the root zone. The CWSI_d is stable under transitional weather conditions as it reflects the daily activity of an apple crop.

Introduction

Irrigation is necessary for producing apples in semiarid climates such as those in eastern and central Washington. The quality and size of apple fruits greatly depend on soil water availability during the growing season (Mpelasoka et al. 2001). Soil moisture monitoring using neutron probe (NP) is the scientifically based method for irrigation scheduling and midday stem water potential (ψ_{stem}) a widely accepted indicator of apple trees water status (Lakso 2003). These approaches are, however, very labor-intensive and time-consuming in nature and not feasible for many growers without technical support.

Soil water deficit can result in stomatal closure and consequently an elevated canopy temperature (Pou et al. 2014). This fact has long been known and become a basis for developing thermal indices as an alternative to soil-based methods (Tormann 1986; Garrot et al. 1993). The crop water stress index (CWSI) is one of the well-known thermal-based techniques first introduced by Jackson et al. (1981) and Idso et al. (1981). CWSI is defined by a comparison of measured canopy and air temperature difference ($\Delta T_m = T_c - T_a$) with an upper water-stressed baseline (WSBL: ΔT_u) and a lower non-water-stressed baseline (NWSBL: ΔT_l):

$$\text{CWSI} = \frac{\Delta T_m - \Delta T_l}{\Delta T_u - \Delta T_l} \quad (1)$$

where ΔT_l is the temperature difference between canopy and air temperatures under non-limiting soil water availability (well-watered tree canopy), ΔT_u is the canopy and air temperature difference for a non-transpiring canopy, and ΔT_m is the difference between measured canopy (T_c) and air (T_a) temperatures.

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The value of the CWSI ranges from zero in a crop under no stress to one for a severely stressed crop. The upper and lower baselines are calculated using empirical or theoretical approaches. The theoretical approach is based on an energy budget model and requires several input variables including wind speed and net radiation which are difficult to measure or estimate. The empirical approach first suggested by Idso et al. (1981), on the other hand, only requires the knowledge of air vapor pressure deficit (VPD) where ΔT_l is defined as a linear function of VPD. Previous literature has shown the empirical CWSI to be reliable and in some cases exceeds that of the theoretical approach (Agam et al. 2013b).

In recent years, an increasing number of studies have been reported on the application of thermal indices in tree crops. Empirical and theoretical CWSI baselines have been developed for different trees such as pistachio (Testi et al. 2008), peach (Wang and Gartung 2010; Paltineanu et al. 2013), olive (Agam et al. 2013a; Berni et al. 2009; Ben-Gal et al. 2009; Akkuzu et al. 2013), and citrus trees (Gonzalez-Dugo et al. 2014). To our knowledge, a limited number of reports are available on thermal sensing in apple trees. Osroosh et al. (2014) developed a model based on infrared thermometry and the energy budget of a single apple leaf to estimate actual transpiration. Osroosh et al. (2015b) used an adaptive irrigation scheduling algorithm based on a theoretical CWSI to automatically irrigate drip-irrigated apple trees. Andrews et al. (1992) reported their unsuccessful experience of using CWSI in heterogeneous canopies of apple trees in a temperate and humid climate. The limitation of applying CWSI in humid conditions is well known (Jones 1999, 2004). Considering the advances in technology in the past few decades and successful experiences of other authors in tree crops, there may be still a potential for this method in semiarid climates.

Since the early study of Idso et al. (1981) and Jackson et al. (1981) on infrared thermometry, it is known that the measurements of microclimatic parameters should ideally take place as close as possible to plant canopies. However, in many cases, the most feasible data are acquirable from a weather station in the vicinity of the field (Evet et al. 2012). Study of the microclimate formed around large tree canopies can probably allow for improving the estimations of CWSI. In recent years, remote sensing of canopy temperature using thermal imagers has gained considerable popularity (Cohen et al. 2012; Möller et al. 2007). However, considering the high cost of thermal cameras, complicated image processing requirement, and inadequate resolution of satellite images (Testi et al. 2008), infrared thermometers (IRTs) are still the main tool to measure canopy temperature. Infrared thermometry in sparse apple tree canopies, even when the cover is complete, is a difficult

task as an inclusion of non-transpiring components and soil background in the view of the sensor is very probable (Wanjura et al. 1984; Andrews et al. 1992; Blonquist et al. 2009). Increasing the number of point measurements can decrease the uncertainty; however, it might be too costly (Berni et al. 2009). Appropriate mounting and position and use of IRTs with narrow field of view can minimize interference from unwanted sources of thermal radiation (Jones 1999; O'Shaughnessy et al. 2011).

The CWSI has been conventionally used for crop water status monitoring at midday. This has been based on the fact that row crops mainly respond to net radiation which is maximum at midday. However, tree crops have shown a stomatal activity extended beyond midday. Testi et al. (2008) developed NWSBLs for different times during daylight hours and a 3-h midday average in pistachio. Agam et al. (2013a) also showed that the CWSI could be used as a stress signal throughout the day in olive trees. Assuming this is the case in apple trees, our hypothesis here was that CWSI averaged over daylight hours could be a more sensitive and stable indicator of water status than midday CWSI. The goal was to develop and evaluate CWSI for continuous monitoring of the water status of apple trees within the management allowable depletion (MAD) or mildly stressed range. The specific objectives were to (a) investigate the uncertainties associated with field measurements of canopy temperature and microclimatic variables, (b) develop and compare empirical midday and daylight non-water-stressed baselines, and (c) examine the relationships between the CWSI and stem water potential (ψ_{stem}), as well as the CWSI and soil water deficit/depletion (SWD).

Materials and methods

Study area and treatments

The study was conducted in a plot of Fuji apple trees on the Roza Farm of the Washington State University Irrigated Agriculture Research and Extension Center near Prosser, WA (46.26°N, 119.74°W), during the irrigation period of 2013. The site's soil was Warden Silt Loam, ~1 m deep limited by a rocky layer to shallow depths of <0.6 m in some locations. The average volumetric water content at field capacity, θ_{FC} , and permanent wilting point, θ_{PWP} , were 32.5 % (measured as drained soil water content after an irrigation event) and 13.8 % (estimated; Saxton and Rawls 2006), respectively. Prosser is located in a semiarid zone with an average annual precipitation of 217 mm and little summer rainfall. The trees were spaced 4 m (row spacing) by 2.5 m (tree spacing) apart. The orchard was irrigated with two lines of pressure compensating drip tubing

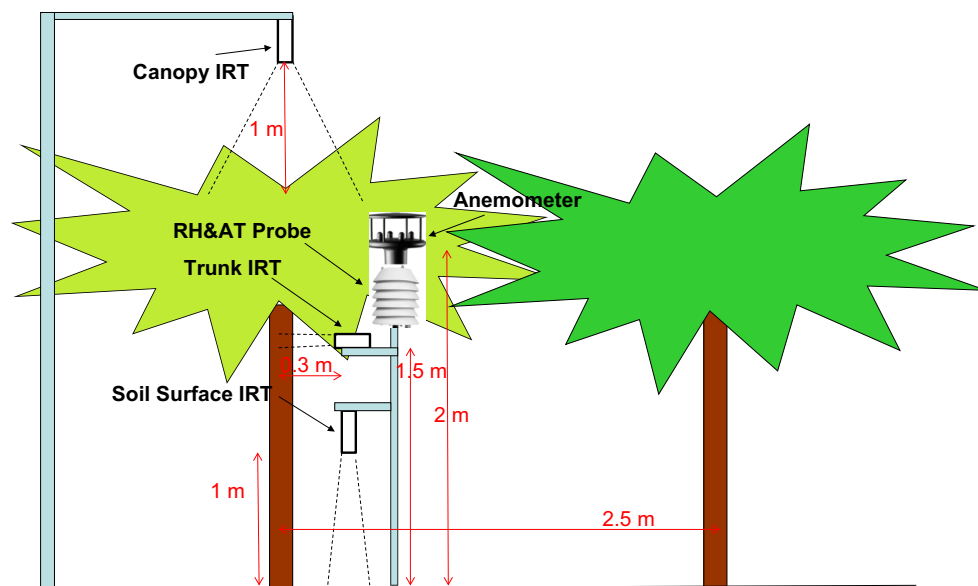


Fig. 1 The sensor suite was comprised of two IRTs to measure the surface temperatures of shaded soil under canopy (T_s) and tree trunk (T_{tr}), a sonic anemometer, a shielded air temperature and relative humidity probe (RH&AT). The suite was installed in the middle of rows in-line with trees. The suite was used to conduct measure-

ments in different plots in the orchard. In each plot, an IRT was also mounted above a tree (canopy IRT) to measure crown temperature. Canopy IRTs were permanently installed in place. The distances are approximate

laterals (~ 0.6 m apart) of in-line 2.0 L h^{-1} (equivalent to 1.1 mm h^{-1}) drippers (BlueLine[®] PC, The Toro Company, El Cajon, CA), spaced at 91.4-cm intervals along the laterals. The treatments were: (1) a fully watered/non-stressed treatment (FW) where the soil water content was close to field capacity as determined by weekly measurements of neutron probe with minor occasions of mild stress and (2) a mildly stressed (on average) treatment (MS) where SWD fluctuated between 0 and MAD of 50 % (fully watered to moderately stressed).

Thermal and microclimatic measurements

Meteorological data were obtained from the nearest agricultural weather station (Roza, Washington State Agricultural Weather Network) located ~ 0.5 km away from the orchard. A portable suite of sensors was also developed to monitor one tree at a time (Fig. 1). The sensor suite included two IRTs with a narrow field of view of 11° (IRT/c.5: Type J, Exergen, Watertown, Mass.) to measure surface temperatures of trunk (T_{tr}) and shaded soil (T_s), a sonic anemometer (WindSonic, Gill Instruments Ltd., Hampshire, UK), and a shielded air temperature and relative humidity probe (RH&AT) (HMP35C, Vaisala Inc., Woburn, MA). The soil IRT was placed nadir over shaded soil under the tree at 1 m high, and the IRT pointed at the tree trunk was mounted 1.5 m high, ~ 0.3 m away from the

trunk. The IRTs and other sensors were in-line with tree rows and wired to a Campbell CR3000 datalogger (Campbell Scientific, Logan, UT, USA). Other authors have measured T_a and RH 1 m over the tree crowns (Berni et al. 2009; Gonzalez-Dugo et al. 2014). Our intention here was to make a comparison between data obtained from the sensor suite and weather station at the same height. This was also the same height as canopy leaves targeted by IRT. The RH&AT probe and anemometer were mounted at 2 m high, near the crown.

Four pre-calibrated infrared thermometers (IRT/c.2: Type J, Exergen, Watertown, Mass.) with field of view of 35° were used to measure canopy temperature. Following an installation procedure described by Sepulcre-Canto et al. (2006), the canopy IRTs were shielded by PVC white case and mounted perpendicularly above four apple trees ~ 1.0 m high from the center of the crown. Each IRT was installed on a tree at the center of a plot of $15 \text{ m} \times 12 \text{ m}$. Two plots per treatment were monitored. The absolute accuracy of the IRTs was $\pm 0.6^\circ \text{C}$ over the range of $0\text{--}50^\circ \text{C}$. Considering that the IRTs were calibrated for a precise measurement at 27°C , the actual error was smaller. The IRTs were checked using a blackbody calibrator (BB701, Omega Engineering, Inc., Stamford, CT). The IRTs had fixed positions and were wired to Campbell CR10(X) datalogger (Campbell Scientific, Logan, UT, USA). To take measurements, the sensor suit was moved to different plots across the orchard. The

readings from all sensors were recorded at 15-min time intervals.

Stem water potential measurements

Stem water potential (ψ_{stem}) was measured at midday (between 13:00 and 15:00) with a pressure bomb (Model 615, PMS Instrument Co., Albany, OR) once per week in the plots under the FW and MS treatments. Every time shaded leaves from the lower inner part of tree, close to the trunk, were targeted. They were enclosed in plastic envelopes covered with aluminum foil, and left attached to the tree for a period of 15–60 min (Fulton et al. 2001). On sampling days, a total of four ψ_{stem} readings (two readings per tree) were averaged to calculate the ψ_{stem} corresponding to each treatment.

Soil moisture measurements

Soil water content was measured on a weekly basis using a neutron probe (503DR Hydroprobe, Campbell Pacific Nuclear, Concord, CA) in the center of each irrigation plot where an IRT was mounted. Due to the presence of a rocky layer in the experimental plots, soil moisture readings down to 0.6 m (0.15 m increments) were used for the purpose of monitoring. PVC access tubes were placed between the drip tubing laterals about 1.25 m from tree trunk. The neutron probe was previously on-site calibrated (Evelt 2008). The details of calibration can be found in Osroosh et al. (2015b). SWD (mm) was calculated as $D \times [\theta_{\text{FC}} - \theta_{\text{S}}]$, where D is the soil depth and θ_{S} is the measured volumetric soil water content. The MAD (mm) for the soil depth was calculated as 0.5 TAW as recommended by Allen et al. (1998) for apple trees.

CWSI calculation

The empirical lower boundary (i.e., NWSBL) was established by a linear regression between ΔT_{m} and VPD: $\Delta T_{\text{m}} = a - b\text{VPD}$, where $\text{VPD} = e_{\text{s}} - e_{\text{a}}$ (Idso et al. 1981), e_{s} is the saturated vapor pressure (kPa) at the air temperature (T_{a}) and $e_{\text{a}} = e_{\text{s}} \text{RH}$ is the actual vapor pressure of air (kPa). Once a (intercept) and b (slope) were obtained, ΔT_{l} was computed for specific VPD. The upper boundary canopy temperature was calculated by adding 5 °C to T_{a} ($\Delta T_{\text{u}} = 5$ °C: Jackson 1982). Canopy temperature (T_{c}), air temperature (T_{a}), and relative humidity (RH) were required measurements to estimate the CWSI.

The 15-min field measurements of RH, T_{a} , and T_{c} averaged over midday hours (1:00–3:00 pm) were used to calculate ΔT_{m} and VPD at midday for a specific day. To calculate the daylight values of ΔT_{m} and VPD, the 15-min measurements were averaged over daylight hours. Midday

NWSBL baseline (NWSBL_{Mid}) and daylight NWSBL (NWSBL_d) were constructed using the measurements from the fully watered treatment. Midday CWSI (CWSI_m) and daylight CWSI (CWSI_d) were calculated using the midday and daylight values of ΔT_{m} , VPD and NWSBL, respectively. The relationships between CWSI_d/CWSI_m and midday ψ_{stem} , and SWD were explored.

Data analysis

The main statistical methods used were: (a) the root mean square error (RMSE) as a measure of the variance between the measurements, (b) a linear regression between two variables, and (c) standard deviation (STD) to calculate measurement variations.

Results and discussion

Variability of microclimatic measurements

Statistical analysis was performed on the average values of measurements calculated over daylight hours and midday. The average measurements of air temperature from the weather station and orchard were analyzed and compared with each other. The results of statistical analysis are presented in Table 1. Readings were taken using the sensor suite across the orchard during several weeks. Air temperature measurements in the orchard showed good agreements with those from the weather station with $R^2 = 0.96$ ($p < 0.001$) and $R^2 = 0.93$ ($p < 0.001$), and RMSEs of 0.5 and 0.7 °C for the daylight and midday averages, respectively.

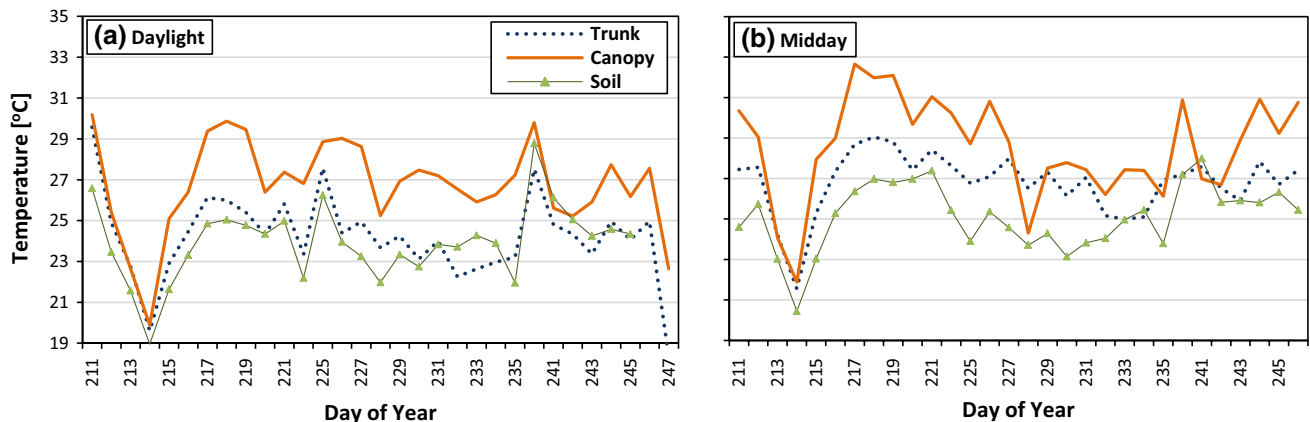
In general, mean in-orchard RH was slightly higher than RH from the weather station with average differences of 7.7 and 12.2 % for the daylight and midday, respectively. However, there were occasions when RH at the weather station was very high while in-orchard RH remained low. This was due to a temporary change in the weather station microclimate caused by operating sprinklers upwind of the

Table 1 Comparisons of daylight and midday average temperatures (T_{a} , °C) from the orchard and weather station (WS)

	Daylight		Midday	
	WS	Orchard	WS	Orchard
Mean	26.6	27.0	29.1	29.5
STD	2.2	2.4	2.7	2.6
Orchard versus WS		Orchard versus WS		
RMSE	0.5		0.7	
R ²	0.96		0.93	

Table 2 Comparisons of the daylight and midday averages of thermal measurements (°C)

	Daylight			Midday		
	Canopy	Soil	Trunk	Canopy	Soil	Trunk
Mean	26.7	23.8	24.2	28.6	25.1	26.8
STD	2.3	2.0	2.1	2.5	1.6	1.5
	Soil versus canopy		Trunk versus canopy	Soil versus canopy		Trunk versus canopy
RMSE	2.9		3.3	3.9		2.3
R ²	0.66		0.56	0.52		0.66

**Fig. 2** Seasonal course of daylight (a) and midday (b) averages of canopy, shaded soil and trunk surface temperatures

weather station. Excluding these occasions, there was a good agreement between the two sets of measurements of RH for the daylight average with $R^2 = 0.88$ ($p < 0.001$) and RMSE = 4.4 %. The variability at midday was more pronounced with $R^2 = 0.51$ ($p < 0.001$) and RMSE = 4.9 %. Overall, the spatial variations of T_a and RH were small enough to conclude that measurements from the nearby weather station were an alternative to within-orchard measurements. These results, however, might not be applicable to other places or crops under other irrigation systems as their response to surface irrigation or sprinkler may be different (Steiner et al. 1983).

There was a fairly good correlation between the daylight averages of wind speed in the orchard (u_o) and the weather station (u_{ws}) ($u_o = 0.05u_{ws} + 0.09$, $R^2 = 0.52$, $p < 0.001$) compared with a poor agreement at midday ($u_o = 0.05u_{ws} + 0.13$, $R^2 = 0.21$, $p = 0.028$). The average difference between the orchard and weather station measurements was 1.7 and 1.9 m s⁻¹, respectively. Wind speed in the orchard was approximately five times slower than weather station showing a significant attenuation by the tree canopies. Although wind speed is not a variable in the empirical CWSI equation, it is known to affect the NWSBL by increasing heat conductance at the leaf boundary layer (discussed later).

Effect of trunk and soil background on canopy temperature

Trunk and branches, as relatively large components of tree, and soil surface were partially in the view of the canopy IRTs. We, therefore, monitored T_{tr} and T_s to inspect their effect on canopy temperature measurements. The results of comparisons between canopy temperature, and trunk and soil thermal measurements from different treatment plots are listed in Table 2. The averages of both the midday and daylight canopy temperatures were higher than the corresponding average trunk temperatures (Fig. 2). The analysis revealed large differences between T_{tr} and T_c with RMSEs of 2.3 and 3.3 °C for the midday and daylight averages, respectively. The differences between T_s and T_c were also high with RMSEs of 3.9 and 2.9 °C for the midday and daylight averages, respectively. In both situations (i.e., midday and daylight), $T_s < T_{tr} < T_c$, which could be explained by the fact that T_s was the temperature of shaded soil. Considering the significant difference of canopy temperature with trunk and soil surface temperatures, both could have affected IRT readings.

The correlations between T_c and T_{tr} were not strong with $R^2 = 0.56$ and $R^2 = 0.66$ for the midday and daylight averages, respectively. Similar results were obtained for the

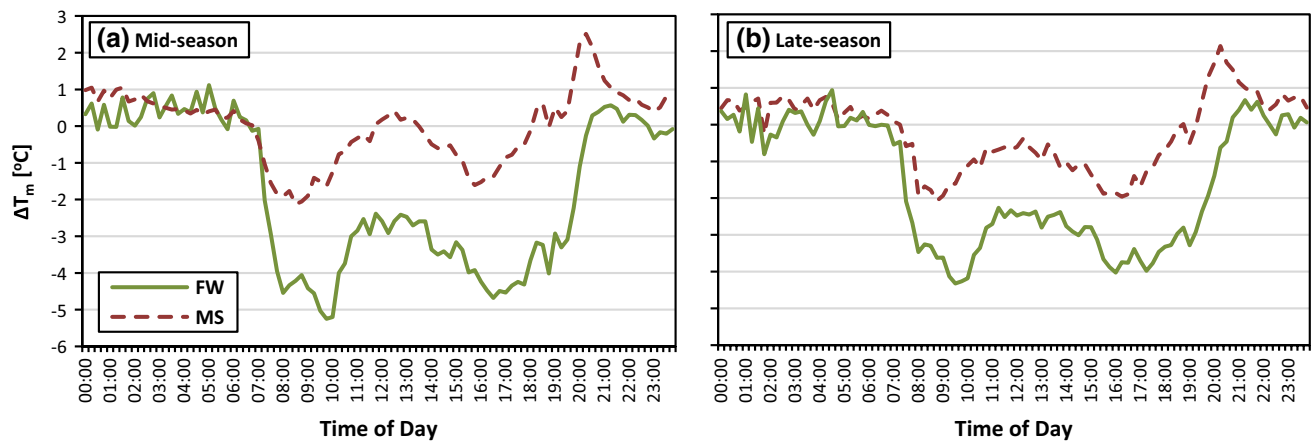


Fig. 3 Diurnal course of measured canopy and air temperature difference (ΔT_m) in the FW and MS treatments during mid (a) and late (b) season of 2013. Each curve exhibits the average of three consecu-

tive sunny days. The trees under FW were non-stressed and the ones under MS were moderately stressed

midday and daylight averages of T_c and T_s with $R^2 = 0.66$ and $R^2 = 0.52$, respectively. Given the values for correlations, there was a chance that readings of canopy IRT were affected by trunk and soil background. For that reason, readings from two thermal sensors were averaged to more accurately assess the treatments. These results support the use of IRTs positioned in a nadir view above the sparse canopies of apple trees as the interferences of trunk and soil background were negligible and average readings from two IRTs improved the accuracy.

Diurnal variations of measured ΔT

Diurnal course of measured canopy and air temperature difference (ΔT_m) in the treatments for two typical sunny days is illustrated in Fig. 3. A consistent difference between the FW (non-stressed) and MS (mildly stressed) treatments can be clearly seen throughout the day. The ΔT_m of non-stressed trees remained significantly lower (larger magnitude) than the ΔT_m of mildly stressed trees at any time during daylight hours. Regardless of the difference, both the non-stressed and mildly stressed trees showed intense stomatal activity (larger canopy and air temperature differences) late in the morning followed by a noticeable decrease in the afternoon (smaller canopy and air temperature difference). Elevated canopy temperatures were probably due to stomatal regulation to minimize water loss at an increased atmospheric demand.

The activity increased again late in the afternoon. Field observations by Tokei and Dunkel (2005) have confirmed this phenomenon in apple trees. The difference between the treatments was maximum late in the morning and late in the afternoon when the activity was intense. The trees in both the treatments maintained average canopy and air

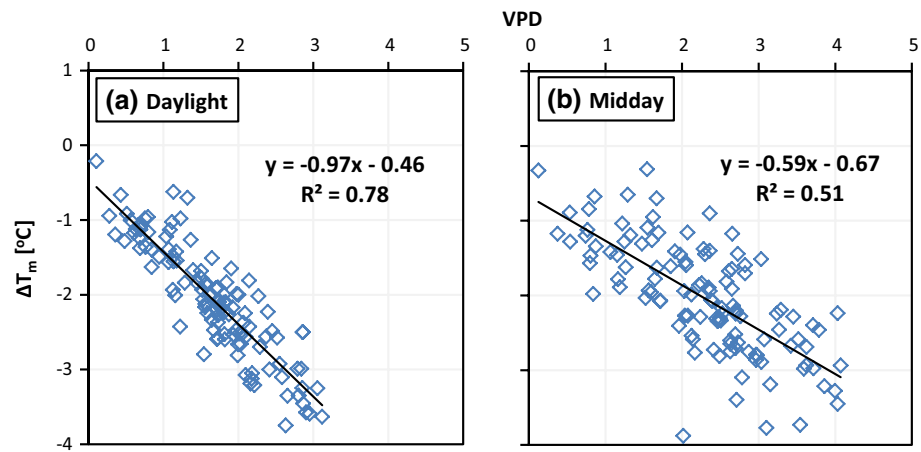
temperature differences in several degrees below 0 °C which was similar to the observations of Testi et al. (2008) in pistachio and different than citrus (Gonzalez-Dugo et al. 2014) and olive trees (Berni et al. 2009) where even in well-watered trees $\Delta T > 0$.

Establishment of empirical upper and lower baselines

Our observations revealed that the empirically set canopy temperature ($T_c = T_a + 5$ °C) as the upper limit was large enough to contain canopy temperatures in the MS treatment. This empirical relationship has also shown to be reliable in olive trees (Ben-Gal et al. 2009; Agam et al. 2013b). To establish NWSBL, we investigated the linear relationship between VPD and ΔT_m averages ($\Delta T_m = a + m\text{VPD}$) over daylight hours and a 2-h average centered at mid-day. The results of linear regressions for the midday and daylight averages in non-stressed trees are presented in Fig. 4a–b.

During the growing period of 2013, the weather conditions were dominantly stable and dry with some occasions of humid and overcast days. As explained by Agam et al. (2013b), canopy temperature of well-watered trees is minimally affected by abrupt changes in solar radiation. We therefore did not exclude cloudy days from the calculations. We analyzed the effect of change in radiation on the baseline separately (discussed later). The daylight NWSBL (NWSBL_d) showed a high correlation between VPD and ΔT_m with $R^2 = 0.78$ ($p < 0.001$). Midday NWSBL ($\text{NWSBL}_{\text{Mid}}$) also yielded a good agreement between VPD and ΔT_m ; however, larger scatters yielded moderately lower R^2 value of 0.51 ($p < 0.001$). NWSBL_d provided a larger magnitude (distance between the upper and lower water stress boundaries) than $\text{NWSBL}_{\text{Mid}}$ and consequently a better

Fig. 4 Non-water-stressed baselines (NWSBL): daylight (a; $p < 0.001$), and midday (b; $p < 0.001$) values of air vapor pressure deficit (VPD) versus measured canopy and air temperature difference (ΔT_m). Data were obtained from the non-stressed FW plots



signal-to-noise ratio. The slope of $NWSBL_d$ was sharper than midday NWSBLs reported in the literature for other trees such as olive and citrus trees (Berni et al. 2009; Gonzalez-Dugo et al. 2014) while smaller compared with pistachio (Testi et al. 2008).

It is known that apple leaves are well coupled to the atmosphere and therefore respond to change in relative humidity (Rana et al. 2005; Dragoni et al. 2005). This gives apple trees the ability to limit their water loss by stomatal regulation during the hot summer afternoons when evaporative demand is high. Midday NWSBL has also shown high sensitivity to wind speed and radiation (Hipps et al. 1985; Jackson et al. 1988; Andrews et al. 1992; Jones 1999), which are not accounted for in the empirical form. The relationship between ΔT_l and these factors was theoretically explained by Osroosh et al. (2015a) for apple trees:

$$\Delta T_l = R_n \frac{1}{\gamma + s} - \frac{1}{P_a(\gamma + s)} VPD \quad (2)$$

where $s = \Delta/P_a$, P_a is the atmospheric pressure (kPa), λ is the latent heat of vaporization ($J \text{ mol}^{-1}$), C_p is the heat capacity of air ($29.17 J \text{ mol}^{-1} \text{ C}^{-1}$), Δ is the slope of the relationship between saturation vapor pressure (e_s , kPa) and air temperature (T_a , °C). $\gamma = (g_{Hr}C_p - n)/\lambda g_v$ is similar to the psychrometric constant defined by Campbell and Norman (1998), $g_{Hr} = 2g_H$, and g_H is the air boundary layer conductance to heat transfer for an apple leaf (Campbell and Norman, 1998). g_v is the vapor conductance ($\text{mol m}^{-2} \text{ s}^{-1}$) estimated using the following equation (Osroosh et al. 2015a):

$$g_v = b \frac{P_a R_n}{\lambda VPD} \quad (3)$$

where b is the calibration adjustment coefficient. R_n and n are functions of longwave and shortwave radiation, and optical/thermal properties of an apple leaf. More

information on the calculation of R_n and n can be found in Osroosh et al. (2015a).

The value of b in Eq. 3 changes from year to year as a function of average stomatal activity. The stomatal conductance (and consequently transpiration) of apple leaves is greatly affected by fruit load and decreases by a reduction in load (Wunsche et al. 2000; Lakso 2003; Reyes et al. 2006). Given that the intercept and slope of NWSBL are functions of g_v , both are expected to change if there is a change in fruit load. Gonzalez-Dugo et al. (2014) reported a positive relationship between the intercept of the midday non-water-stressed baseline and fruit load in well-watered orange and mandarin trees. The intercept and slope also vary during the day as a function of atmospheric conditions. The vapor conductance decreases in the afternoon leading to an elevated canopy temperature while higher levels of stomatal activity in the morning cause the canopy temperature to drop. This is why $NWSBL_{Mid}$ had a smaller slope compared with $NWSBL_d$. Stomatal regulations at midday can make NWSBL unreliable and variable from canopy to canopy and day to day. The average activity of trees during the day, on the other hand, is expected to be more consistent as was observed in the apple trees.

Among the variables in Eq. 3, solar radiation and wind speed can be the most variable. The intercept of the relationship is a function of R_n and therefore changes with solar radiation. Wind speed also has an effect on both the intercept and slope through g_h . This behavior has been verified in other trees such as pistachio and olive (Testi et al. 2008; Berni et al. 2009). Increased wind speed drives more transpiration and consequently reduces canopy temperature.

Daylight NWSBLs for two arbitrary wind speed levels of $u < 2 \text{ m s}^{-1}$ and $u \geq 2 \text{ m s}^{-1}$ and that for two arbitrary global solar radiation levels of $S_r < 520 \text{ W m}^{-2}$ and $S_r \geq 520 \text{ W m}^{-2}$ are illustrated in Fig. 5a, b, respectively. Both solar radiation and wind speed seem to have slightly affected the daylight baseline. With an increase in wind

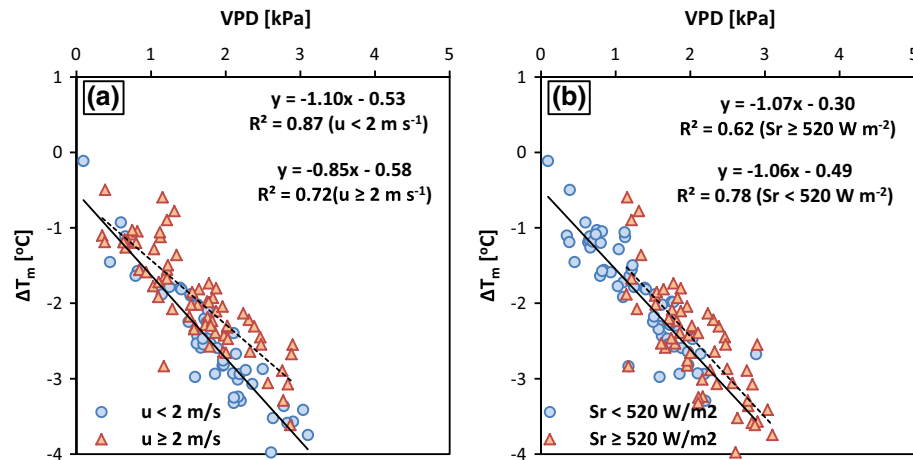


Fig. 5 Daylight non-water-stressed baselines (NWSBL: $\Delta T_m = a + b\text{VPD}$) for two arbitrary wind speed levels of $u < 2 \text{ m s}^{-1}$ and $u \geq 2 \text{ m s}^{-1}$ (a). Daylight non-water-stressed baselines for two arbitrary global solar radiation levels of $S_r < 520 \text{ W m}^{-2}$ and

$S_r \geq 520 \text{ W m}^{-2}$ (b). Wind speed was obtained from the nearby weather station. ΔT_m and VPD are the measured canopy and air temperature difference of the non-stressed trees (FW treatment), and air vapor pressure deficit, respectively. In all equations $p < 0.001$

speed, the correlation has slightly degraded ($R^2 = 0.72$), and with its decrease, a stronger linear relationship has been achieved ($R^2 = 0.87$). Andrews et al. (1992) reported a significant affect of wind speed on their measurements in an apple orchard, whereas Testi et al. (2008) experienced a negligible impact of air boundary layer conductance on the NWSBL. Results for wind speed are highly site specific and might not be applicable to other places especially in the semiarid southern Great Plains where advection plays an important role. In general, the wind was not strong in the study site with the daylight average values smaller than 6 m s^{-1} (measured at the weather station) during the experiment. If there is any effect on the baseline due to varying wind speeds, daylight average can smooth it.

Variations in radiation caused by cloud cover resulted in parallel lines. This was similar to the results from the theoretical and empirical approaches of Berni et al. (2009), and Testi et al. (2008), respectively, for NWSBLs for different times of day. The difference between the intercepts of the lines under different radiation levels was negligible. Changes in radiation normally occur due to variations in cloud cover or the change in the zenith solar angle during the day. It is known that change in radiation can affect canopy temperature; thus, many authors have removed cloudy days from their data before establishing NWSBL. Agam et al. (2013b) have extensively discussed how solar radiation might affect CWSI. According to them, CWSI of stressed olive trees showed higher fluctuations in response to change in solar radiation level while non-stressed trees CWSI remained close to 0. Cloudy days are unpredictable and might cover a fair number of days over the irrigation season. In both cases, the difference between the baselines, in relation to various levels of wind speed and

solar radiation, was not statistically significant. It seems that empirical NWSBL_d can be reliably determined with cloudy and windy day data included. Gonzalez-Dugo et al. (2014) mentioned canopy growth as a source of uncertainty in using CWSI as it changes the sun exposure of leaves viewed by IRTs. This does not seem to be a problem with NWSBL_d as it averages the data collected before and after solar noon.

CWSI and water status

Seasonal courses of midday ψ_{stem} and relationships between ψ_{stem} and CWSI at midday for the trees under the non-stressed FW treatment and the ones under the mildly stressed MS treatment are depicted in Fig. 6a, b, respectively. Midday ψ_{stem} values in the non-stressed treatment were limited to a range between -0.35 and -0.88 MPa . Midday ψ_{stem} of mildly stressed treatment ranged between -0.37 and -1.1 MPa . Non-stressed trees maintained a relatively higher average ψ_{stem} (-0.60 MPa) over the period compared with the mildly stressed trees with an average of -0.77 MPa . The values of ψ_{stem} were in agreement with the reference values reported in well-watered woody plants in general (De Swaef et al. 2009) and apple trees specifically (Naor and Cohen 2003).

The linear regression resulted in no significant agreement between CWSI and ψ_{stem} . However, the average ψ_{stem} and CWSI_m values for the two treatments showed that higher CWSI_m was corresponding with a smaller ψ_{stem} and higher soil water deficit. It can be seen that both ψ_{stem} and CWSI_m in the FW treatment have a wide range of values under different weather conditions. Experiments in other

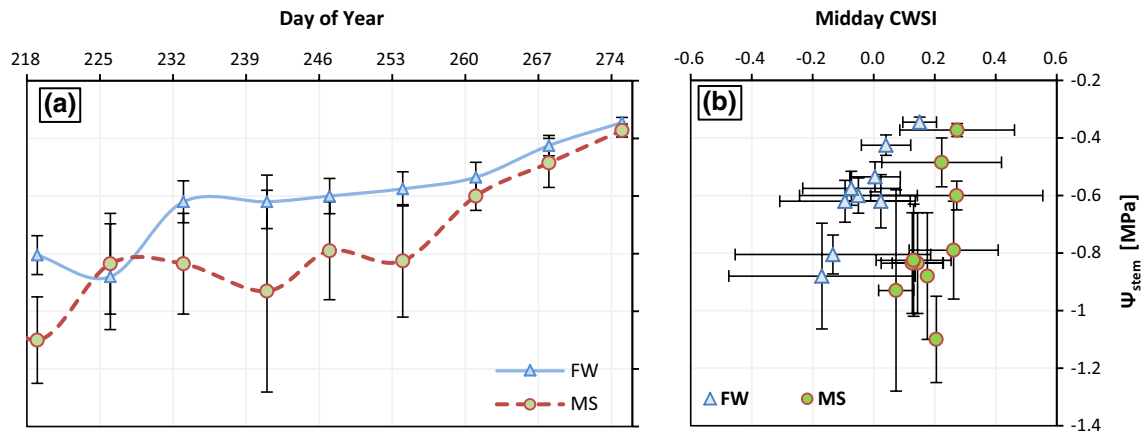
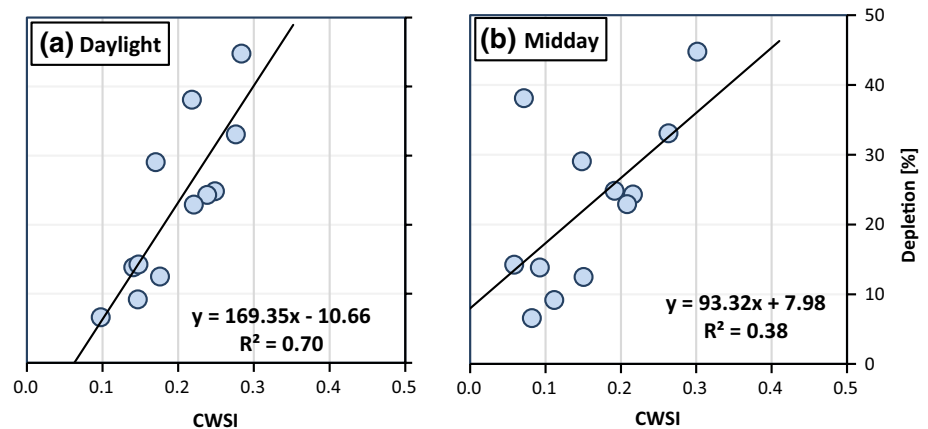


Fig. 6 Seasonal courses of midday ψ_{stem} in the MS and FW treatments (a). Relationships between ψ_{stem} [MPa] and CWSI at midday for the trees under the non-stressed treatment, FW, and the ones under

the mildly stressed treatment, MS (b). The error bars show the standard error of the mean

Fig. 7 Linear relationship between SWD and daylight CWSI ($CWSI_d$) (a; $p < 0.001$) and between SWD and midday CWSI ($CWSI_m$) (b; $p = 0.033$)



tree crops have shown that plant water potential does not have a significant relationship with CWSI in the moderately stressed range (Testi et al. 2008; Gonzalez-Dugo et al. 2014). This is because CWSI is a function of relative transpiration (Jackson et al. 1981) and highly sensitive to change in soil water content while, in this range of soil water content, ψ_{stem} is rather responsive to atmospheric demand (Doltra et al. 2007; Fereres and Goldhamer 2003).

Considering the fact that double laterals were used for irrigating the trees and the soil type was Silt Loam, a large wetted area of ~ 2.5 m wide was expected (Keller and Bliesner 1990). The neutron probe also provided enough precision and volume of influence to meet our requirements for the study given its sensing volume of up to 4.2 m³ depending on soil water content (Evetts et al. 2009). Spatial and temporal soil water variability was not an issue as access tubes were installed at the center of the wetted area. Soil water deficit of the MS treatment ranged from 0 to 50 mm. A depletion of 56 mm was the

maximum allowed deficit for the measurement depth ($D = 0.6$ m). The linear regression between $CWSI_d$ and SWD resulted in fairly good agreement. $CWSI_d$ and SWD had a stronger correlation with $R^2 = 0.70$ ($p < 0.001$; Fig. 7a) compared with $R^2 = 0.38$ for the relationship between $CWSI_m$ and SWD ($p < 0.033$; Fig. 7b). The strong agreement between SWD and $CWSI_d$ suggests $CWSI_d$ as a suitable indicator of soil water status to a depth of 60 cm. SWD reached MAD at $CWSI_d = 0.36$, which can be taken as a threshold for irrigation purposes. The close relationship between SWD and $CWSI_d$ under well-watered status ($SWD \leq MAD$) can help establish stress thresholds and improve the feasibility of CWSI as an irrigation signal. The stability of $CWSI_d$ in the face of temporary change in weather conditions (i.e., clouds and dust) and a fairly good correlation with soil water deficit revealed its sensitivity to mild levels of water stress. This supports the use of $CWSI_d$ as a reliable water stress indicator in apple trees.

Conclusions

In this study, CWSI was calculated using empirical baselines and automatic measurements of canopy temperature with point IRT sensors. Supplemental measurements including air temperature and relative humidity were obtained from a proximal sensor suite in the orchard and a nearby weather station. It was demonstrated that empirical CWSI averaged over daylight hours is a sensitive water status indicator of apple trees in the semiarid region of central Washington. The daylight CWSI was able to detect small changes in the soil water content in the management allowable depletion range, while ψ_{stem} showed little sensitivity. The CWSI exhibited an extreme sensitivity to changes in soil water content under mildly stressed conditions. Considering the non-homogeneity of apple tree canopies, as in our case, averaging the readings from several IRTs might be critical for calculating reliable CWSI values. The average CWSI calculated over daylight hours may be a promising tool for replacing irrigation scheduling methods like neutron probe and pressure bomb, because it allows for continuous monitoring of water stress and provides a basis for automatic irrigation of apple orchards.

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