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Empirical validation of the relationship between the crop water stress index and relative transpiration in almond trees

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ABSTRACT

There is growing interest in the use of canopy temperature to evaluate the water status of crops for irrigation water management. One of the main indicators currently used is the Crop Water Stress Index (CWSI). In this index, the canopy temperature is normalized by the environmental conditions to account for the evaporative demand of the atmosphere. The theoretical framework, based on the Penman-Monteith equation, defined the CWSI as one minus the ratio between actual and potential water use (Jackson et al., 1981). For the first time in tree crops, we have related the actual transpiration of almond trees measured with heat-pulse sap flow probes with the CWSI, calculated using an empirical Non-Water Stress Baseline. The relationship obtained between the CWSI and the relative transpiration fitted the theoretical relationship, although it showed a large scatter ($R^2 = 0.69$; RMSE = 0.13). The variability in micrometeorological conditions among different parts of the canopy, the scatter of the NWSB, or inherent measurement errors are identified as probable causes of this scatter. Finally, the effect of this scatter on the accurate assessment of actual transpiration from canopy temperature is analyzed for practical irrigation management purposes. We found an error of about 10% in the relative transpiration, which seems acceptable for irrigation management applications.

1. Introduction

The optimization of consumptive and beneficial water use in agriculture is a key issue to maximize irrigation efficiency (Burt et al., 1997), especially considering the scarcity of water resources. Accurate assessment of crop evapotranspiration (ET) is essential for the optimization of irrigation water use, although its estimation is challenging, especially in tree crops, considering the wide range of ground cover and tree density patterns (Testi et al., 2004). In many irrigation schemes, tree orchards are drip irrigated, which reduces significantly the losses of water from soil evaporation and makes plant transpiration alone the main component of irrigation water use. The heat-pulse method has been used successfully for measuring the sap flux and thus used as a direct assessment of tree transpiration (Allen and Grime, 1995). With these systems, it is possible to measure tree transpiration and monitor water status (López-Bernal et al.,2012), although it requires advanced agronomical and computational skills for its operation (Jones, 2004). Moreover, it is a plant-based measure performed on individuals. On the other hand, infrared thermometry can provide an operational tool to derive tree transpiration remotely over large areas, which is of foremost importance for management purposes and to assess the within-orchard spatial variability of the water status.

Canopy temperature (T_c) has attracted much attention in recent decades as a means to estimate crop water status. Since the discovery of the relation between canopy temperature and heat dissipation from plant transpiration in the early 60′s (Gates, 1964), researchers have developed a series of indices derived from T_c to evaluate water status, such as the Crop Water Stress Index (CWSI, Jackson et al., 1981) or the Apparent Thermal Inertia (ATI, Tramutoli et al., 2000). The advantages of using T_c are significant; compared to monitoring plant water status using the pressure bomb, or porometry, it provides a practical approach to monitor water status remotely at large scales. The recent development of high resolution thermal cameras opened up the possibilities of using thermal imagery acquired from airborne systems (unmanned aerial vehicles and manned aircraft) for large scale monitoring of crop water status, as long as the spatial resolution of the images allow

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targeting the pure vegetation canopy component (Khanal et al., 2017). As an example, simple thermal-based indicators such as Tc minus the air temperature (Ta) successfully detected water stress in individual olive trees grown under deficit irrigation schemes using airborne thermal imaging collected on single dates, i.e. avoiding changes in the environmental conditions (Sepulcre-Canto et al., 2006). The Crop Water Stress Index (CWSI) proposed by Idso et al. (1981), is one of the most widely used thermal-based indices, defined as follows:

$$CWSI = \frac{(Tc - Ta) - (Tc - Ta)_{LL}}{(Tc - Ta)_{UL} - (Tc - Ta)_{LL}} \quad (1)$$

being T_c-T_a the difference between the canopy and the air temperature. LL and UL correspond to the lower and upper limits, respectively. Therefore, the CWSI varies between 0 and 1. The lower limit corresponds to a well-watered crop transpiring at its maximum, while the upper limit corresponds to a crop where the transpiration is nil. The lower limit can be computed empirically using the Non-Water Stress Baseline (NWSB), and is obtained by regressing Tc-Ta values and VPD at noon. Based on the Penman-Monteith equation, Jackson et al. (1981) defined the theoretical value of the CWSI as:

$$CWSI = 1 - \frac{ET_a}{ET_{pot}} = \frac{\gamma(1 + r_c/r_a) - \gamma(1 + r_{cp}/r_a)}{\Delta + \gamma(1 + r_c/r_a)} \quad (2)$$

Where ET_a and ET_{pot} are actual and potential evapotranspiration, γ is the psychrometric constant, Δ is the slope of the saturated vapor pressure versus temperature, r_c and r_{cp} are the actual and potential canopy resistance, respectively and r_a the aerodynamic resistance. The potential ET is defined as the unstressed ET of the crop for the given environmental conditions.

According to Eq. (2), and considering that evaporation from soil in drip-irrigated tree crops is low, it is theoretically possible to calculate the actual tree transpiration as a function of CWSI and the potential transpiration. Using a similar approach, Taghvaeian et al. (2014) found that the calculated transpiration in maize was similar to that obtained using the FAO-56 approach. In a previous paper, these authors observed that the transpiration derived from CWSI was similar to the crop evapotranspiration (ET) obtained by running a Remotely-sensed Surface Energy Balance (RSEB) model, as long as the soil was fully covered by vegetation (Taghvaeian et al., 2012). Inoue and Moran (1997) developed a methodology to assess the actual transpiration in soybean canopies derived from the CWSI theory. In this case, the potential transpiration was estimated using an empirical function of the instantaneous measurement of the Soil Adjusted Vegetation Index (SAVI) and the daily solar radiation. They observed that CWSI tends to systematically underestimate daily actual transpiration, probably because the ratio E/E_{pot} is often minimum around noon. By applying a fixed coefficient (0.6 in the case of soybean), the CWSI was able to correctly estimate the actual transpiration. Such coefficient was 0.86 for cowpea, according to Sepaskah and Ilampour (1996), although in this case, the transpiration was calculated seasonally. It remains unknown whether this type of adjustment should also be done in orchard trees, considering the differences between the smooth canopies, characteristic of annual crops and the rough and complex canopies typically found in orchard trees. Transpiration in poorly coupled canopies with high aerodynamic resistance, such as grasses and annual crops is mainly driven by net radiation, while in tree crops (coupled canopies with low aerodynamic resistance), transpiration is driven by net radiation, stomatal conductance and vapor pressure deficit (Jarvis and McNaughton, 1986). As far as we know, the relation between relative transpiration and CWSI has never been determined experimentally in tree crops. The objective of this work was to experimentally determine the relationship between the CWSI and the relative transpiration in almond trees and to assess the sources of uncertainty in the estimates of transpiration from CWSI values. Moreover, this study aims to evaluate the error associated with the estimation of tree transpiration from the CWSI in the context of irrigation management.

2. Materials and methods

2.1. Site description and experimental design

An experiment was performed during 2014 and 2015 in an almond orchard located at the IFAPA facilities in Alameda del Obispo, Cordoba, Spain (37°52′N, 4°49′W). The experimental design is detailed in Lopez-Lopez et al. (2018a). The trees were planted on 2009 with 6 × 7 m tree spacing. Two treatments were selected for this study: i) control, which was irrigated to meet the crop water requirements, and ii) severe regulated deficit irrigation treatment, where irrigation dose was reduced to 15% and 20% of the control in 2014 and 2015, respectively. The irrigation cutoff was applied during the kernel filling stage (preharvest period), usually occurring from mid-June to late-July in the area. According to values obtained by Lopez-Lopez et al. (2018b), water potential in the control treatment was maintained between −1 and −1.2 MPa throughout the season, while it reached values below −3 MPa in the severe regulated deficit irrigation.

2.2. Conceptual framework

The comparison between tree transpiration and the CWSI was performed according to Eq. (2), where the CWSI is related to the ratio between actual and potential evapotranspiration. In this work, this ratio was assumed equivalent to the ratio of actual to potential tree transpiration, based on the following assumptions. During summer under semi-arid conditions, the soil evaporation is small (compared to tree transpiration) and results almost exclusively from the surface wetted by the emitters. As the number of emitters was the same for the two treatments, it is expected that soil evaporation was similar for both treatments. Therefore, Eq. (2) can be written as follows:

$$CWSI \cong 1 - \frac{E_a}{E_{pot}} \cong 1 - RT \quad (3)$$

Where E_a and E_{pot} are the actual and potential transpiration, respectively, and RT is the relative transpiration, calculated in this study for the stressed tree. The methodology applied can be observed in the workflow in Fig. S1. The transpiration of control trees was assumed to be maximal, considering there were no water supply restrictions. This hypothesis was validated by monitoring soil water content with a neutron probe (Lopez-Lopez et al., 2018a). Moreover, it was confirmed using the transpiration model developed by Villalobos et al. (2013) which was parameterized for almond trees by Espadafor et al. (2017). This model estimates daily tree transpiration from the fraction of PAR intercepted by the canopy and meteorological data. The model output was compared against daily transpiration data obtained with the sap flow probes, and there was a good agreement for the two years under study ($R^2 = 0.74$; data not shown). Therefore, it confirmed that the control treatment represented the potential or maximum transpiration rate.

The study was performed using hourly mean values around noon (from 11.30 to 12.30, solar time). The NWSB was developed at midday (Gonzalez-Dugo et al., 2019), so the CWSI calculation was restricted to the same timeframe. Similarly, the transpiration rate used in this study was calculated as the mean value from 11.30 to 12.30.

2.3. Sap flow measurement and transpiration assessment

Sap velocity was monitored in two trees (one tree per treatment) with sap flow probes. The sap flow system was developed at the Instituto de Agricultura Sostenible (IAS-CSIC, Cordoba, Spain) and used the compensation heat pulse and calibrated average gradient techniques (Testi and Villalobos, 2009). Two probes were installed in the trunk of each tree, below main branches. Each probe measured the sap flow velocity at four different depths, 5, 15, 25 and 35 mm below the cambium. Measurement were recorded every 15 min, and the values were averaged hourly. Besides, in order to improve the reliability of the transpiration estimates, sap flow records were calibrated in the post-processing of data, as described in Lopez-Lopez et al. (2018a).

Transpiration of the control, well-watered tree was used to estimate the potential transpiration for the stressed tree. This procedure might introduce an error associated to the different canopy size between the two trees. To eliminate this issue, the transpiration of both trees was compared during a 4-day period at the beginning of each season under well-watered conditions. From that comparison, we obtained a calibration coefficient that was applied throughout the season, thus removing the offset due to tree size.

The canopy conductance (Gc) for both trees was calculated from transpiration data obtained with the sap flow probes by inverting the imposed evaporation according to the Penman-Monteith equation, assuming a negligible aerodynamic resistance (Villalobos et al., 2013).

2.4. Temperature measurement and CWSI calculations

The infrared thermometers (IRT) were installed over the tree on a mast, pointing to the upper part of the tree crown. These sensors were installed on the south part of the crown, targeting the top of the canopy with a 45° angle with respect to the ground. Two trees per treatment were monitored with these systems, although only the trees monitored with the sap flow probes were used in this study. The IRT measured every minute and stored the 5-minute average. The CWSI was calculated using the canopy temperature, and the NWSB that was previously calibrated by Gonzalez-Dugo et al. (2019) in the same orchard. Hourly meteorological data were obtained from a standard weather station installed 600 m away from the experimental orchard. As for transpiration, the canopy temperature was averaged to get hourly values. Photographs of the IRT sensors and of sap flow probes, as well as of the experimental orchard can be found in Figure S2.

3. Results and discussion

3.1. Relationship between CWSI and the relative transpiration

The ratio between actual and potential transpiration, the relative transpiration (RT), was compared to CWSI in the deficit irrigated (DI) treatment for both years (Fig. 1). The RT and CWSI were calculated at noon. Only data from the summer (June, July and August) was used and cloudy days were discarded from the study. Showing large scatter, the linear regression (RT = −0.87CWSI + 0.93) yielded R^2 = 0.69 and RMSE = 0.13 (RMSEr = 23%), and was not statistically different from the theoretical line (y = 1-x) (Fig. 1). Linear regressions for each individual year were not statistically different.

3.2. Assessment of the sources of uncertainty in the estimates of transpiration from CWSI values

The large scatter found in the relationships between RT and CWSI (Fig. 1) may have several explanations. First of all, the scattering in the Non-Water Stress Baseline (NWSB) used for the calculation of the CWSI may produce a noise in the signal that can be partly responsible for this effect. The NWSBs that have been reported in annual crops showed a very good fit (Idso, 1982; Irmak et al., 2000). In comparison, orchard trees often show in the literature large scatter in the relationship between Tc-Ta and VPD for well-watered trees. The R^2 ranged from 0.87 in pistachio (Testi et al., 2008), 0.70 in peach (Bellvert et al., 2016), 0.65 in nectarine (Garcia et al., 2000), to 0.5 and 0.41 in mandarin and orange, respectively (Gonzalez-Dugo et al., 2014). In a vineyard, Bellvert et al. (2015) observed R^2 values for different cultivars and stages that ranged from 0.40 to 0.67. A similar range of variation (from 0.56 to 0.82) was observed in super-high density olive by

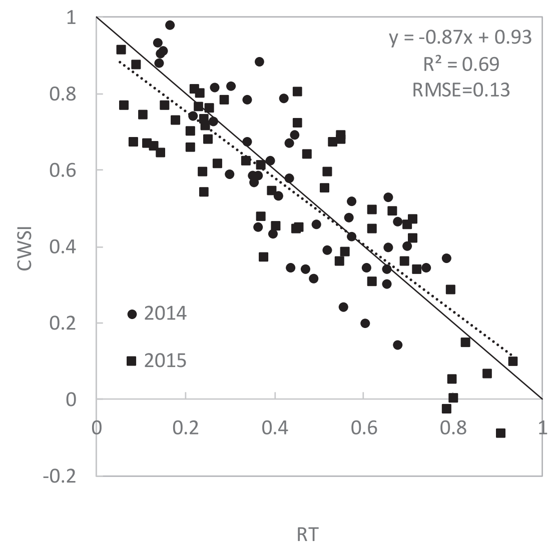

Fig. 1. Relationship between the relative transpiration and the CWSI measured at noon in an almond orchard in 2014 and 2015 in Cordoba, Spain. The discontinuous line shows the linear regression while the solid line indicates the theoretical relation according to Jackson et al. (1981).

Egea et al. (2017). In almond, Gonzalez-Dugo et al. (2019) reported an R^2 of 0.71. The NWSB relationship used for calculating CWSI in this study (Tc-Ta = -1.21VPD + 3.42) was similar to the one reported by Bellvert et al. (2018) for almonds in California. The source of the high scatter observed in the NWSB of trees and vines remains unclear. In citrus, Gonzalez-Dugo et al. (2014) observed large high-frequency oscillations in canopy temperature that seem to be related to the hydraulic dynamics at the tree level (Dzikiti et al., 2007). These fluctuations have also been observed in the transpiration rate in young olive trees (Lopez-Bernal et al., 2018). This instability has been related to feedback mechanisms of water status at the plant level and might affect the relationship between the tree transpiration and the evaporative demand, which is at the base of the NWSB. However, no oscillatory patterns were noticed in our study when we carefully inspected the diurnal time courses of both transpiration and canopy temperature at 15 and 5 min time intervals, respectively.

Another source of variation may be due to differences in environmental parameters other than temperature. For computing the effect of other climatic conditions on the relationship between CWSI and RT, the residuals relative to the theoretical line observed in Fig. 1 were correlated with wind speed, vapor pressure deficit and solar radiation, as shown in Fig. 2. It is important to note that data were previously filtered and cloudy days were discarded from this analysis, so the range of variation for solar radiation was rather small. From Fig. 2, it can be concluded that the scatter observed in Fig. 1 was not related to the meteorological conditions. The effect of the solar angle on the residuals was also analyzed, and we observed no clear relationship (R^2 = 0.01; *data not shown*).

An additional source of uncertainty in the RT-CWSI relationship of this study could be the differences between the target foliage of the IRT sensors and that of sap flow probes. Fig. 2 confirmed that the residual was not affected by the VPD, wind speed or solar radiation measured in the standard weather station nearby the experimental site, but the magnitude of both parameters changes within the orchard. The orchard configuration (row orientation, planting density, ground cover, etc.) might influence the microclimate in different parts of the tree crowns, such as the top of the canopy and the lateral side. While the sap flow probes measure the transpiration of the whole tree, the IRT sensors detect the temperature of the uppermost part of the tree canopy, which is the most exposed to solar radiation and wind. This difference should acquire special relevance for complex and coupled canopies, such as tall

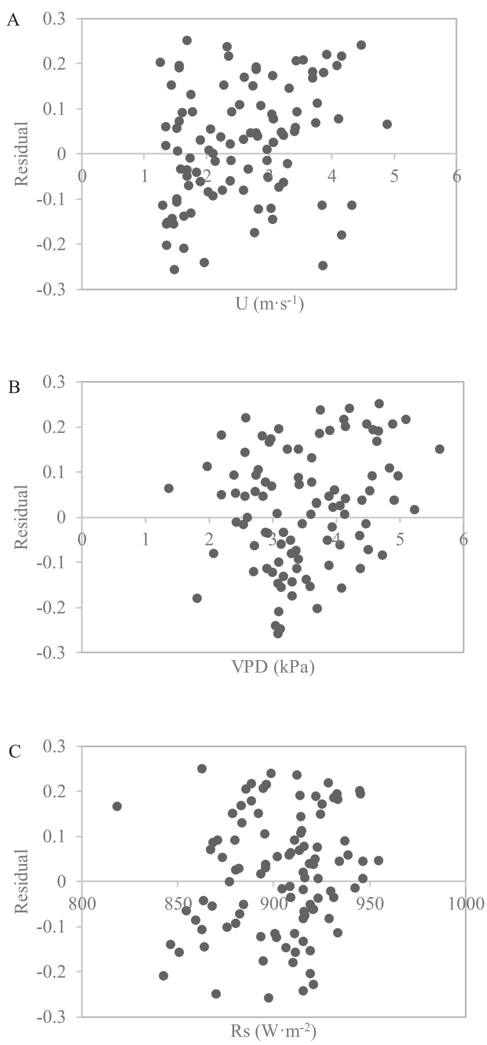

Fig. 2. Relationship between the residuals from Fig. 1 and wind speed (m•s^{-1}; A), ambient VPD (kPa; B), and solar radiation (W•m^{-2}; C).

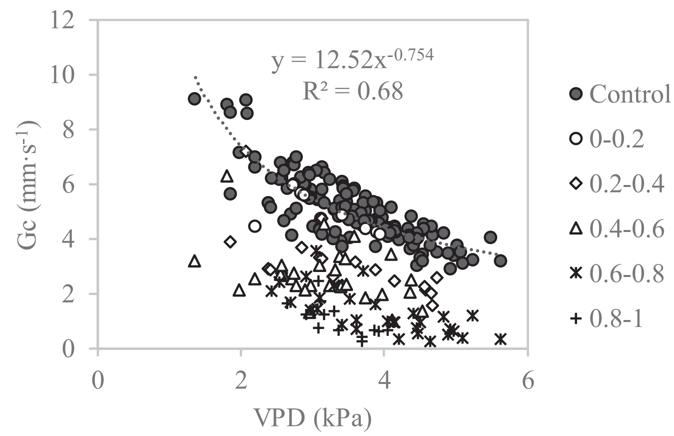

Fig. 3. Relationship between canopy conductance (Gc, mm•s^{-1}), and vapor pressure deficit (VPD; kPa) for control and stressed trees (classified according to CWSI-ranges.). A power function was fitted to the control dataset.

almond trees. It can be hypothesized that the CWSI measured on the top of the tree canopies probably would overestimate the water deficit as compared to relative transpiration. Nevertheless, this effect should lead to a shift towards higher values of CWSI, rather than increasing the scattering in the results. More research is required to explore this effect in detail.

Jackson et al. (1981) used the concept of potential evapotranspiration to compute the lower limit, i.e., the minimum Tc-Ta for the crop at a given VPD value. Rather than assuming the evaporation from a free water surface (where canopy resistance is set equal to 0), they implemented the potential evapotranspiration, characterized by a potential canopy resistance. In the Penman-Monteith approach, the canopy conductance was conceived as a fixed term, although it has been observed that it may be dependent on evaporative demand in orchard trees (Dragoni et al., 2005). In our study, the canopy conductance (Gc) was calculated by inverting the imposed evaporation according to the Penman-Monteith equation (Fig. 3). It can be observed that the canopy conductance for a well-watered (control) tree decreased as VPD increased, because of the high coupling of the almond canopy to the atmosphere. This finding agreed with the model developed by Villalobos et al. (2013). A similar effect was observed for the DI dataset, once the observations were classified according to CWSI ranges (Fig. 3). As soil water was depleted, the CWSI increased and the canopy conductance was thus affected by both the evaporative demand and soil water deficit. Assuming a fixed canopy resistance might add some noise to the computation of the crop water status using the CWSI. Data showed by Jackson et al. (1981) seemed to validate this hypothesis. They observed that for VPD values above 3 kPa, the Tc-Ta was higher than expected. They stated that under warm temperatures, wheat plants were not able to maintain the theoretical potential evapotranspiration rate (Jackson et al., 1981). It can be argued that potential canopy resistance was not constant, but increased under high VPD values. Our results agree with this conclusion. Furthermore if the canopy resistance increases with VPD, even under well-watered conditions, the non-water stress baseline should not be fitted to a straight line but to a curve where the slope decreases under dry conditions. A non-linear NWSB has been observed for some vineyard varieties (Bellvert et al., 2013). This conclusion requires further experimental validation, as the scatter that is usually observed in the NSWB and the reduced number of observations under high VPD values did not allow performing the analysis properly.

Other possible sources of scatter can be identified. IRT sensors have a fixed angular field of view, which was 44°. These sensors must be installed at a certain distance from the target, so that the measurement is representative of the whole tree, while avoiding non-transpiring surfaces like stems and branches, and background effects, such as the soil beneath the tree. It is possible that the target temperature would include not only pure vegetation, but also some soil background and canopy shadows. This can affect the robustness of the canopy temperature and the CWSI as indicators of the water status. It can lead to discrepancies in the relation with the sap flow (this effect is absent in sap flow sensors) as well as be partly responsible for the relatively low R^2 in the NWSB observed in some orchard trees.

The estimation of tree transpiration from the sap flow probes can also add some noise to the relationship observed in Fig. 1. The sap flow methodology is based on radial measurements of sap velocity that are integrated across the trunk section, considering the trunk as a homogeneous media. But the natural azimuthal variability in sap flow and anatomical characteristics might generate a bias in the transpiration estimation. Lopez-Bernal et al. (2010) demonstrated that if fewer than six probes are installed in the trunk of olive trees, the deviation from the actual total sap flow can be higher than 10%. However, these errors are not likely be relevant in our study, given that sap flow records were calibrated.

3.3. Evaluation of the CWSI as a tool for monitoring water needs

In order to evaluate the CWSI as a tool for monitoring irrigation needs, which are usually scheduled weekly, we first checked if a CWSI measurement performed at noon can be used to compute the daily

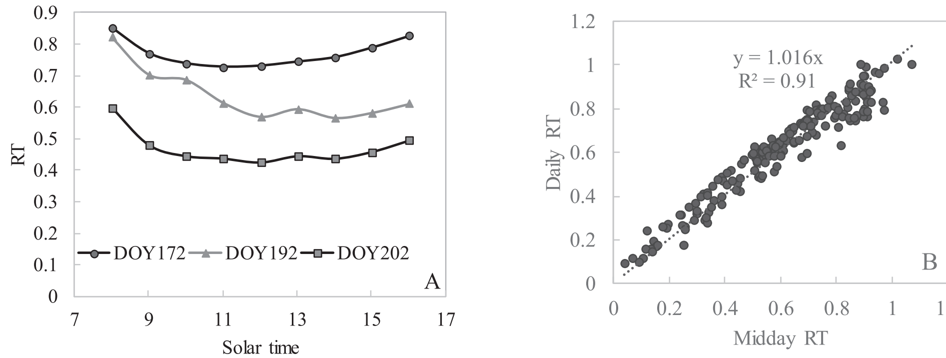

Fig. 4. A. Time course of hourly relative transpiration for three selected days of 2014: DOY 172, 192 and 202. B. Relationship between daily and midday relative transpiration for both years. The fitted linear regression (n = 216) is shown.

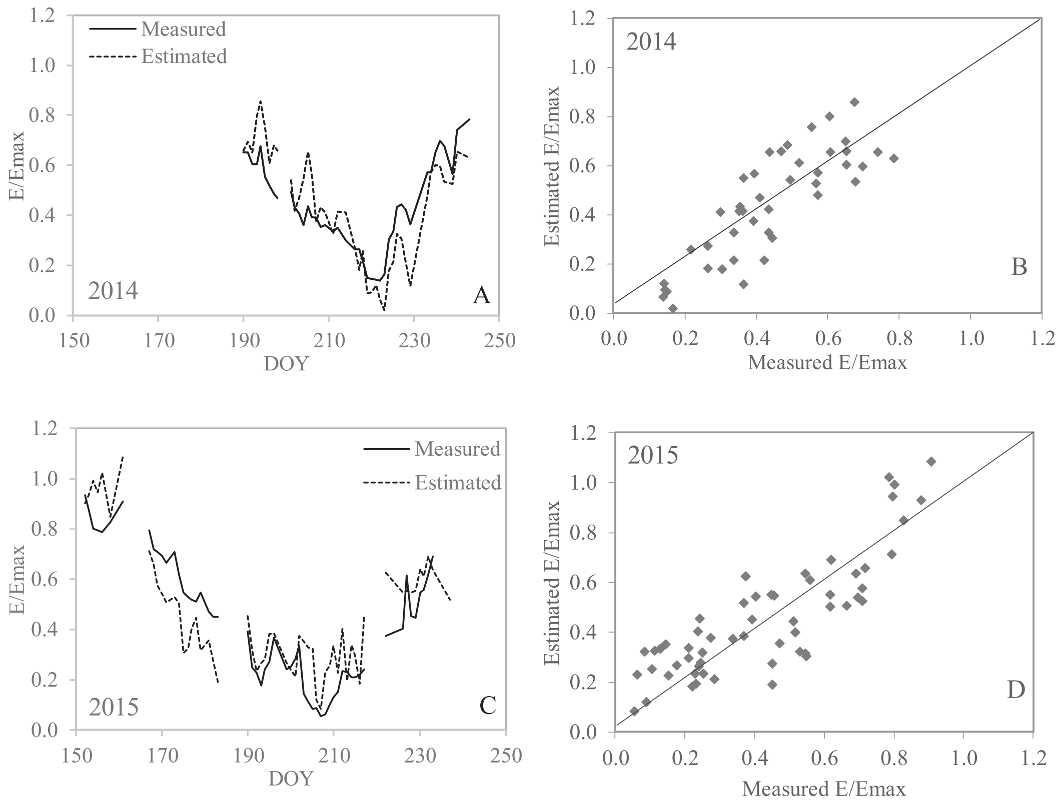

Fig. 5. Time course of the relative transpiration measured with sap flow and estimated from the CWSI for 2014 (A) and 2015 (C). The relationship between estimated and measured RT was plotted in B and D.

relative transpiration. Fig. 4A shows the time course of hourly RT for three selected days in the middle of the season with contrasting values of RT at noon. Relative transpiration was fairly constant during most of the daytime but was higher in the early morning and late afternoon. This effect was already observed in almond (Espadafor et al., 2017), and also in other Mediterranean orchard tree species, such as olive (Villalobos et al., 2012) or citrus (Roccuzzo et al., 2014). VPD at these timeframes is usually lower, which is more favorable for opening stomata due to the fact that the intake of CO_2 occurs at a lower cost in terms of transpired water. In any case, this will have a small effect on total daily transpiration considering the low transpiration rates at early morning and late afternoon, which was confirmed by plotting daily RT versus midday RT (Fig. 4B). These measures were linearly correlated, and the regression was not statistically different from the 1:1 line, which supports that, in this case, noon relative transpiration is a good predictor of the daily RT value. It contrasts with daily patterns observed in annuals (Inoue and Moran, 1997).

From Fig. 4, it may be concluded that an instantaneous observation around noon of the CWSI may be a good indicator of daily RT and thus of the water status of almond trees. It remains unclear whether this result can be extrapolated to other orchard tree species. Figs. 5A and 5C present the comparison between the RT measured with sap flow and the value estimated from the CWSI. The relationship between estimated and measured RT was close to the 1:1 line (Figs. 5B and 5D), and demonstrated that the maximum difference between the two measurements was 0.25.

We calculated the average value of the residual for 0.1-unit intervals of CWSI to identify the mean error on the computation of RT from the CWSI, using the results from the two years. Because of the low data density between 0 and 0.3, all the values within this range were averaged. The results of this analysis are plotted in Fig. 6, showing that the range of variation of the residual was not related to the CWSI value. On

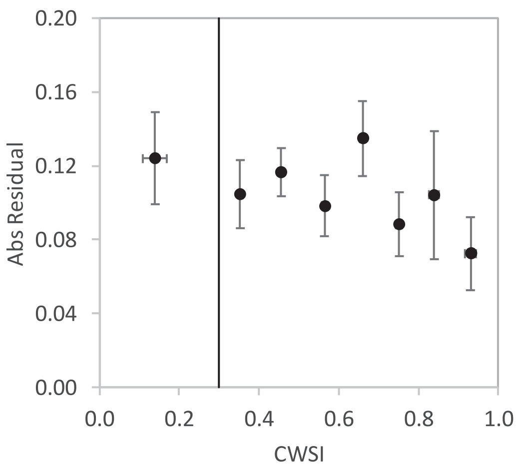

Fig. 6. Average residual (in absolute terms) for 0.1-unit intervals of CWSI. All values between 0 and 0.3 were averaged into a single value.

average, the error associated with the computation of the CWSI was 0.10. This value would be high in relative terms for low CWSI values. Nevertheless, for conditions typically observed in the field during summer, this error (i.e. 10% in the relative transpiration) should be acceptable for irrigation scheduling applications.

4. Conclusion

The simultaneous assessment of transpiration and canopy temperature has enabled the first experimental validation of the CWSI theory in orchard trees. The relationship obtained between CWSI and the relative transpiration showed a large scatter. This paper analyzes some of the sources that may originate the scatter: i) the micrometeorological conditions in the different parts of the canopy; ii) the portion of the tree crown targeted by infrared thermometers (uppermost part of the tree), which differs from the average foliage responsible for the total tree sap flow; iii) the scatter of the NWSB, and iv) methodological errors associated to the measurement of tree transpiration and the estimation of the CWSI. All these potential factors result in inaccuracies in determining actual CWSI for the assessment of tree water status. Our results conclude that once the residuals between the two measures were computed and averaged for CWSI intervals, the error in RT is around 10%. More research is required to reduce this error, which will optimize the use of CWSI for irrigation management of orchard trees.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2020.108128.

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