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Assessing plant water status in a hedgerow olive orchard from thermography at plant level

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Abstract

Water scarcity is the most limiting factor in many irrigated areas of Mediterranean countries such as South Spain. Olive growing has been traditionally associated to rain-fed agriculture, although irrigation and practices related to intensive agriculture have been progressively introduced, requiring a more precise irrigation scheduling to save water. Thermal imaging is among the alternatives to assess the crop water status, especially when deficit irrigation (DI) strategies are applied. However, this technique requires of new advances to be more user friendly and robust for practical usage. The aims of this study were: i) to define threshold values of canopy temperature (T_C), Crop Water Stress Index (*CWSI*) and the temperature difference between canopy and the surrounding air ($\Delta T_{canopy\text{-}air}$) for the assessment of the olive water status when a DI strategy is applied; ii) to define the best time of the day and the best area of the canopy to carry out thermal measurements, and iii) to obtain relationships between thermal indicators and main physiological parameters useful to estimate the crop water status from thermal data. The trial was conducted during 2015, in a hedgerow olive orchard (SW Spain) with 8-year-old trees (*Olea europaea* L., *cv*. Arbequina), under three irrigation regimes: a full-irrigation treatment (FI) and two regulated deficit irrigation treatments aimed to supplying 45% of the irrigation needs. In one of them, irrigation was scheduled from leaf turgor pressure related measurements ($45RDI_{TP}$). In the other, the crop coefficient approach was used to schedule irrigation ($45RDI_{CC}$). Significant correlations between *T*c versus stem water potential (Ψ_{st}) and leaf gas-exchange parameters (stomatal conductance to water vapor, g_s; net CO_2 assimilation, A_N; transpiration, *E*) were obtained ($p \leq 0.05$), in particular from measurements taken at 10:30 GMT in the lower part of the sunlit side of the canopy. Moreover, the relationships between both $\Delta T_{canopy\text{-}air}$ and *CWSI* with the monitored physiological variables were very robust. We concluded that values of $\Delta T_{canopy\text{-}air}$ higher than 0 ºC and values of *CWSI* up to 0.2 reliably reflect the plant water stress. Our results, therefore, suggest that both $\Delta T_{canopy\text{-}air}$ and *CWSI* measured at midday provide reliable information on the tree water status and are useful to schedule irrigation in hedgerow olive orchards, especially under DI conditions.

Keywords: Thermography, thermal indexes, water stress, irrigation scheduling, leaf-gas exchange parameters, water potential.

1.- Introduction

Olive represents the most important tree crop in the worldwide in terms of surface, with a global area close to 11 x 10^6 ha. Most of the growing areas are located in Mediterranean European countries, being Spain the most relevant in terms of production, with over 2.5 x 10^6 ha devoted to this crop, from which ca. 400.000 ha are under irrigation (MAGRAMA 2016).

The number of olive orchards has significantly increased in the last few years and, in many countries, hedgerow olive orchards with high plant densities (over 1500 trees ha^{-1}), also called super-high-density (SHD) orchards, are becoming popular. This type of orchard covers a surface of ca. 100,000 ha (Rius and Lacarte, 2015). According to forecast predictions (IPCC, 2014), water can be the most limiting factor for olive growing, particularly for irrigated SHD orchards (Vossen et al., 2004). Therefore, effective water management is crucial to increase the productivity of this natural resource, especially in areas such as South Spain, where climatic conditions are characterized by rainfall scarcity and a highly irregular spatial and temporal distribution of the rainfall events (García-Tejero et al., 2013).

Deficit irrigation (DI) strategies are highly effective for both improving water productivity and achieving a sustainable agricultural development. A properly chosen DI strategy saves water without highly affecting yield, and it has usually with a positive impact on quality (Fereres and Soriano, 2007; Geerts and Raes, 2009; Ruiz-Sánchez et al., 2010). Moreover, DI limits excessive growth, which is important in SHD orchards, where tree size has to be controlled for both optimum illumination and mechanical harvesting (Cuevas et al., 2013). In this line, authors such as Fernández et al. (2013), Gómez del Campo (2013) and Padilla-Díaz et al. (2016) have demonstrated that regulated deficit irrigation (RDI) can be a suitable strategy to improve irrigation water management and water productivity in SHD olive orchards. RDI strategies are based on avoiding excessive water stress in the periods of the growing cycle when the crop is highly sensitive to drought, so the effective monitoring of plant water status along the crop growing cycle becomes crucial (Poblete-Echeverría et al., 2014; Fernández 2014a).

There is a substantial amount of literature on the usefulness of different methods for the continuous monitoring of crop water status, such as those based on the use of dendrometers (Moriana et al., 2010 or Cuevas et al., 2010), sap-flow (Fernández et al., 2008a; Fernández, 2014a) or leaf turgor pressure probes (Zimmerman et al., 2008; Fernández et al., 2011a). Studies on their applicability to commercial orchards proved that additional information on crop-water status is often required to properly evaluate the information collected by those sensors (Fernández, 2014b). Thus, leaf or stem water potential and gas-exchange related measurements, apart of being used alone to monitor the plant water status, are often combined with the methods mentioned above. These water stress indicators have also their limitations. According to Martín-Vertedor (2011) and Fernández (2014a,b), leaf or stem water potential

measurements are good indicators of olive water status, but they are not suitable for precision agriculture because they cannot be automated. In fact, their use is based on destructive, non-continuous, high labour- and time-consuming measurements. Something similar occurs with gas-exchange measurements, such that they are more widely used with research purposes than in commercial orchards (Poblete Echeverría et al., 2016).

New irrigation approaches, such as precise irrigation, are technically demanding. This is behind the increasing interest in the use of remote sensing to monitor crop water status at different scales (at plant or orchard level). In this sense, thermal imaging emerged as a non-invasive approach to assess the crop-water status and to schedule irrigation, as probed from findings in citrus trees (García-Tejero et al., 2011; González-Dugo et al., 2014); almonds (García-Tejero et al., 2012), vines (Costa et al., 2012; García-Tejero et al., 2016) and olives (Berni et al., 2009; Poblete-Echeverría et al., 2014, 2016), among other crops. The principle of thermography relies on the leaf energy balance. Water stress induces stomatal closure, which in turn limits leaf transpiration, and hence the evaporative cooling process. This results in higher leaf/canopy temperature values (Jones, 1999, 2004). Thermal readings provide reliable information on the crop physiological status. Still, relationships between thermal information and main physiological parameters such as the stomatal conductance to water vapour (g_s), net CO_2 assimilation (A_N), transpiration (E), or the crop water status (in the basis on the leaf or stem water potential) are usually required to properly evaluate the information provided by thermal readings (Jones 2004; Jones et al., 2009). These relationships, however, depend on weather variables as T_{air}, incident radiation, the angle of incident radiation, wind speed and vapour pressure deficit (Jones, 1999; 2004). They also depend on monitoring proceedings (González-Dugo et al., 2012; Costa el al., 2013), cultivars (Costa et al., 2012; García-Tejero et al., 2016) and developmental stage (Cohen et al., 2015), among other factors. This has led to the testing of different strategies to optimize thermography, which included the development of effective protocols for field measurements based on thermal indices (Jones et al., 2002; 2009; Grant et al., 2006; Möller et al., 2007; Baluja et al., 2012; Bellvert et al., 2014) and robust relationships between thermal information and physiological parameters. However, some questions are still under debate, e.g. which is the most practical, although robust, thermal index that can be a proxy of plant physiological traits (e.g. leaf gas-exchange behavior). Another matter of debate is whether the thermal measurements could be directly used, without any additional relationship with other physiological variables, and whether threshold values, similar to those defined for stem or leaf water potential, or stomatal conductance, can be established.

We hypothesize that thermography could be a suitable approach to assess the crop water status in a SHD olive orchard. To test our hypothesis, we carried this work in a representative, fully productive SHD olive orchard with the aims of: (i) to derive threshold values for the plant water status from thermal related data collected in the orchard (canopy temperature, T_C; the temperature difference between canopy and the surrounding air, $\Delta T_{canopy\text{-}air}$; and the crop water stress index, *CWSI*) ; and (ii) to derive relationships between thermal readings and main physiological variables (stem water potential, Ψ_{st};

stomatal conductance to water vapor, g_s; net CO_2 assimilation, A_N, and transpiration, E). We explored the suitability of taking the thermal readings at different moments of the day and in different locations of the canopies.

2.- Material and Methods

2.1.- Experimental Site

The trial was conducted during the irrigation season of 2015, in a super-high-density olive (*Olea europaea* L., cv. Arbequina) orchard located at 25 km of Seville (37º15'N, 5º48' W). The trees were planted in 2007 at the top of 0.4 m high ridges and spaced 4 m x 1.5 m (1667 trees ha^{-1}), with the rows oriented N-NE to S-SW.

The orchard soil is an Arenic Albaqualf (USDA, 2010) with a sandy loam top layer (77.7 % sand, 20.1 % clay and 2.2 % silt) of 1.73 Mg m^{-3} bulk density (ρ) and soil hydraulic conductivity near saturation (K_{sat}) of 40.7 cm day^{-1}. Downwards there was a sandy clay layer (60.9 % sand, 37.1 % clay and 2.0 % silt) with ρ=1.82 Mg m^{-3} and K_{sat}= 3.54 cm day^{-1}. The average depth from the top of the ridges to the clayey soil layer was 0.6 m. The clay layer was not reached by the roots, since the maximum depth of the root system was 0.45 m (Diaz-Espejo et al., 2012).

Trees were irrigated with an automatic controller (Agronic 2000, Sistemes Electrònics PROGRÉS, S.A., Lérida, Spain) and a pipe line per row, with three 2 L h^{-1} drippers per tree, spaced 0.5 m. Fertilizers were injected into the irrigation system once a week during the irrigation period, receiving all trees the same amount of nutrients, enough to cover the crop needs (Fernández et al., 2013).

The climate of the experimental area is Mediterranean, with mild winters and hot dry summers. Most rainfall events in the area occurs between September and May, the summers being dry and hot. The average values of precipitation and potential evapotranspiration are 537.3 mm and 1504.0 mm, respectively (2010-2015 period). During the hottest months (July and August) the maximum values of air temperature can easily go over 40 ºC, whereas in the coolest months (December and January) air temperature rarely drops below -5 ºC.

2.2.- Experimental design and irrigation treatments

The experimental design was a randomized complete block with four replicates per treatment. The experimental unit (192 m^2) had four rows with eight trees per row, being the eight central trees (four trees for the two central rows) considered as sampling trees, surrounded by 24 border trees. Three irrigation treatments were defined: (i) A full irrigation (FI) treatment, in which the trees were daily irrigated to replace 100% of the irrigation needs (IN). The latter were calculated as the difference between crop evapotranspiration (ET_C) and effective precipitation (P_e). ET_C was calculated with the crop coefficient approach (Allen et al., 1998; see Fernández et al., 2013, for details). (ii) A regulated deficit irrigation treatment ($45RDI_{CC}$) aimed to replace 45% of IN (see Padilla-Díaz et al., 2016, for details). Basically, daily irrigation amounts (IA) similar to IN were applied in the three periods of the growing

cycle when the crop is most sensitive to water stress, defined as Period 1 (around bloom, in April) Period 2 (during the maximum rate of pit hardening, in June) and Period 3 (during the stage of fast oil accumulation, from the end of August to mid-September) (Fernández, 2014a). Between Periods 1 and 2 an irrigation event per week was applied when the soil water content was below 70% of the maximum soil water holding capacity. Between Periods 2 and 3, two irrigation events per week were applied (iii) a second 45RDI treatment similar to the already described, but in which irrigation was scheduled from leaf turgor pressure readings ($45RDI_{TP}$) (see Padilla-Díaz et al., 2016, for details).

2.3.- Soil and ~~Plant~~ plant measurements

The effect of the irrigation treatments on main physiological variables, including canopy temperature, was established from measurements in June 18th (day of year –DOY- 169), July 2nd, 16th and 22th (DOY 183, 197 and 203), August 6th, 13th and 27th (DOY 218, 225 and 239), and September 10th (DOY 253). Measurements of stem water potential at midday (Ψ_{st}) were made with a Scholander-type pressure chamber (PMS Instrument Company, Albany, Oregon, USA). One leaf per tree close to a main branch was sampled, from two representative trees per plot (n = 8), at around 12:00 GTM, the time for minimum Ψ_{st} in olive. The chosen leaves were wrapped in aluminum foil ca. 2 h before sampling. Measurements of stomatal conductance to water vapor (g_s), net CO_2 assimilation (A_N) and transpiration (E) were made with a portable infrared gas analyzer (LI-6400; LiCor Inc., Lincoln, Nebraska, USA), with a 6 cm^2 transparent leaf chamber and the air-flow rate set at 350 µmol s^{-1}. Measurements were taken in one fully expanded and sunlit leaf per tested tree, using 8 trees per irrigation treatment (n = 8). Measurements were made around 08:30 GMT, the time for maximum g_s in olive.

Canopy temperature (Tc) was derived from thermal images were made on the same days that the mentioned physiological measurements, both at 08:30 and 12:00 GTM, and both at the bottom (1.5 m from the soil surface) and the top (2.5 m from the soil surface) of the sunlit side of eight trees per treatment (n = 8). These regions were previously defined, and the canopy surface taken in each image corresponded with a single tree (the first one for the down area of the canopy, and the second one for the upper area of the canopy). We use a ThermaCam (Flir SC660, Flir Systems, USA, 7-13 µm, 640x480 pixels). Each pixel corresponded to an effective temperature reading and the emissivity (ε) was set at 0.96. The background temperature was determined by measuring the temperature of a crumpled sheet of aluminum foil placed near the sampled leaves using ε= 1 (Jones et al., 2002). The imager was placed perpendicularly to the canopy, at about 2 m from the sunlit side. For the images taken in the down part, a cooled white screen was used as background, that being placed behind of each monitored tree to simplify the isolation of the canopy surface through image processing. For the images of the upper part, the regions of sky were used as the background. Thermal images were analysed with the software developed by García-Tejero et al. (2012). This software allows to work with up to three sections for each analyzed image, to select the temperature range corresponding to pixels of the

canopy, and to remove those areas or pixels that do not have to be considered, i.e. those corresponding to the stem and the background (Figure. 1).

In order to normalize the thermal information and taking the absolute values of T_C as the starting point, two thermal indexes were estimated: the difference between canopy and the surrounding air ($\Delta T_{canopy\text{-}air}$) and the crop water stress index (CWSI); these being calculated as follows (Idso, 1981; Jackson et al., 1981):

$$\Delta T_{canopy\text{-}air} = T_C - T_{air} \quad (1)$$

$$CWSI = \frac{\Delta T - \Delta Twet}{\Delta Tdry - \Delta Twet} \quad (2)$$

where $\Delta T_{canopy\text{-}air}$, ΔT_{dry} and ΔT_{wet} is the difference between canopy and air temperature in the moment of the measurement, T_C is the temperature of the canopy, T_{air} is the temperature of the surrounding air, and ΔT_{dry} and ΔT_{wet} are the difference between canopy and air temperature when the crop has the stomata fully closed and when is fully transpiring, respectively.

To obtain the reference values of ΔT_{wet} we calculated the non-water stress baselines ($\Delta T_{canopy\text{-}air}$ = a + b**VPD*) according to Idso et al. (1981), and used a ΔT_{dry} value equal to 5 ºC, as proposed by Jackson et al. (1982). Non-water stress baselines were defined for two different moments of the day (08:30 and 12:00 GTM, respectively), i.e. when T_C readings were made. Moreover, as T_C readings were obtained from two different areas of the tree (down and topside), these functions were defined for each location. Thus, four relationships between *VPD vs.* $\Delta T_{canopy\text{-}air}$ were estimated for each monitoring time (08:30 and 12:00 GTM) and parts of the canopy (at the bottom and top). In all cases, these relationships were derived from the canopy temperature readings in FI trees.

Finally, s~~S~~oil water content was measured by using a Profile probe (Delta-T Devices Ltd., Cambridge, UK), recording the volumetric soil water content (θ) values in the root zones of three trees per treatment. Each access tube was installed at 0.5 m from the tree trunk, measuring the soil-water content at 10, 20, 30, and 40 cm, coinciding the measurement days with those days in which the physiological measurements were done. Previously, the Profile probe was calibrated in situ as it was described by Fernández et al. (2011b).

2.4.- Statistical analysis

For each measurement day, an exploratory and descriptive analysis of physiological measurements and canopy readings was made after applying a Levene's test to check the variance homogeneity of the studied variables. Significant differences between irrigation treatments ($p \leq 0.05$ and $p \leq 0.01$) in the

studied variables were identified by applying a one way ANOVA and a Tukey's test for treatment separation, with the SPSS statistical software (SPSS Inc., 15.0 Statistical package; Chicago, IL, USA).

To evaluate the non-water stress baselines for each sampling time and canopy location, a linear correlation analysis was made (n = 8) with a covariance analysis at a confidence level of 95%. That allowed to compare the functions (slope and intercept) and evaluate significant differences.

To evaluate the relationships between variables, a linear correlation analysis between the thermal indicators (T_C, $\Delta T_{canopy\text{-}air}$ and *CWSI*) and the physiological variables (Ψ_{st}, g_s, A_N and *E*) and θ at the different depths was made for each sampling time and location (n = 24). The obtained correlation coefficients were used to identify both the best time and location to carry out T_C readings. This allowed us to assess the reliability of the mentioned thermal indicators as a proxy for crop physiology traits.

Once selected the best moment of the day to carry out the T_C readings, and the most representative thermal indicator, the obtained linear regressions for each sampling location in the canopy were compared (slope and intercept) using a covariance analysis at a confidence level of 95%.

3.- Results and discussion

3.1. Meteorological conditions, irrigation events and physiological measurements

Figure 2 shows the irrigation events applied in each irrigation treatment. According to the chosen irrigation strategies (more details in Padilla-Díaz et al. 2016), in Period 1 (DOY 98-124), Period 2 (DOY 146 to 173) and Period 3 (DOY 237 to 257) all the trees were daily irrigated to replace crop requirements. In Period 2 the FI trees received 102% of irrigation needs (IN), whereas $45RDI_{TP}$ and $45RDI_{CC}$ trees received 90% and 79% of IN, respectively. In between Periods 2 and 3 (DOY 174 to 236), FI trees received 107% of IN, whereas both $45RDI_{TP}$ and $45RDI_{CC}$ received 24% and 25% IN respectively, with two or three irrigation events per week. Finally, during Period 3 all trees were daily irrigated again, receiving 106% of IN the FI trees 89% the $45RDI_{TP}$ trees and 107% the $45RDI_{CC}$ trees.

Seasonal courses of main weather variables recorded at the two sampling times of the day are shown in Figure. 3. The highest values of temperature and net radiation were recorded at the beginning of the experimental period (June), while top values of relative humidity were recorded at the end (September). Values of vapor pressure deficit were quite high all along the experimental period, especially at the beginning.

The seasonal courses of Ψ_{st} and gas exchange measurements were in line with the irrigation strategies applied in each treatment (Figure 4). At the beginning of the experimental period (DOY 169) no differences between treatments were found for any physiological variable. This is in agreement with the fact that during Period 2 all trees received irrigation amounts close to the irrigation needs (Figure 2).

At the beginning of the stress-increasing period (DOY 183, nine days after the end of Period 2) we found a faster decrease in gas exchange than in Ψ_{st}. A similar behaviour was observed by Torres-Ruiz etal. (2013) and Pérez-Martín et al. (2014) in 'Manzanilla' olive trees. They related this behaviour with

the effective stomata control of plant water status in this species, mainly in the first stages of water stress (Fernández et al., 1997; Fernández 2014a). Later, from DOY 183 to 225, stomatal conductance (g_s), net CO_2 assimilation (A_N) and consequently leaf transpiration (E), decreased progressively in the RDI trees. This is in accordance with those trees were receiving just ca. 25% of IN in that Period. The lowest values of these three variables were recorded on DOY 218.

Later in the season, and in agreement with the greater water supplies of Period 3, g_s, A_N and E values in RDI trees became similar to those recorded in FI trees, showing a full recovery of the trees on that period. However, at the beginning of this period, values of Ψ_{st} recovered quicker than those of gas exchange related variables. This is also typical in olive (Fernández, 2013, Perez-Martin et al., 2014). The FI trees showed values of Ψ_{st}, g_s, A_N and E close to the maximum for olive trees under non-limiting conditions (Diaz-Espejo et al., 2006), all along the experimental period.

Significant differences in Ψ_{st} among treatments were observed in between Periods 2 and 3, when these values were progressively descending in 45RDI trees till reaching a minimum value of -4.4 ± 0.1 MPa on DOY 218 and 225. This descend was accompanied with a depletion in gas-exchange parameters, being recorded the minimum values when Ψ_{st} was close to -3 MPa. (Figure 4).

3.2. Diurnal evolution of canopy temperature and related thermal indices

Figure 5 shows the average of canopy temperature readings taken at the two sampling times and locations, for the three irrigation treatments during the monitoring period. For all treatments and sampling times, differences were observed between the down and the upper part. These differences were especially remarkable at 08:30 GMT, when values in the upper part were up to 5 ºC below those from the down part. This could be due to heat transmission from the soil to the down part of the canopy or to greater heat dissipation in the upper part because of the wind. The first differences between FI and RDI trees appeared on DOY 197, these differences being more evident at 08:30 GMT on the down part, whereas, at 12:00 GMT the differences were significant in both sampling areas. Differences in T_C between treatments increased along the season, being greater at 12:00 than at 08:30 GMT, and in the lower part of the canopy that at the upper part. Depending on the location and sampling time, differences among treatments ranged from 2 to 6 ºC.

Our results agree with those reported for other olive orchards of different locations and characteristics. Sepulcré-Cantó et al. (2006) detected differences close to 2 ºC by using infrared sensors installed 1 m above the olive crown. Poblete-Echeverría et al. (2016), in a study developed in 'Arbequina' trees, registered temperature differences around 4 – 5 ºC, at the moments of maximum stress level (Ψ_{st} < – 5 MPa). Other authors such as Testi et al. (2008) in Pistachio, García-Tejero et al. (2011) in citrus trees, and García-Tejero (2016) in vines reported temperature differences of 2-6 ºC between fully irrigated and stressed trees.

It is noticeable that differences between treatments in T_C were detected when the lowest g_s values were recorded (DOY 197 to 225 DOY, Figures 4 and 5). Nevertheless, T_C readings in FI treatment showed a

high variation, probably associated to differences in meteorological conditions during the sampling days. As it has been previously stated, the effect of stomatal regulation (partial closure) under a mild or moderate water stress is that leaf temperature trends to increase, because of a decrease in the heat dissipated by transpiration (Jones et al., 2002; 2009; Jones and Vaughan, 2010). According to Jones et al. (2009) and Jones and Vaughan (2010), there are many variables such as the radiation level, air temperature, vapour pressure deficit, the relative humidity or the angle of the radiation incident on the leaf surface that will influence decisively on the absolute value of T_C. Therefore all of them must be taken into account when making an assessment of crop water status from thermal information. This explains the difficulty of establishing a threshold value of T_C for irrigation scheduling and crop-water status monitoring. This is a limitation of the thermal approach as compared to Ψ_{st} or g_s, variables for which threshold values for water stress can be more easily established (Fernández et al. 2008b; Moriana et al., 2012).

Once normalized the T_C readings by estimating the difference between canopy and the surrounding air ($\Delta T_{canopy\text{-}air}$), we observed $\Delta T_{canopy\text{-}air}$ values below 0 ºC for the FI trees, especially at 12:00 GMT, and with a temporal variation much less than detected for T_C readings (Figure 6). This is in line with the results reported by Sepulcré-Cantó (2006) and Poblete-Echeverría (2016), from readings taken in similar conditions. This corroborates what we have stated above for the thermal readings at 12:00 GMT and in the down part of the canopy, these being the most informative in terms of tree water status. Thus, by comparing the $\Delta T_{canopy\text{-}air}$ values detected in FI trees versus those in RDI trees, we defined a threshold value of $\Delta T_{canopy\text{-}air}$ = 0 ºC, above which a severe water stress situation would be being supported by the crop.

After using the methodology proposed by Idso et al. (1981) and Jackson et al. (1981) to derive non-water stressed baselines from the $\Delta T_{canopy\text{-}air}$ values obtained from the FI trees and *VPD* values registered for each time and monitoring day, significant relationships were obtained for the four sampling situations, especially for the measurements at 12:00 h (Table 1). For the readings taken at 12:00 GMT in the down part, the slope was similar to that obtained by other authors such as Berni et al. (2009) in 'Arbequina' olive trees (-0.35) from measurements 1 m above the trees, although the intercept point was different (2.08). According to these authors, the explanation of the low slopes derived from the non-water stressed baselines would the small size of the olive leaves, which are very coupled to the atmosphere (Villalobos et al., 2000) and because of the marked stomatal control even in full irrigated trees, when the evaporative demand is very high. As a consequence of this slope, *CWSI* estimation in olive trees is very much affected by errors in both the estimation of *T*c and the measurement of T_{air} (Berni et al., 2009). More interesting were the reflections argued by these authors, when they compared effect of net radiation and wind speed in the interception point, suggesting that the slopes obtained for different non-water stressed baselines estimated from a theorist proposed model by them were very similar to the obtained from empirical information; and the highest variations were observed in the interception point. Similar results were reported Testi et al. (2008) in pistachio trees, evidencing that

daily variations in net radiation resulted in parallel baselines, i.e. the slope of the baseline was not affected.

Figure 7 shows the *CWSI* evolution calculated by using the non-water stressed baselines defined in Table 1 according to the T_C values of *FI*. The seasonal course of this index was similar to that of $\Delta T_{canopy\text{-}air}$ (Figures 6 and 7). The greatest differences in CWSI between treatments were reached from DOY198 to DOY 225, especially at 12:00 GTM. The lowest *CWSI* values were found in the FI trees, being around 0 (dimensionless), especially during the readings taken at 12:00 and at 08:30 GTM in the down part. However, *CWSI* values derived from the thermal readings at 12:00 GMT in both parts of the canopy were occasionally higher than 0 ºC in the FI trees, which were under non-limiting soil water conditions. This could be related to the sensitiveness of CWSI to weather conditions, e.g. solar radiation (Agam et al., 2013), or to tree architecture (González-Dugo et al., 2014). In any case, this is a limitation of *CWSI* that curtails its potential as a reliable index to schedule irrigation. Such limitation was not detected for $\Delta T_{canopy\text{-}air}$. The fact that threshold values for the assessment of the crop water status cannot be easily derived from thermal readings is acknowledged as one of the main limitations of this technique to schedule irrigation in commercial orchards.

3.3.- Relationships between the thermal information, ~~and versus~~ physiological variables and soil-water content

In the last few years, many works have been developed to optimize the use of thermography to assess the crop-water status and to schedule irrigation (Jones et al., 2002; Leinonen and Jones, 2004), reporting significant correlations between thermal information and other related physiological variables (Berni et al., 2009; Poblete-Echeverría et al., 2014; Osroosh et al., 2016). In our case, relationships between thermal and physiological data were derived to define the most efficient thermal index and the best sampling time to assess the crop water status. Table 2 shows the Pearson's correlation coefficients obtained for the relationships corresponding to the measurements taken at 08:30 and 12:00 GMT in the lower and upper part. Regarding T_C, the most significant correlations were obtained at 12:00 GTM, these being very similar for both the readings in the down part and in the upper part. Moreover, a similar robustness was observed for the relationships derived from the readings taken at 08:30 in the down part. This did not apply to measurements from the upper part. Regarding the coefficients obtained for $\Delta T_{canopy\text{-}air}$ and *CWSI* with the physiological parameters, these were better than those for *Tc*, especially for the readings taken at 12:00 GMT. This indicates the feasibility and robustness of both thermal indexes, especially $\Delta T_{canopy\text{-}air}$, because of its simplicity in comparison to *CWSI*.

Additionally, thermal information obtained at 8:30 and 12:00 GTM in the lower and upper part was related to the soil-water content measurements registered at different depths (Table 3). On overall, thermal data obtained at 10:30 GTM did not reflect with enough robustness the soil-water status, in comparison to the relationships obtained by using the thermal information derived from the measurements taken at 12:00 GTM. In this agreement, as T_C as the related thermal indexes (*CWSI* and

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$\Delta T_{canopy\text{-}air}$) reported significant relationships with the θ obtained at different layers. Within the measurements taken at 12:00 GTM, the best relationships were obtained when comparing the thermal information derived from the images taken in the lower part, and within them, by using the readings of θ corresponding to the first soil layers (at 10 and 20 cm depth, respectively). These results would suggest the possibility of stablishing deficit irrigation programmes combining the information obtained in the three levels of the soil-plant-atmosphere system: weather data (T_{air} and VPD), soil (θ) and plant (T_C and the related thermal indexes).

~~Taking into account that~~In agreement with this, the most significant relationships between these thermal indexes and physiological parameters were obtained from readings taken at 12:00 GMT. Different functions were defined depending of measurements being taken in the down part or in the upper part (Figure 8). One of the most remarkable findings was the coincidence of the threshold values determined for $\Delta T_{canopy\text{-}air}$ and *CWSI* in terms of Ψ_{st}, *CWSI*, and A_N. As it can be observed in Figure 8, taking into account the readings obtained in the upside, $\Delta T_{canopy\text{-}air}$ close to zero would be associated with $\Psi_{st} \leq -3$ MPa; $g_s \leq 0.1$ mol m^{-2} s^{-1} and $A_N \leq 8$ µmol m^{-2} s^{-1}, these values having been defined as indicators of situations of severe water stress (Fernández et al., 2013, Díaz-Espejo et al., 2012; Pérez-Martín et al., 2014; Hernández-Santana et al., 2016; Padilla-Díaz et al., 2016; among others). Something similar occurred taking as reference the values of *CWSI*, these being around 0.2 when $\Delta T_{canopy\text{-}air}$ was close to zero.

When considering the readings from the down part, the defined threshold values for a moderate-to-severe water stress for $\Delta T_{canopy\text{-}air}$ would be between 1.5 to 2 ºC, and between 0.4 to 0.5 in terms of *CWSI* (Figure 8).

Likewise, the applicability of these relationships is reduced at farm level, because of their high variability within the orchard crop (García-Tejero et al., 2016), being more advisable the use of threshold values such as those derived from our results. In this regard, the robustness observed in the relationships between $\Delta T_{canopy\text{-}air}$ and the studied physiological parameters would justify the use of this thermal index stablishing a threshold value of $\Delta T_{canopy\text{-}air}$ close to zero when thermal readings are taken at 12:00 GTM in the down part of the canopy.

Conclusions

Crop water monitoring by using thermal information in olive is highly dependent on the procedure of thermal acquisition. This work demonstrates the sensitiveness of this technique to the monitoring process; observing different results when measurements are taken at different hours and in different parts of the tree. Owing to this phenomenon, it could be difficult to compare our results with other obtained by using other kind of thermal sensors or also by applying different image processing and capture. In spite of this constraint, on overall, our result suggest that as $\Delta T_{canopy\text{-}air}$ as *CWSI* can be considered as robust indicators of crop-water status, as it was demonstrated by the relationships

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derived from monitored the physiological variables such as g_s or Ψ_{st}. In line with this conclusion, $\Delta T_{canopy-air}$ would allow stablishing deficit irrigations scheduling exclusively by using thermal information, not being necessary the use of relationships with other physiological parameters; and taking a threshold value close to zero, as the point above which a moderate stress situation is being supported by the crop. Likewise, as $\Delta T_{canopy-air}$ as *CWSI* showed significant relationships with crop water potential and gas exchange measurements, especially with the readings taken at 12:30 GTM; being possible to estimate these values throughout thermal information. Moreover, these thermal indexes showed significant relationships with the soil water content at different depths, especially by using the soil moisture readings taken in the first 20 cm, evidencing the possibility of define irrigation programming based on measurements of crop and soil water status. Nevertheless, these relationships could not be assumed for other different situations, cultivars, image capturing and processing, being advisable to define specific functions in the case of estimating the crop-water status or gas-exchange levels exclusively using thermal information.

Acknowledgements

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TABLES

Table 1. Fitted parameters for the baselines from non-stressed trees ($\Delta T_{canopy\text{-}air}$ = a +b*VPD). Data obtained for the DOY 169 to 253 (n = 8).

GTM	Side	Slope (ºC kPa^{-1})	Intercept (ºC)	R^2
08:30	Down	-1.92	5.65	0.76
	Upper	-1.74	2.08	0.87
12:00	Down	-0.39	0.95	0.82
	Upper	-0.67	0.09	0.87

Table 2. Pearson's correlation coefficients between thermal indicators and physiological variables at the two sampling times and sampled canopy location.

GMT	location	Thermal Indicator	Ψ_{st}	A_N	g_s	E
10:30	Down	T_C	-0.61**	-0.74**	-0.74**	-0.53**
		$\Delta T_{canopy\text{-}air}$	-0.42*	ns	-0.41*	-0.55**
		CWSI	-0.66**	-0.61**	-0.69**	-0.71**
	Up	T_C	ns	-0.50*	-0.53**	ns
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	ns	ns	ns	ns
12:30	Down	T_C	-0.57**	-0.68**	-0.65**	-0.46*
		$\Delta T_{canopy\text{-}air}$	-0.78**	-0.81**	-0.80**	-0.78**
		CWSI	-0.74**	-0.83**	-0.80**	-0.70**
	Up	T_C	-0.57**	-0.70**	-0.65**	-0.48*
		$\Delta T_{canopy\text{-}air}$	-0.83**	-0.83**	-0.78**	-0.81**
		CWSI	-0.71**	-0.80**	-0.77**	-0.70**

Ψ_{st}, stem-water potential;; A_N, net-photosynthesis; g_s, stomatal conductance to water vapour; E, transpiration; T_C, canopy temperature; $\Delta T_{canopy\text{-}air}$, difference between canopy and air temperature; *CWSI*, crop-water stress index. ns, no significant relationships; * and ** evidence significant correlations at 95 and 99%, respectively.

Table 3. Pearson's correlation coefficients between thermal indicators obtained at the two sampling times and sampled canopy location; and the volumetric soil-water content (θ, m^3 m^{-3}) measured at different depths (10, 20, 30 and 40 cm, respectively).

GMT	location	Thermal Indicator	θ_{10}	θ_{20}	θ_{30}	θ_{40}
10:30	Down	T_C	-0.58**	-0.66**	-0.52*	-0.48*
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	-0.44*	-0.57*	-0.54*	-0.46*
	Up	T_C	-0.43*	-0.49*	ns	ns
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	ns	ns	ns	ns
12:30	Down	T_C	-0.76**	-0.57**	-0.42*	-0.39*
		$\Delta T_{canopy\text{-}air}$	-0.82**	-0.76**	-0.65**	-0.59**
		CWSI	-0.79**	-0.72**	-0.60**	-0.56*
	Up	T_C	-0.58**	-0.69**	-0.46*	-0.48*
		$\Delta T_{canopy\text{-}air}$	-0.58**	-0.60**	-0.55*	-0.61**
		CWSI	-0.69**	-0.70**	-0.62**	-0.66**

T_C, canopy temperature; $\Delta T_{canopy\text{-}air}$, difference between canopy and air temperature; *CWSI*, crop-water stress index; θ_{10}, θ_{20}, θ_{30}, θ_{40}, volumetric soil-water content at 10, 20, 30 and 40 cm depth respectively; ns, no significant relationships; * and ** evidence significant correlations at 95 and 99%, respectively.

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FIGURES

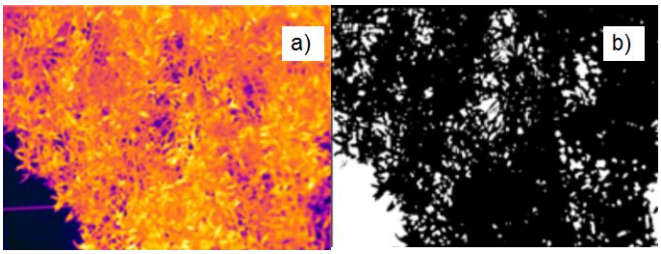

Figure 1. False colored image of downside olive tree (a) and post-processing image (monochrome image) representing in black the areas corresponding to pixels of leaves (b). This process allows deleting those pixels corresponding to branches, stem and the background (all these areas in white).

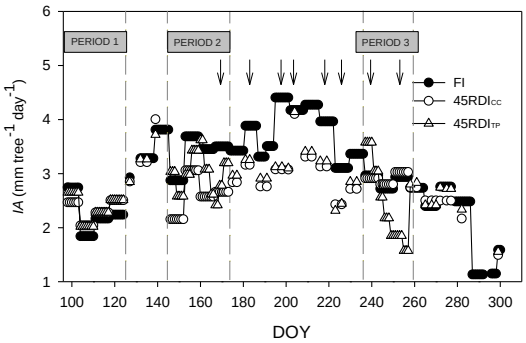

Figure 2. Irrigation applied (IA) in each irrigation treatment: full-irrigated (FI), crop-coefficient regulated deficit irrigation (45RDI$_{CC}$), regulated deficit irrigation based on turgor pressure related measurements (45RDI$_{TP}$). Arrows down show the days on which the thermal measurements were made..

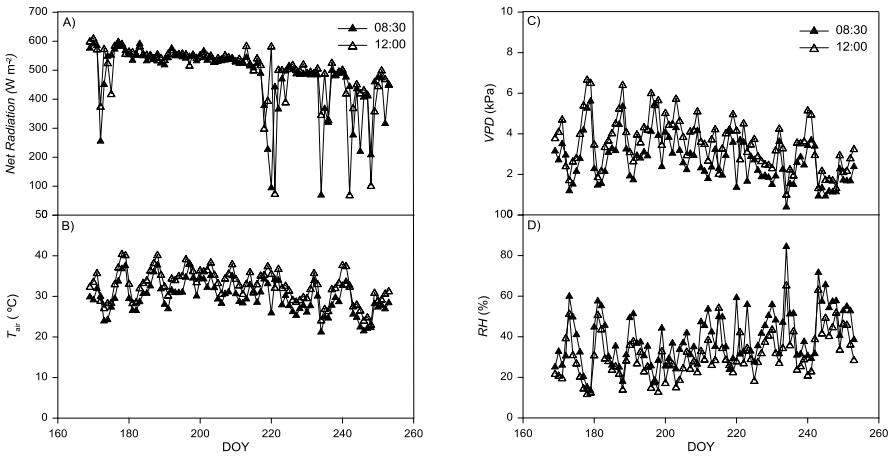

Figure 3. Seasonal course of net radiation (A), air temperature (B), vapour pressure deficit (C) and relative humidity (D), measured at 08:30 and 12:00 GMT.

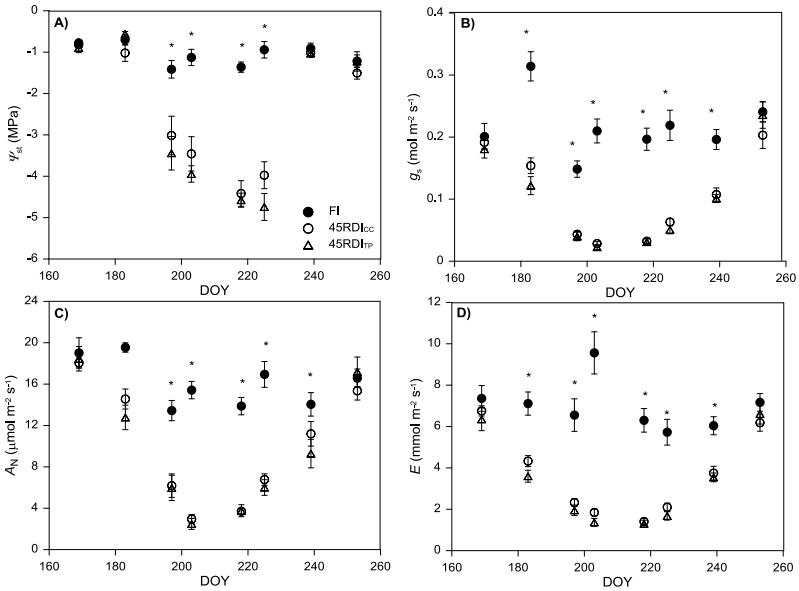

Figure 4. Seasonal course of stem water potential (Ψ_{st}) (a), stomatal conductance (g_s) (b), net CO_2 assimilation (A_N) (c), and transpiration (E) (d), measured in trees of the three irrigation treatments. * shows significant differences between FI and RDI trees (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

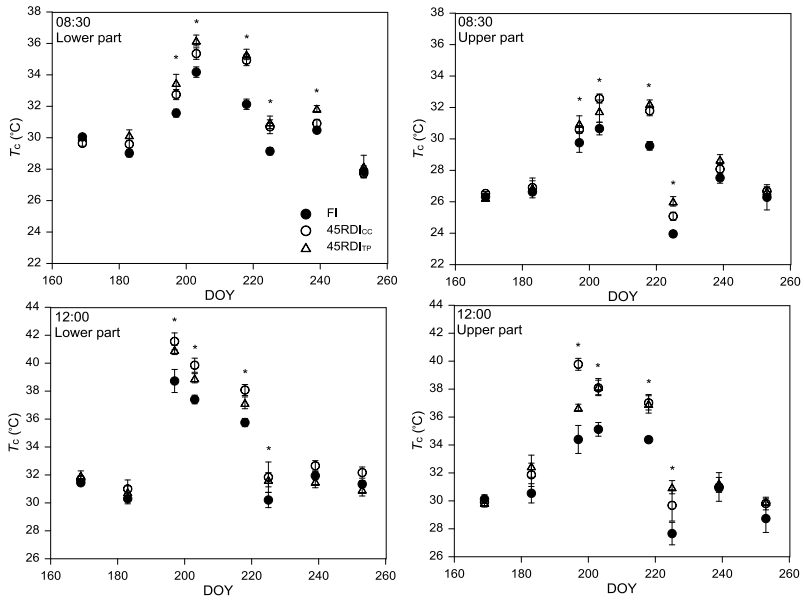

Figure 5. Seasonal evolution of the canopy temperature (T_C) measured at the two times (08:30 and 12:00 GTM) and sampling locations in the canopy (lower and upper part), in trees of the three irrigation treatments. * shows significant differences between FI and RDI treatments (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

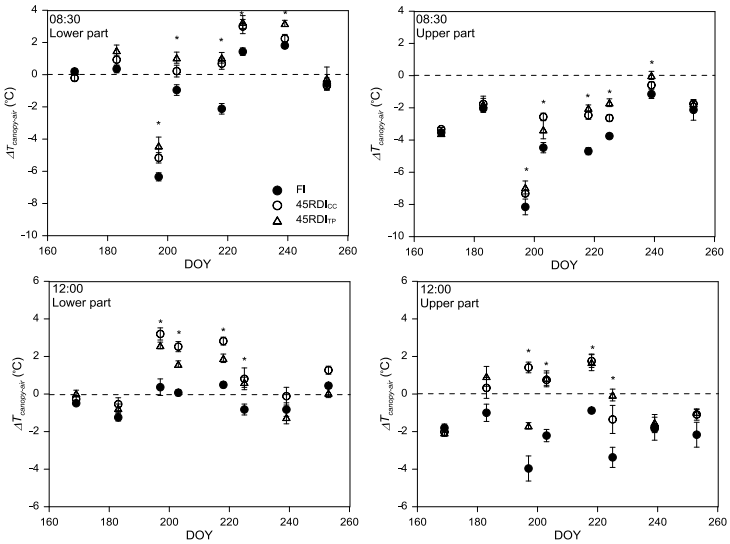

Figure 6. Seasonal evolution of the difference between canopy and air temperature ($\Delta T_{Canopy-air}$) measured at the two times (08:30 and 12:00 GTM) and sampling locations in the canopy (lower and upper part), in trees of the three irrigation treatments. * shows significant differences between FI and RDI treatments (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

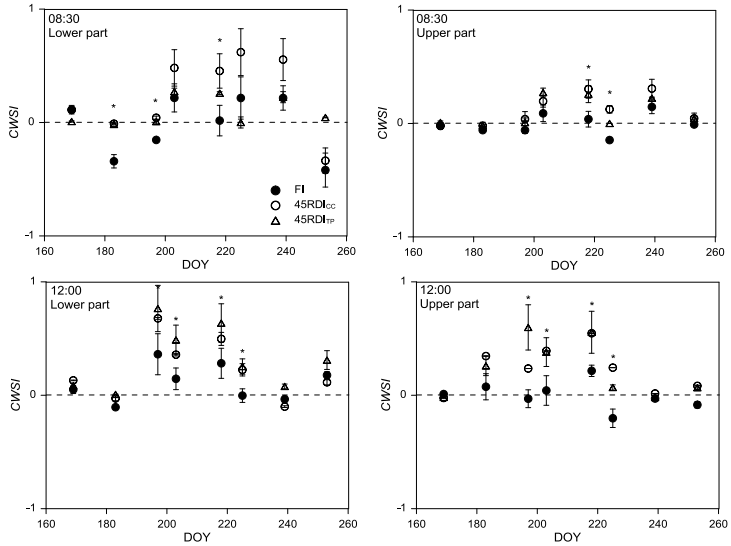

Figure 7. Seasonal evolution of the Crop Water Stress Index (*CWSI*) measured at the two times (08:30 and 12:00 GTM) and sampling locations in the canopy (lower and upper part), in trees of the three irrigation treatments. * shows significant differences between FI and RDI treatments (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

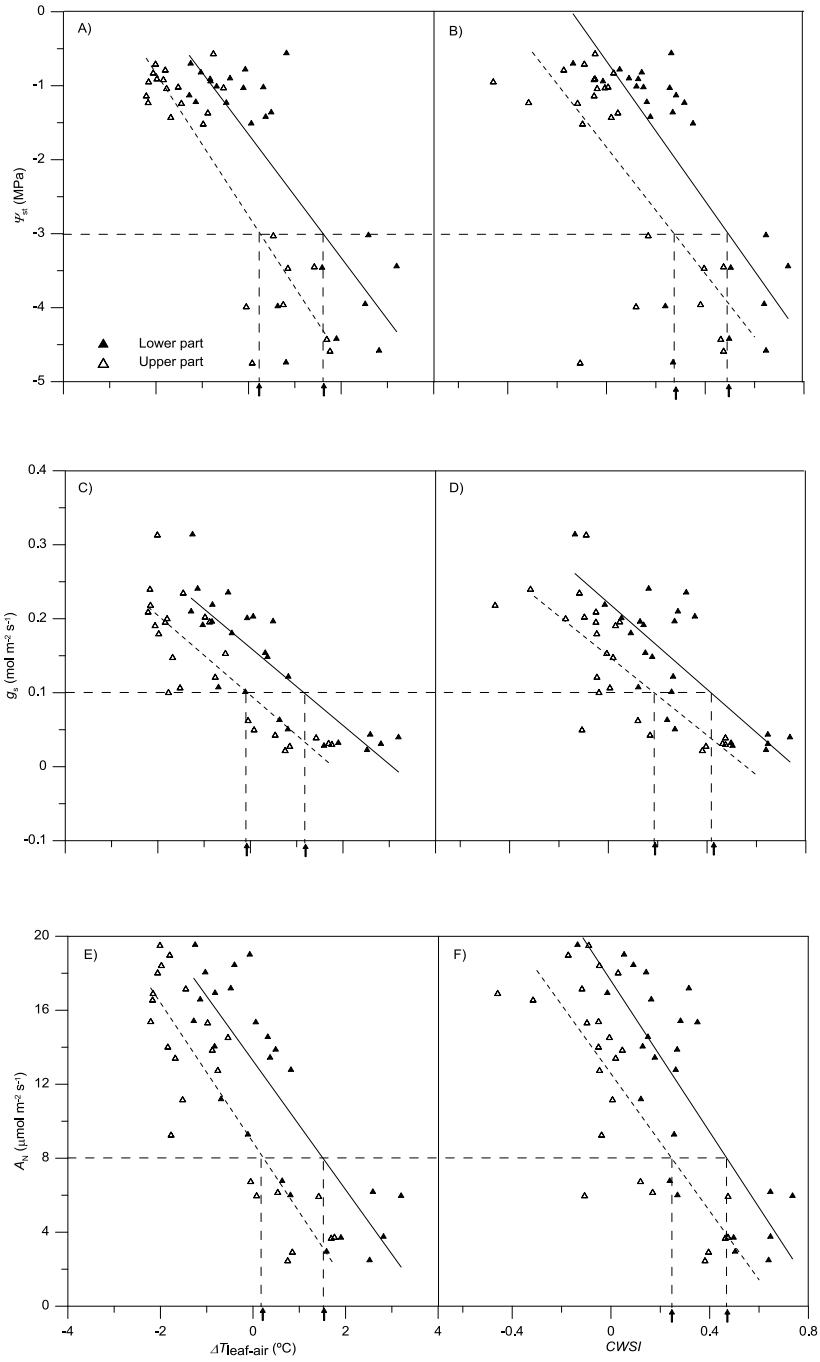

Figure 8. Linear regressions between the difference between canopy and air temperature ($\Delta T_{canopy-air}$) and the crop-water stress index (*CWSI*, dimensionless) with the stem-water potential (Ψ_{st}), stomatal conductance (g_s) and net CO_2 assimilation (A_n), using the readings taken at 12:00 in the lower part of the canopy (▲) and in the upper part (Δ).

Table 1
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Table 1. Fitted parameters for the baselines from non-stressed trees ($\Delta T_{canopy\text{-}air}$ = a +bVPD*). Data obtained for the DOY 169 to 253 (n = 8).**

GTM	Side	Slope (ºC kPa^{-1})	Intercept (ºC)	R^2
08:30	Down	-1.92	5.65	0.76
	Upper	-1.74	2.08	0.87
12:00	Down	-0.39	0.95	0.82
	Upper	-0.67	0.09	0.87

Table 2

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Table 2. Pearson's correlation coefficients between thermal indicators and physiological variables at the two sampling times and sampled canopy location.

GMT	location	Thermal Indicator	Ψ_{st}	A_N	g_s	E
10:30	Down	T_C	-0.61**	-0.74**	-0.74**	-0.53**
		$\Delta T_{canopy\text{-}air}$	-0.42*	ns	-0.41*	-0.55**
		CWSI	-0.66**	-0.61**	-0.69**	-0.71**
	Up	T_C	ns	-0.50*	-0.53**	ns
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	ns	ns	ns	ns
12:30	Down	T_C	-0.57**	-0.68**	-0.65**	-0.46*
		$\Delta T_{canopy\text{-}air}$	-0.78**	-0.81**	-0.80**	-0.78**
		CWSI	-0.74**	-0.83**	-0.80**	-0.70**
	Up	T_C	-0.57**	-0.70**	-0.65**	-0.48*
		$\Delta T_{canopy\text{-}air}$	-0.83**	-0.83**	-0.78**	-0.81**
		CWSI	-0.71**	-0.80**	-0.77**	-0.70**

Ψ_{st}, stem-water potential;; A_N, net-photosynthesis; g_s, stomatal conductance to water vapour; E, transpiration; T_C, canopy temperature; $\Delta T_{canopy\text{-}air}$, difference between canopy and air temperature; *CWSI*, crop-water stress index. ns, no significant relationships; * and ** evidence significant correlations at 95 and 99%, respectively.

Table 3

Table 3. Pearson's correlation coefficients between thermal indicators obtained at the two sampling times and sampled canopy location; and the volumetric soil-water content (θ, m^3 m^{-3}) measured at different depths (10, 20, 30 and 40 cm, respectively).

GMT	location	Thermal Indicator	θ_{10}	θ_{20}	θ_{30}	θ_{40}
10:30	Down	T_C	-0.58**	-0.66**	-0.52*	-0.48*
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	-0.44*	-0.57*	-0.54*	-0.46*
	Up	T_C	-0.43*	-0.49*	ns	ns
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	ns	ns	ns	ns
12:30	Down	T_C	-0.76**	-0.57**	-0.42*	-0.39*
		$\Delta T_{canopy\text{-}air}$	-0.82**	-0.76**	-0.65**	-0.59**
		CWSI	-0.79**	-0.72**	-0.60**	-0.56*
	Up	T_C	-0.58**	-0.69**	-0.46*	-0.48*
		$\Delta T_{canopy\text{-}air}$	-0.58**	-0.60**	-0.55*	-0.61**
		CWSI	-0.69**	-0.70**	-0.62**	-0.66**

T_C, canopy temperature; $\Delta T_{canopy\text{-}air}$, difference between canopy and air temperature; *CWSI*, crop-water stress index; θ_{10}, θ_{20}, θ_{30}, θ_{40}, volumetric soil-water content at 10, 20, 30 and 40 cm depth respectively; ns, no significant relationships; * and ** evidence significant correlations at 95 and 99%, respectively.

Figure 1
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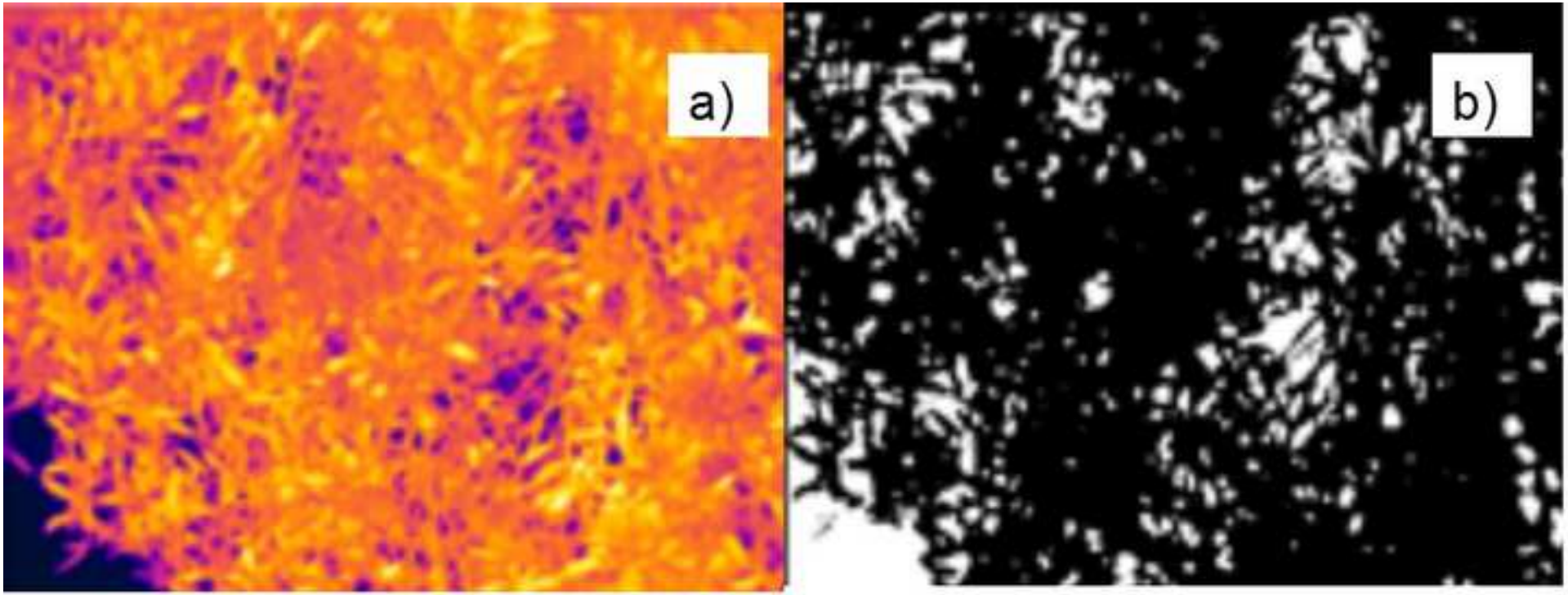

Figure 2
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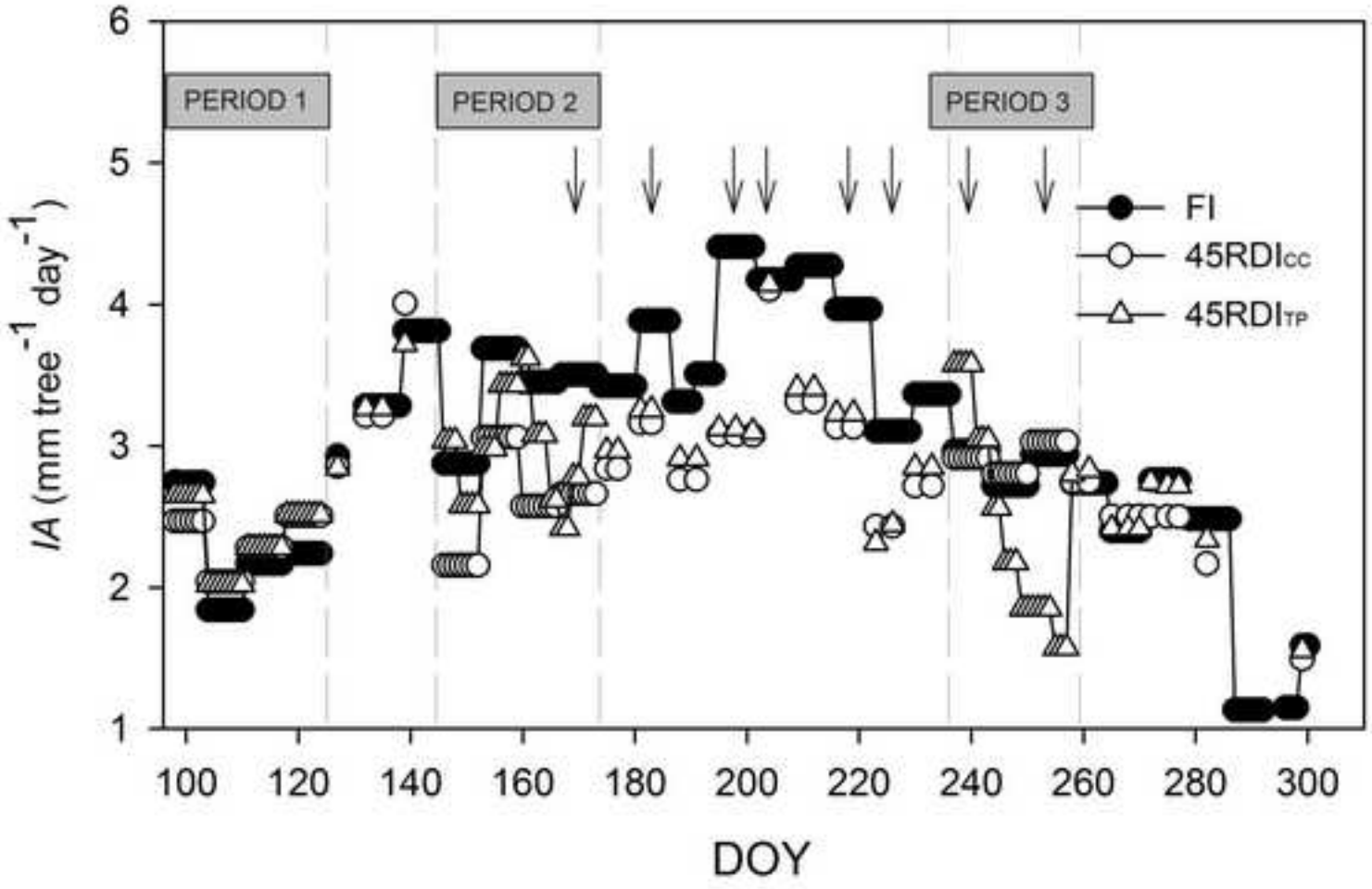

Figure 3

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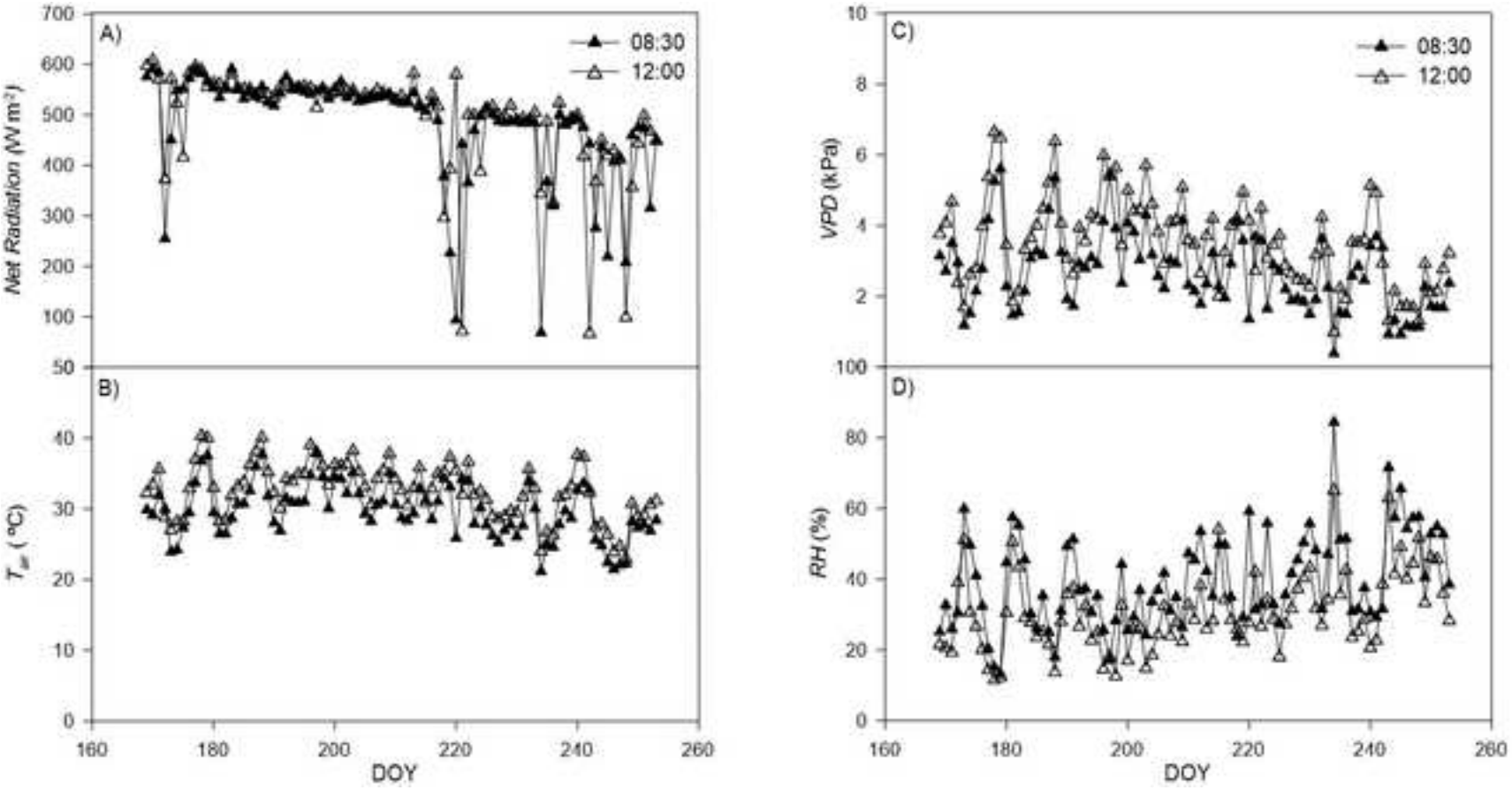

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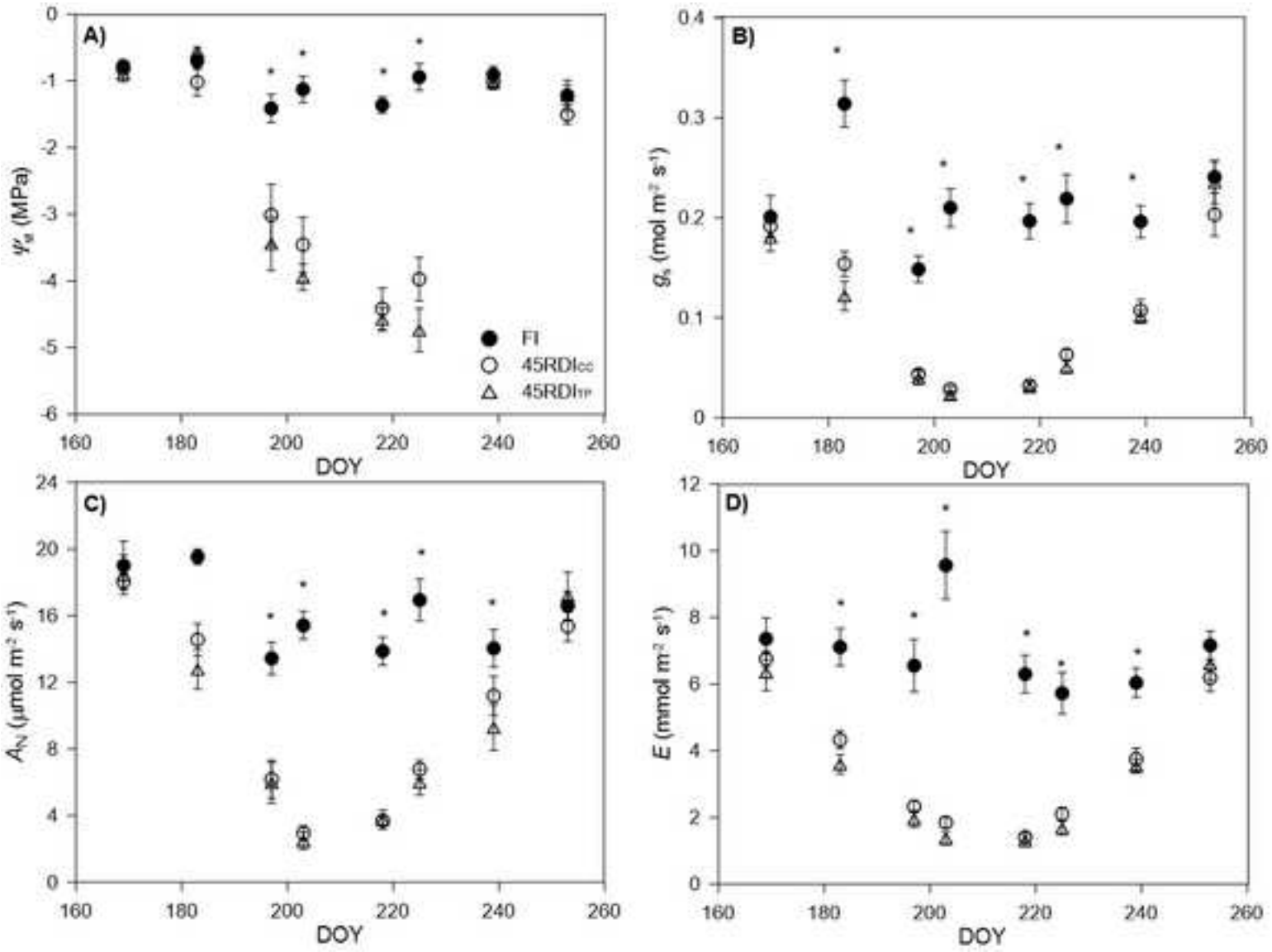

Figure 5

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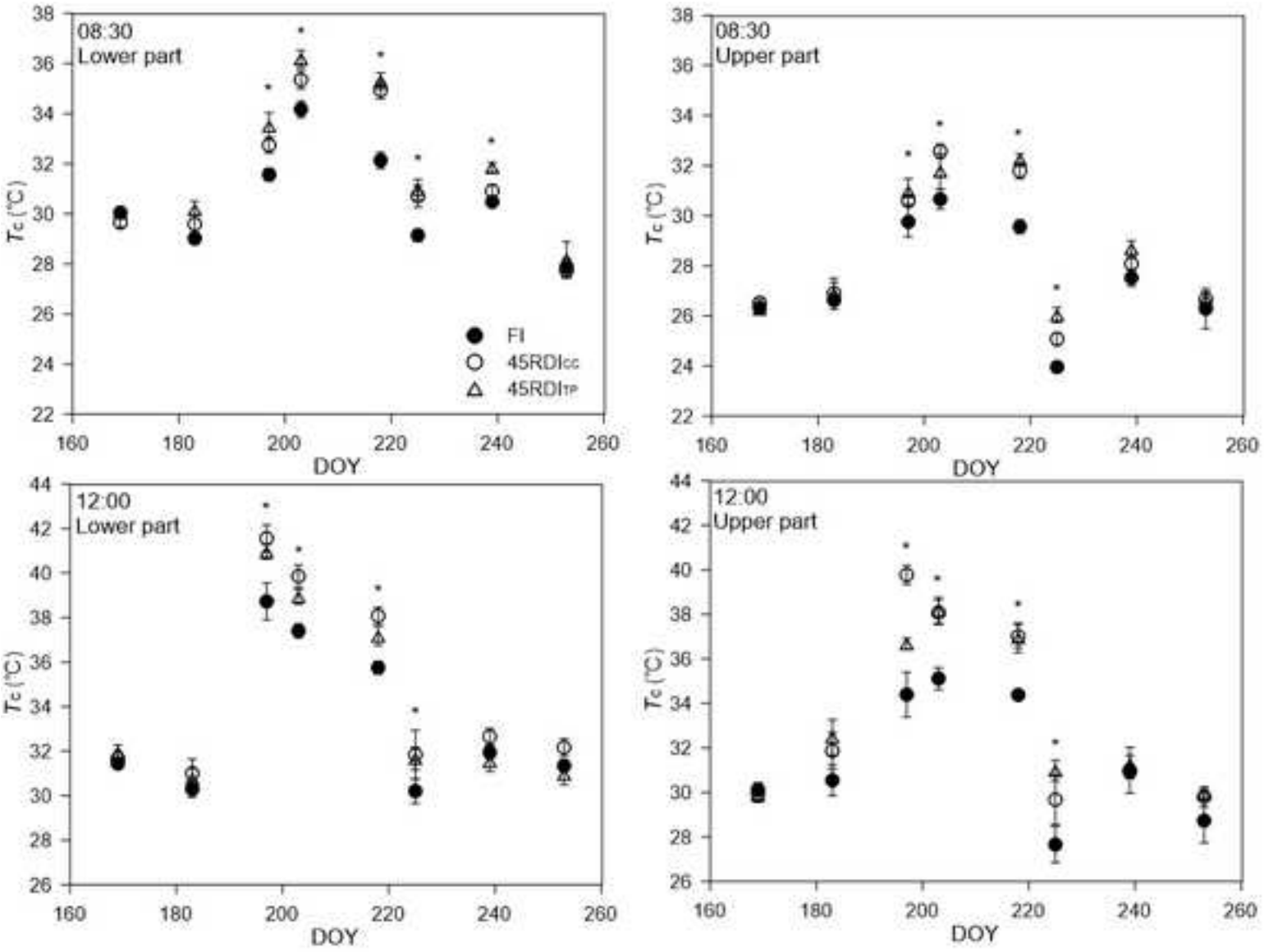

Figure 6

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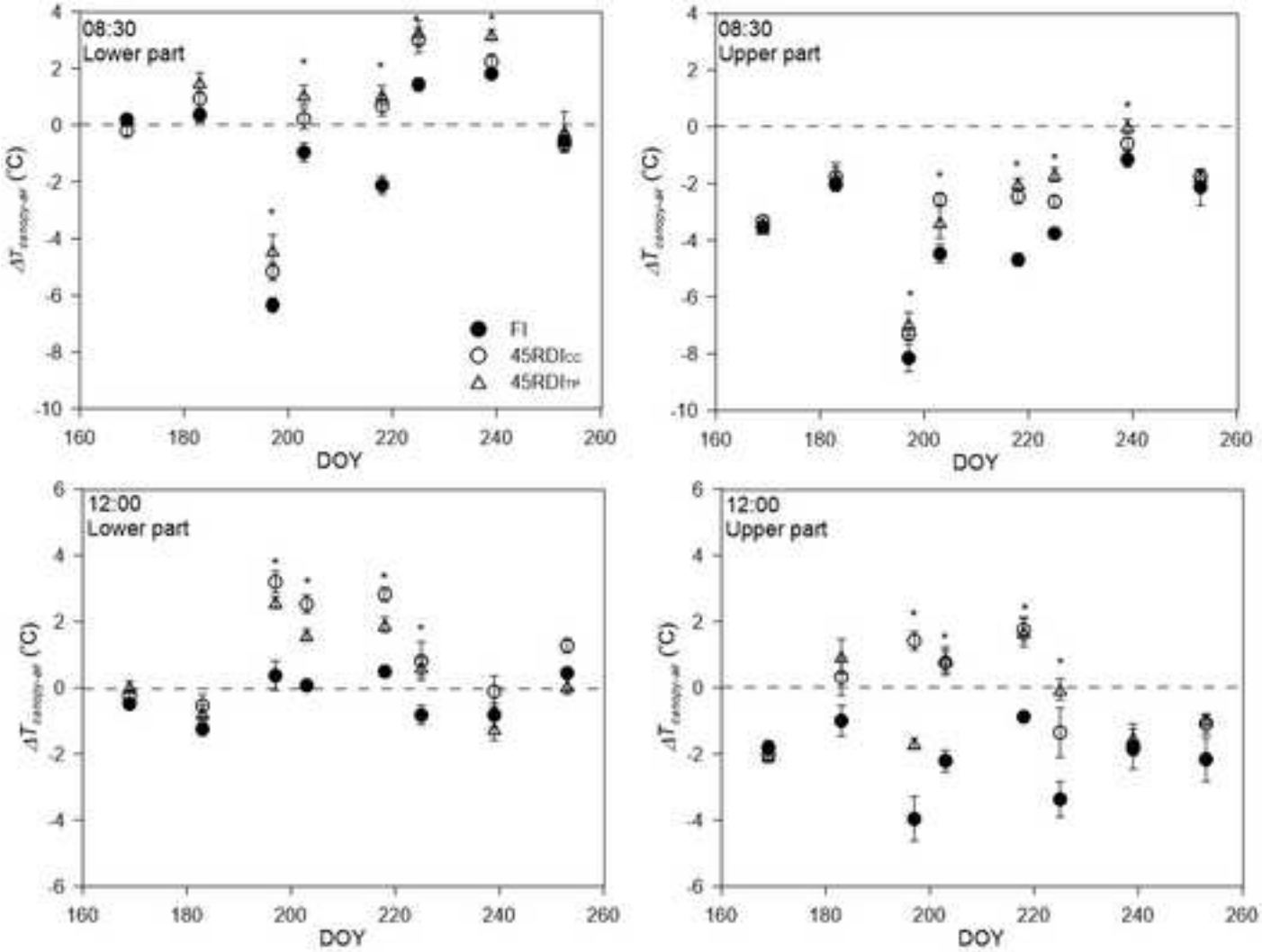

Figure 7

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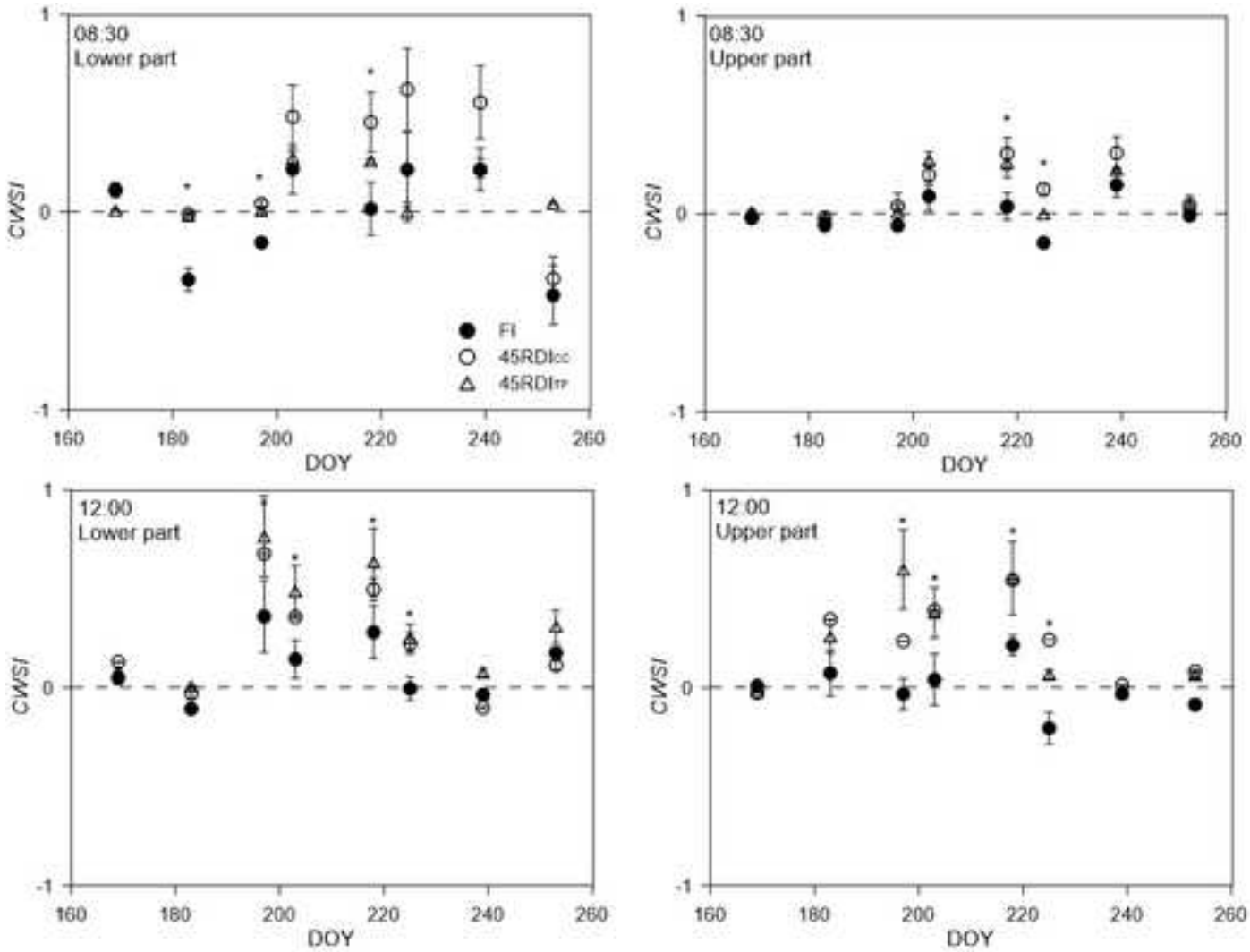

Figure 8

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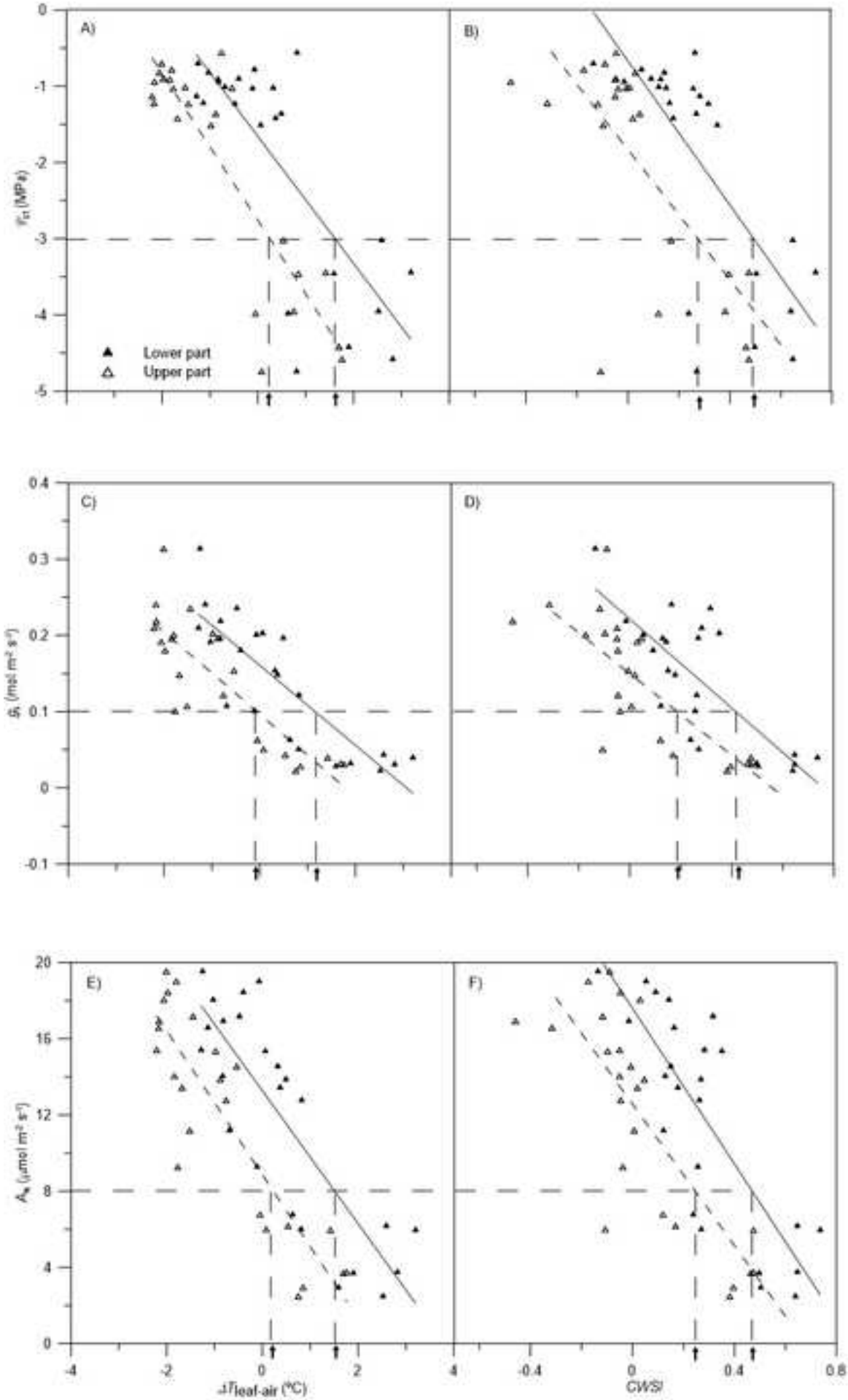

Assessing plant water status in a hedgerow olive orchard from thermography at plant level

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Abstract

Water scarcity is the most limiting factor in many irrigated areas of Mediterranean countries such as South Spain. Olive growing has been traditionally associated to rain-fed agriculture, although irrigation and practices related to intensive agriculture have been progressively introduced, requiring a more precise irrigation scheduling to save water. Thermal imaging is among the alternatives to assess the crop water status, especially when deficit irrigation (DI) strategies are applied. However, this technique requires of new advances to be more user friendly and robust for practical usage. The aims of this study were: i) to define threshold values of canopy temperature (T_C), Crop Water Stress Index (*CWSI*) and the temperature difference between canopy and the surrounding air ($\Delta T_{canopy\text{-}air}$) for the assessment of the olive water status when a DI strategy is applied; ii) to define the best time of the day and the best area of the canopy to carry out thermal measurements, and iii) to obtain relationships between thermal indicators and main physiological parameters useful to estimate the crop water status from thermal data. The trial was conducted during 2015, in a hedgerow olive orchard (SW Spain) with 8-year-old trees (*Olea europaea* L., *cv*. Arbequina), under three irrigation regimes: a full-irrigation treatment (FI) and two regulated deficit irrigation treatments aimed to supplying 45% of the irrigation needs. In one of them, irrigation was scheduled from leaf turgor pressure related measurements ($45RDI_{TP}$). In the other, the crop coefficient approach was used to schedule irrigation ($45RDI_{CC}$). Significant correlations between *T*c versus stem water potential (Ψ_{st}) and leaf gas-exchange parameters (stomatal conductance to water vapor, g_s; net CO_2 assimilation, A_N; transpiration, *E*) were obtained ($p \leq 0.05$), in particular from measurements taken at 10:30 GMT in the lower part of the sunlit side of the canopy. Moreover, the relationships between both $\Delta T_{canopy\text{-}air}$ and *CWSI* with the monitored physiological variables were very robust. We concluded that values of $\Delta T_{canopy\text{-}air}$ higher than 0 ºC and values of *CWSI* up to 0.2 reliably reflect the plant water stress. Our results, therefore, suggest that both $\Delta T_{canopy\text{-}air}$ and *CWSI* measured at midday provide reliable information on the tree water status and are useful to schedule irrigation in hedgerow olive orchards, especially under DI conditions.

Keywords: Thermography, thermal indexes, water stress, irrigation scheduling, leaf-gas exchange parameters, water potential.

1.- Introduction

Olive represents the most important tree crop in the worldwide in terms of surface, with a global area close to 11 x 10^6 ha. Most of the growing areas are located in Mediterranean European countries, being Spain the most relevant in terms of production, with over 2.5 x 10^6 ha devoted to this crop, from which ca. 400.000 ha are under irrigation (MAGRAMA 2016).

The number of olive orchards has significantly increased in the last few years and, in many countries, hedgerow olive orchards with high plant densities (over 1500 trees ha^{-1}), also called super-high-density (SHD) orchards, are becoming popular. This type of orchard covers a surface of ca. 100,000 ha (Rius and Lacarte, 2015). According to forecast predictions (IPCC, 2014), water can be the most limiting factor for olive growing, particularly for irrigated SHD orchards (Vossen et al., 2004). Therefore, effective water management is crucial to increase the productivity of this natural resource, especially in areas such as South Spain, where climatic conditions are characterized by rainfall scarcity and a highly irregular spatial and temporal distribution of the rainfall events (García-Tejero et al., 2013).

Deficit irrigation (DI) strategies are highly effective for both improving water productivity and achieving a sustainable agricultural development. A properly chosen DI strategy saves water without highly affecting yield, and it has usually with a positive impact on quality (Fereres and Soriano, 2007; Geerts and Raes, 2009; Ruiz-Sánchez et al., 2010). Moreover, DI limits excessive growth, which is important in SHD orchards, where tree size has to be controlled for both optimum illumination and mechanical harvesting (Cuevas et al., 2013). In this line, authors such as Fernández et al. (2013), Gómez del Campo (2013) and Padilla-Díaz et al. (2016) have demonstrated that regulated deficit irrigation (RDI) can be a suitable strategy to improve irrigation water management and water productivity in SHD olive orchards. RDI strategies are based on avoiding excessive water stress in the periods of the growing cycle when the crop is highly sensitive to drought, so the effective monitoring of plant water status along the crop growing cycle becomes crucial (Poblete-Echeverría et al., 2014; Fernández 2014a).

There is a substantial amount of literature on the usefulness of different methods for the continuous monitoring of crop water status, such as those based on the use of dendrometers (Moriana et al., 2010 or Cuevas et al., 2010), sap-flow (Fernández et al., 2008a; Fernández, 2014a) or leaf turgor pressure probes (Zimmerman et al., 2008; Fernández et al., 2011a). Studies on their applicability to commercial orchards proved that additional information on crop-water status is often required to properly evaluate the information collected by those sensors (Fernández, 2014b). Thus, leaf or stem water potential and gas-exchange related measurements, apart of being used alone to monitor the plant water status, are often combined with the methods mentioned above. These water stress indicators have also their limitations. According to Martín-Vertedor (2011) and Fernández (2014a,b), leaf or stem water potential

measurements are good indicators of olive water status, but they are not suitable for precision agriculture because they cannot be automated. In fact, their use is based on destructive, non-continuous, high labour- and time-consuming measurements. Something similar occurs with gas-exchange measurements, such that they are more widely used with research purposes than in commercial orchards (Poblete Echeverría et al., 2016).

New irrigation approaches, such as precise irrigation, are technically demanding. This is behind the increasing interest in the use of remote sensing to monitor crop water status at different scales (at plant or orchard level). In this sense, thermal imaging emerged as a non-invasive approach to assess the crop-water status and to schedule irrigation, as probed from findings in citrus trees (García-Tejero et al., 2011; González-Dugo et al., 2014); almonds (García-Tejero et al., 2012), vines (Costa et al., 2012; García-Tejero et al., 2016) and olives (Berni et al., 2009; Poblete-Echeverría et al., 2014, 2016), among other crops. The principle of thermography relies on the leaf energy balance. Water stress induces stomatal closure, which in turn limits leaf transpiration, and hence the evaporative cooling process. This results in higher leaf/canopy temperature values (Jones, 1999, 2004). Thermal readings provide reliable information on the crop physiological status. Still, relationships between thermal information and main physiological parameters such as the stomatal conductance to water vapour (g_s), net CO_2 assimilation (A_N), transpiration (E), or the crop water status (in the basis on the leaf or stem water potential) are usually required to properly evaluate the information provided by thermal readings (Jones 2004; Jones et al., 2009). These relationships, however, depend on weather variables as T_{air}, incident radiation, the angle of incident radiation, wind speed and vapour pressure deficit (Jones, 1999; 2004). They also depend on monitoring proceedings (González-Dugo et al., 2012; Costa el al., 2013), cultivars (Costa et al., 2012; García-Tejero et al., 2016) and developmental stage (Cohen et al., 2015), among other factors. This has led to the testing of different strategies to optimize thermography, which included the development of effective protocols for field measurements based on thermal indices (Jones et al., 2002; 2009; Grant et al., 2006; Möller et al., 2007; Baluja et al., 2012; Bellvert et al., 2014) and robust relationships between thermal information and physiological parameters. However, some questions are still under debate, e.g. which is the most practical, although robust, thermal index that can be a proxy of plant physiological traits (e.g. leaf gas-exchange behavior). Another matter of debate is whether the thermal measurements could be directly used, without any additional relationship with other physiological variables, and whether threshold values, similar to those defined for stem or leaf water potential, or stomatal conductance, can be established.

We hypothesize that thermography could be a suitable approach to assess the crop water status in a SHD olive orchard. To test our hypothesis, we carried this work in a representative, fully productive SHD olive orchard with the aims of: (i) to derive threshold values for the plant water status from thermal related data collected in the orchard (canopy temperature, T_C; the temperature difference between canopy and the surrounding air, $\Delta T_{canopy\text{-}air}$; and the crop water stress index, *CWSI*) ; and (ii) to derive relationships between thermal readings and main physiological variables (stem water potential, Ψ_{st};

stomatal conductance to water vapor, g_s; net CO_2 assimilation, A_N, and transpiration, E). We explored the suitability of taking the thermal readings at different moments of the day and in different locations of the canopies.

2.- Material and Methods

2.1.- Experimental Site

The trial was conducted during the irrigation season of 2015, in a super-high-density olive (*Olea europaea* L., cv. Arbequina) orchard located at 25 km of Seville (37º15'N, 5º48' W). The trees were planted in 2007 at the top of 0.4 m high ridges and spaced 4 m x 1.5 m (1667 trees ha^{-1}), with the rows oriented N-NE to S-SW.

The orchard soil is an Arenic Albaqualf (USDA, 2010) with a sandy loam top layer (77.7 % sand, 20.1 % clay and 2.2 % silt) of 1.73 Mg m^{-3} bulk density (ρ) and soil hydraulic conductivity near saturation (K_{sat}) of 40.7 cm day^{-1}. Downwards there was a sandy clay layer (60.9 % sand, 37.1 % clay and 2.0 % silt) with ρ=1.82 Mg m^{-3} and K_{sat}= 3.54 cm day^{-1}. The average depth from the top of the ridges to the clayey soil layer was 0.6 m. The clay layer was not reached by the roots, since the maximum depth of the root system was 0.45 m (Diaz-Espejo et al., 2012).

Trees were irrigated with an automatic controller (Agronic 2000, Sistemes Electrònics PROGRÉS, S.A., Lérida, Spain) and a pipe line per row, with three 2 L h^{-1} drippers per tree, spaced 0.5 m. Fertilizers were injected into the irrigation system once a week during the irrigation period, receiving all trees the same amount of nutrients, enough to cover the crop needs (Fernández et al., 2013).

The climate of the experimental area is Mediterranean, with mild winters and hot dry summers. Most rainfall events in the area occurs between September and May, the summers being dry and hot. The average values of precipitation and potential evapotranspiration are 537.3 mm and 1504.0 mm, respectively (2010-2015 period). During the hottest months (July and August) the maximum values of air temperature can easily go over 40 ºC, whereas in the coolest months (December and January) air temperature rarely drops below -5 ºC.

2.2.- Experimental design and irrigation treatments

The experimental design was a randomized complete block with four replicates per treatment. The experimental unit (192 m^2) had four rows with eight trees per row, being the eight central trees (four trees for the two central rows) considered as sampling trees, surrounded by 24 border trees. Three irrigation treatments were defined: (i) A full irrigation (FI) treatment, in which the trees were daily irrigated to replace 100% of the irrigation needs (IN). The latter were calculated as the difference between crop evapotranspiration (ET_C) and effective precipitation (P_e). ET_C was calculated with the crop coefficient approach (Allen et al., 1998; see Fernández et al., 2013, for details). (ii) A regulated deficit irrigation treatment ($45RDI_{CC}$) aimed to replace 45% of IN (see Padilla-Díaz et al., 2016, for details). Basically, daily irrigation amounts (IA) similar to IN were applied in the three periods of the growing

cycle when the crop is most sensitive to water stress, defined as Period 1 (around bloom, in April) Period 2 (during the maximum rate of pit hardening, in June) and Period 3 (during the stage of fast oil accumulation, from the end of August to mid-September) (Fernández, 2014a). Between Periods 1 and 2 an irrigation event per week was applied when the soil water content was below 70% of the maximum soil water holding capacity. Between Periods 2 and 3, two irrigation events per week were applied (iii) a second 45RDI treatment similar to the already described, but in which irrigation was scheduled from leaf turgor pressure readings ($45RDI_{TP}$) (see Padilla-Díaz et al., 2016, for details).

2.3.- Soil and plant measurements

The effect of the irrigation treatments on main physiological variables, including canopy temperature, was established from measurements in June 18th (day of year –DOY- 169), July 2nd, 16th and 22th (DOY 183, 197 and 203), August 6th, 13th and 27th (DOY 218, 225 and 239), and September 10th (DOY 253). Measurements of stem water potential at midday (Ψ_{st}) were made with a Scholander-type pressure chamber (PMS Instrument Company, Albany, Oregon, USA). One leaf per tree close to a main branch was sampled, from two representative trees per plot (n = 8), at around 12:00 GTM, the time for minimum Ψ_{st} in olive. The chosen leaves were wrapped in aluminum foil ca. 2 h before sampling. Measurements of stomatal conductance to water vapor (g_s), net CO_2 assimilation (A_N) and transpiration (E) were made with a portable infrared gas analyzer (LI-6400; LiCor Inc., Lincoln, Nebraska, USA), with a 6 cm^2 transparent leaf chamber and the air-flow rate set at 350 µmol s^{-1}. Measurements were taken in one fully expanded and sunlit leaf per tested tree, using 8 trees per irrigation treatment (n = 8). Measurements were made around 08:30 GMT, the time for maximum g_s in olive.

Canopy temperature (Tc) was derived from thermal images were made on the same days that the mentioned physiological measurements, both at 08:30 and 12:00 GTM, and both at the bottom (1.5 m from the soil surface) and the top (2.5 m from the soil surface) of the sunlit side of eight trees per treatment (n = 8). These regions were previously defined, and the canopy surface taken in each image corresponded with a single tree (the first one for the down area of the canopy, and the second one for the upper area of the canopy). We use a ThermaCam (Flir SC660, Flir Systems, USA, 7-13 µm, 640x480 pixels). Each pixel corresponded to an effective temperature reading and the emissivity (ε) was set at 0.96. The background temperature was determined by measuring the temperature of a crumpled sheet of aluminum foil placed near the sampled leaves using ε= 1 (Jones et al., 2002). The imager was placed perpendicularly to the canopy, at about 2 m from the sunlit side. For the images taken in the down part, a cooled white screen was used as background, that being placed behind of each monitored tree to simplify the isolation of the canopy surface through image processing. For the images of the upper part, the regions of sky were used as the background. Thermal images were analysed with the software developed by García-Tejero et al. (2012). This software allows to work with up to three sections for each analyzed image, to select the temperature range corresponding to pixels of the

canopy, and to remove those areas or pixels that do not have to be considered, i.e. those corresponding to the stem and the background (Figure. 1).

In order to normalize the thermal information and taking the absolute values of T_C as the starting point, two thermal indexes were estimated: the difference between canopy and the surrounding air ($\Delta T_{canopy\text{-}air}$) and the crop water stress index (CWSI); these being calculated as follows (Idso, 1981; Jackson et al., 1981):

$$\Delta T_{canopy\text{-}air} = T_C - T_{air} \quad (1)$$

$$CWSI = \frac{\Delta T - \Delta Twet}{\Delta Tdry - \Delta Twet} \quad (2)$$

where $\Delta T_{canopy\text{-}air}$, ΔT_{dry} and ΔT_{wet} is the difference between canopy and air temperature in the moment of the measurement, T_C is the temperature of the canopy, T_{air} is the temperature of the surrounding air, and ΔT_{dry} and ΔT_{wet} are the difference between canopy and air temperature when the crop has the stomata fully closed and when is fully transpiring, respectively.

To obtain the reference values of ΔT_{wet} we calculated the non-water stress baselines ($\Delta T_{canopy\text{-}air}$ = a + b*VPD) according to Idso et al. (1981), and used a ΔT_{dry} value equal to 5 ºC, as proposed by Jackson et al. (1982). Non-water stress baselines were defined for two different moments of the day (08:30 and 12:00 GTM, respectively), i.e. when T_C readings were made. Moreover, as T_C readings were obtained from two different areas of the tree (down and topside), these functions were defined for each location. Thus, four relationships between *VPD vs.* $\Delta T_{canopy\text{-}air}$ were estimated for each monitoring time (08:30 and 12:00 GTM) and parts of the canopy (at the bottom and top). In all cases, these relationships were derived from the canopy temperature readings in FI trees.

Finally, soil water content was measured by using a Profile probe (Delta-T Devices Ltd., Cambridge, UK), recording the volumetric soil water content (θ) values in the root zones of three trees per treatment. Each access tube was installed at 0.5 m from the tree trunk, measuring the soil-water content at 10, 20, 30, and 40 cm, coinciding the measurement days with those days in which the physiological measurements were done. Previously, the Profile probe was calibrated in situ as it was described by Fernández et al. (2011b).

2.4.- Statistical analysis

For each measurement day, an exploratory and descriptive analysis of physiological measurements and canopy readings was made after applying a Levene's test to check the variance homogeneity of the studied variables. Significant differences between irrigation treatments ($p \leq 0.05$ and $p \leq 0.01$) in the

studied variables were identified by applying a one way ANOVA and a Tukey's test for treatment separation, with the SPSS statistical software (SPSS Inc., 15.0 Statistical package; Chicago, IL, USA).

To evaluate the non-water stress baselines for each sampling time and canopy location, a linear correlation analysis was made (n = 8) with a covariance analysis at a confidence level of 95%. That allowed to compare the functions (slope and intercept) and evaluate significant differences.

To evaluate the relationships between variables, a linear correlation analysis between the thermal indicators (T_C, $\Delta T_{canopy\text{-}air}$ and *CWSI*) and the physiological variables (Ψ_{st}, g_s, A_N and *E*) and θ at the different depths was made for each sampling time and location (n = 24). The obtained correlation coefficients were used to identify both the best time and location to carry out T_C readings. This allowed us to assess the reliability of the mentioned thermal indicators as a proxy for crop physiology traits.

Once selected the best moment of the day to carry out the T_C readings, and the most representative thermal indicator, the obtained linear regressions for each sampling location in the canopy were compared (slope and intercept) using a covariance analysis at a confidence level of 95%.

3.- Results and discussion

3.1. Meteorological conditions, irrigation events and physiological measurements

Figure 2 shows the irrigation events applied in each irrigation treatment. According to the chosen irrigation strategies (more details in Padilla-Díaz et al. 2016), in Period 1 (DOY 98-124), Period 2 (DOY 146 to 173) and Period 3 (DOY 237 to 257) all the trees were daily irrigated to replace crop requirements. In Period 2 the FI trees received 102% of irrigation needs (IN), whereas $45RDI_{TP}$ and $45RDI_{CC}$ trees received 90% and 79% of IN, respectively. In between Periods 2 and 3 (DOY 174 to 236), FI trees received 107% of IN, whereas both $45RDI_{TP}$ and $45RDI_{CC}$ received 24% and 25% IN respectively, with two or three irrigation events per week. Finally, during Period 3 all trees were daily irrigated again, receiving 106% of IN the FI trees 89% the $45RDI_{TP}$ trees and 107% the $45RDI_{CC}$ trees.

Seasonal courses of main weather variables recorded at the two sampling times of the day are shown in Figure. 3. The highest values of temperature and net radiation were recorded at the beginning of the experimental period (June), while top values of relative humidity were recorded at the end (September). Values of vapor pressure deficit were quite high all along the experimental period, especially at the beginning.

The seasonal courses of Ψ_{st} and gas exchange measurements were in line with the irrigation strategies applied in each treatment (Figure 4). At the beginning of the experimental period (DOY 169) no differences between treatments were found for any physiological variable. This is in agreement with the fact that during Period 2 all trees received irrigation amounts close to the irrigation needs (Figure 2).

At the beginning of the stress-increasing period (DOY 183, nine days after the end of Period 2) we found a faster decrease in gas exchange than in Ψ_{st}. A similar behaviour was observed by Torres-Ruiz etal. (2013) and Pérez-Martín et al. (2014) in 'Manzanilla' olive trees. They related this behaviour with

the effective stomata control of plant water status in this species, mainly in the first stages of water stress (Fernández et al., 1997; Fernández 2014a). Later, from DOY 183 to 225, stomatal conductance (g_s), net CO_2 assimilation (A_N) and consequently leaf transpiration (E), decreased progressively in the RDI trees. This is in accordance with those trees were receiving just ca. 25% of IN in that Period. The lowest values of these three variables were recorded on DOY 218.

Later in the season, and in agreement with the greater water supplies of Period 3, g_s, A_N and E values in RDI trees became similar to those recorded in FI trees, showing a full recovery of the trees on that period. However, at the beginning of this period, values of Ψ_{st} recovered quicker than those of gas exchange related variables. This is also typical in olive (Fernández, 2013, Perez-Martin et al., 2014). The FI trees showed values of Ψ_{st}, g_s, A_N and E close to the maximum for olive trees under non-limiting conditions (Diaz-Espejo et al., 2006), all along the experimental period.

Significant differences in Ψ_{st} among treatments were observed in between Periods 2 and 3, when these values were progressively descending in 45RDI trees till reaching a minimum value of -4.4 ± 0.1 MPa on DOY 218 and 225. This descend was accompanied with a depletion in gas-exchange parameters, being recorded the minimum values when Ψ_{st} was close to -3 MPa. (Figure 4).

3.2. Diurnal evolution of canopy temperature and related thermal indices

Figure 5 shows the average of canopy temperature readings taken at the two sampling times and locations, for the three irrigation treatments during the monitoring period. For all treatments and sampling times, differences were observed between the down and the upper part. These differences were especially remarkable at 08:30 GMT, when values in the upper part were up to 5 ºC below those from the down part. This could be due to heat transmission from the soil to the down part of the canopy or to greater heat dissipation in the upper part because of the wind. The first differences between FI and RDI trees appeared on DOY 197, these differences being more evident at 08:30 GMT on the down part, whereas, at 12:00 GMT the differences were significant in both sampling areas. Differences in T_C between treatments increased along the season, being greater at 12:00 than at 08:30 GMT, and in the lower part of the canopy that at the upper part. Depending on the location and sampling time, differences among treatments ranged from 2 to 6 ºC.

Our results agree with those reported for other olive orchards of different locations and characteristics. Sepulcré-Cantó et al. (2006) detected differences close to 2 ºC by using infrared sensors installed 1 m above the olive crown. Poblete-Echeverría et al. (2016), in a study developed in 'Arbequina' trees, registered temperature differences around 4 – 5 ºC, at the moments of maximum stress level (Ψ_{st} < – 5 MPa). Other authors such as Testi et al. (2008) in Pistachio, García-Tejero et al. (2011) in citrus trees, and García-Tejero (2016) in vines reported temperature differences of 2-6 ºC between fully irrigated and stressed trees.

It is noticeable that differences between treatments in T_C were detected when the lowest g_s values were recorded (DOY 197 to 225 DOY, Figures 4 and 5). Nevertheless, T_C readings in FI treatment showed a

high variation, probably associated to differences in meteorological conditions during the sampling days. As it has been previously stated, the effect of stomatal regulation (partial closure) under a mild or moderate water stress is that leaf temperature trends to increase, because of a decrease in the heat dissipated by transpiration (Jones et al., 2002; 2009; Jones and Vaughan, 2010). According to Jones et al. (2009) and Jones and Vaughan (2010), there are many variables such as the radiation level, air temperature, vapour pressure deficit, the relative humidity or the angle of the radiation incident on the leaf surface that will influence decisively on the absolute value of T_C. Therefore all of them must be taken into account when making an assessment of crop water status from thermal information. This explains the difficulty of establishing a threshold value of T_C for irrigation scheduling and crop-water status monitoring. This is a limitation of the thermal approach as compared to Ψ_{st} or g_s, variables for which threshold values for water stress can be more easily established (Fernández et al. 2008b; Moriana et al., 2012).

Once normalized the T_C readings by estimating the difference between canopy and the surrounding air ($\Delta T_{canopy\text{-}air}$), we observed $\Delta T_{canopy\text{-}air}$ values below 0 ºC for the FI trees, especially at 12:00 GMT, and with a temporal variation much less than detected for T_C readings (Figure 6). This is in line with the results reported by Sepulcré-Cantó (2006) and Poblete-Echeverría (2016), from readings taken in similar conditions. This corroborates what we have stated above for the thermal readings at 12:00 GMT and in the down part of the canopy, these being the most informative in terms of tree water status. Thus, by comparing the $\Delta T_{canopy\text{-}air}$ values detected in FI trees versus those in RDI trees, we defined a threshold value of $\Delta T_{canopy\text{-}air}$ = 0 ºC, above which a severe water stress situation would be being supported by the crop.

After using the methodology proposed by Idso et al. (1981) and Jackson et al. (1981) to derive non-water stressed baselines from the $\Delta T_{canopy\text{-}air}$ values obtained from the FI trees and *VPD* values registered for each time and monitoring day, significant relationships were obtained for the four sampling situations, especially for the measurements at 12:00 h (Table 1). For the readings taken at 12:00 GMT in the down part, the slope was similar to that obtained by other authors such as Berni et al. (2009) in 'Arbequina' olive trees (-0.35) from measurements 1 m above the trees, although the intercept point was different (2.08). According to these authors, the explanation of the low slopes derived from the non-water stressed baselines would the small size of the olive leaves, which are very coupled to the atmosphere (Villalobos et al., 2000) and because of the marked stomatal control even in full irrigated trees, when the evaporative demand is very high. As a consequence of this slope, *CWSI* estimation in olive trees is very much affected by errors in both the estimation of *T*c and the measurement of T_{air} (Berni et al., 2009). More interesting were the reflections argued by these authors, when they compared effect of net radiation and wind speed in the interception point, suggesting that the slopes obtained for different non-water stressed baselines estimated from a theorist proposed model by them were very similar to the obtained from empirical information; and the highest variations were observed in the interception point. Similar results were reported Testi et al. (2008) in pistachio trees, evidencing that

daily variations in net radiation resulted in parallel baselines, i.e. the slope of the baseline was not affected.

Figure 7 shows the *CWSI* evolution calculated by using the non-water stressed baselines defined in Table 1 according to the T_C values of *FI*. The seasonal course of this index was similar to that of $\Delta T_{canopy\text{-}air}$ (Figures 6 and 7). The greatest differences in CWSI between treatments were reached from DOY198 to DOY 225, especially at 12:00 GTM. The lowest *CWSI* values were found in the FI trees, being around 0 (dimensionless), especially during the readings taken at 12:00 and at 08:30 GTM in the down part. However, *CWSI* values derived from the thermal readings at 12:00 GMT in both parts of the canopy were occasionally higher than 0 ºC in the FI trees, which were under non-limiting soil water conditions. This could be related to the sensitiveness of CWSI to weather conditions, e.g. solar radiation (Agam et al., 2013), or to tree architecture (González-Dugo et al., 2014). In any case, this is a limitation of *CWSI* that curtails its potential as a reliable index to schedule irrigation. Such limitation was not detected for $\Delta T_{canopy\text{-}air}$. The fact that threshold values for the assessment of the crop water status cannot be easily derived from thermal readings is acknowledged as one of the main limitations of this technique to schedule irrigation in commercial orchards.

3.3.- Relationships between the thermal information, physiological variables and soil-water content

In the last few years, many works have been developed to optimize the use of thermography to assess the crop-water status and to schedule irrigation (Jones et al., 2002; Leinonen and Jones, 2004), reporting significant correlations between thermal information and other related physiological variables (Berni et al., 2009; Poblete-Echeverría et al., 2014; Osroosh et al., 2016). In our case, relationships between thermal and physiological data were derived to define the most efficient thermal index and the best sampling time to assess the crop water status. Table 2 shows the Pearson's correlation coefficients obtained for the relationships corresponding to the measurements taken at 08:30 and 12:00 GMT in the lower and upper part. Regarding T_C, the most significant correlations were obtained at 12:00 GTM, these being very similar for both the readings in the down part and in the upper part. Moreover, a similar robustness was observed for the relationships derived from the readings taken at 08:30 in the down part. This did not apply to measurements from the upper part. Regarding the coefficients obtained for $\Delta T_{canopy\text{-}air}$ and *CWSI* with the physiological parameters, these were better than those for *T*c, especially for the readings taken at 12:00 GMT. This indicates the feasibility and robustness of both thermal indexes, especially $\Delta T_{canopy\text{-}air}$, because of its simplicity in comparison to *CWSI*.

Additionally, thermal information obtained at 8:30 and 12:00 GTM in the lower and upper part was related to the soil-water content measurements registered at different depths (Table 3). On overall, thermal data obtained at 10:30 GTM did not reflect with enough robustness the soil-water status, in comparison to the relationships obtained by using the thermal information derived from the measurements taken at 12:00 GTM. In this agreement, as T_C as the related thermal indexes (*CWSI* and $\Delta T_{canopy\text{-}air}$) reported significant relationships with the θ obtained at different layers. Within the

measurements taken at 12:00 GTM, the best relationships were obtained when comparing the thermal information derived from the images taken in the lower part, and within them, by using the readings of θ corresponding to the first soil layers (at 10 and 20 cm depth, respectively). These results would suggest the possibility of stablishing deficit irrigation programmes combining the information obtained in the three levels of the soil-plant-atmosphere system: weather data (T_{air} and VPD), soil (θ) and plant (T_C and the related thermal indexes).

In agreement with this, the most significant relationships between these thermal indexes and physiological parameters were obtained from readings taken at 12:00 GMT. Different functions were defined depending of measurements being taken in the down part or in the upper part (Figure 8). One of the most remarkable findings was the coincidence of the threshold values determined for $\Delta T_{canopy\text{-}air}$ and *CWSI* in terms of Ψ_{st}, *CWSI*, and A_N. As it can be observed in Figure 8, taking into account the readings obtained in the upside, $\Delta T_{canopy\text{-}air}$ close to zero would be associated with $\Psi_{st} \leq$ -3 MPa; $g_s \leq 0.1$ mol m^{-2} s^{-1} and $A_N \leq 8$ µmol m^{-2} s^{-1}, these values having been defined as indicators of situations of severe water stress (Fernández et al., 2013, Díaz-Espejo et al., 2012; Pérez-Martín et al., 2014; Hernández-Santana et al., 2016; Padilla-Díaz et al., 2016; among others). Something similar occurred taking as reference the values of *CWSI*, these being around 0.2 when $\Delta T_{canopy\text{-}air}$ was close to zero.

When considering the readings from the down part, the defined threshold values for a moderate-to-severe water stress for $\Delta T_{canopy\text{-}air}$ would be between 1.5 to 2 ºC, and between 0.4 to 0.5 in terms of *CWSI* (Figure 8).

Likewise, the applicability of these relationships is reduced at farm level, because of their high variability within the orchard crop (García-Tejero et al., 2016), being more advisable the use of threshold values such as those derived from our results. In this regard, the robustness observed in the relationships between $\Delta T_{canopy\text{-}air}$ and the studied physiological parameters would justify the use of this thermal index stablishing a threshold value of $\Delta T_{canopy\text{-}air}$ close to zero when thermal readings are taken at 12:00 GTM in the down part of the canopy.

Conclusions

Crop water monitoring by using thermal information in olive is highly dependent on the procedure of thermal acquisition. This work demonstrates the sensitiveness of this technique to the monitoring process; observing different results when measurements are taken at different hours and in different parts of the tree. Owing to this phenomenon, it could be difficult to compare our results with other obtained by using other kind of thermal sensors or also by applying different image processing and capture. In spite of this constraint, on overall, our result suggest that as $\Delta T_{canopy\text{-}air}$ as *CWSI* can be considered as robust indicators of crop-water status, as it was demonstrated by the relationships derived from monitored the physiological variables such as g_s or Ψ_{st}. In line with this conclusion, $\Delta T_{canopy\text{-}air}$ would allow stablishing deficit irrigations scheduling exclusively by using thermal information, not

being necessary the use of relationships with other physiological parameters; and taking a threshold value close to zero, as the point above which a moderate stress situation is being supported by the crop. Likewise, as $\Delta T_{canopy\text{-}air}$ as *CWSI* showed significant relationships with crop water potential and gas exchange measurements, especially with the readings taken at 12:30 GTM; being possible to estimate these values throughout thermal information. Moreover, these thermal indexes showed significant relationships with the soil water content at different depths, especially by using the soil moisture readings taken in the first 20 cm, evidencing the possibility of define irrigation programming based on measurements of crop and soil water status. Nevertheless, these relationships could not be assumed for other different situations, cultivars, image capturing and processing, being advisable to define specific functions in the case of estimating the crop-water status or gas-exchange levels exclusively using thermal information.

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TABLES

Table 1. Fitted parameters for the baselines from non-stressed trees ($\Delta T_{canopy\text{-}air}$ = a +b*VPD). Data obtained for the DOY 169 to 253 (n = 8).

GTM	Side	Slope (ºC kPa^{-1})	Intercept (ºC)	R^2
08:30	Down	-1.92	5.65	0.76
	Upper	-1.74	2.08	0.87
12:00	Down	-0.39	0.95	0.82
	Upper	-0.67	0.09	0.87

Table 2. Pearson's correlation coefficients between thermal indicators and physiological variables at the two sampling times and sampled canopy location.

GMT	location	Thermal Indicator	Ψ_{st}	A_N	g_s	E
10:30	Down	T_C	-0.61**	-0.74**	-0.74**	-0.53**
		$\Delta T_{canopy\text{-}air}$	-0.42*	ns	-0.41*	-0.55**
		CWSI	-0.66**	-0.61**	-0.69**	-0.71**
	Up	T_C	ns	-0.50*	-0.53**	ns
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	ns	ns	ns	ns
12:30	Down	T_C	-0.57**	-0.68**	-0.65**	-0.46*
		$\Delta T_{canopy\text{-}air}$	-0.78**	-0.81**	-0.80**	-0.78**
		CWSI	-0.74**	-0.83**	-0.80**	-0.70**
	Up	T_C	-0.57**	-0.70**	-0.65**	-0.48*
		$\Delta T_{canopy\text{-}air}$	-0.83**	-0.83**	-0.78**	-0.81**
		CWSI	-0.71**	-0.80**	-0.77**	-0.70**

Ψ_{st}, stem-water potential;; A_N, net-photosynthesis; g_s, stomatal conductance to water vapour; E, transpiration; T_C, canopy temperature; $\Delta T_{canopy\text{-}air}$, difference between canopy and air temperature; *CWSI*, crop-water stress index. ns, no significant relationships; * and ** evidence significant correlations at 95 and 99%, respectively.

Table 3. Pearson's correlation coefficients between thermal indicators obtained at the two sampling times and sampled canopy location; and the volumetric soil-water content (θ, m^3 m^{-3}) measured at different depths (10, 20, 30 and 40 cm, respectively).

GMT	location	Thermal Indicator	θ_{10}	θ_{20}	θ_{30}	θ_{40}
10:30	Down	T_C	-0.58**	-0.66**	-0.52*	-0.48*
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	-0.44*	-0.57*	-0.54*	-0.46*
	Up	T_C	-0.43*	-0.49*	ns	ns
		$\Delta T_{canopy\text{-}air}$	ns	ns	ns	ns
		CWSI	ns	ns	ns	ns
12:30	Down	T_C	-0.76**	-0.57**	-0.42*	-0.39*
		$\Delta T_{canopy\text{-}air}$	-0.82**	-0.76**	-0.65**	-0.59**
		CWSI	-0.79**	-0.72**	-0.60**	-0.56*
	Up	T_C	-0.58**	-0.69**	-0.46*	-0.48*
		$\Delta T_{canopy\text{-}air}$	-0.58**	-0.60**	-0.55*	-0.61**
		CWSI	-0.69**	-0.70**	-0.62**	-0.66**

T_C, canopy temperature; $\Delta T_{canopy\text{-}air}$, difference between canopy and air temperature; *CWSI*, crop-water stress index; θ_{10}, θ_{20}, θ_{30}, θ_{40}, volumetric soil-water content at 10, 20, 30 and 40 cm depth respectively; ns, no significant relationships; * and ** evidence significant correlations at 95 and 99%, respectively.

FIGURES

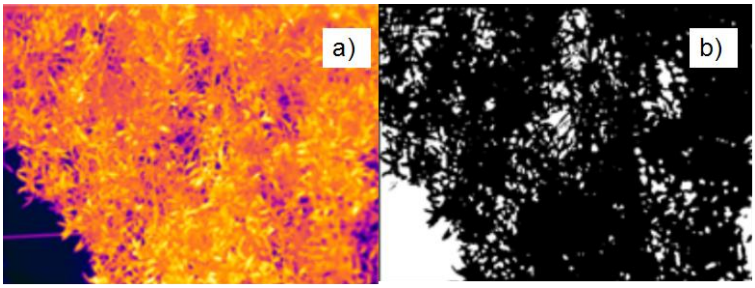

Figure 1. False colored image of downside olive tree (a) and post-processing image (monochrome image) representing in black the areas corresponding to pixels of leaves (b). This process allows deleting those pixels corresponding to branches, stem and the background (all these areas in white).

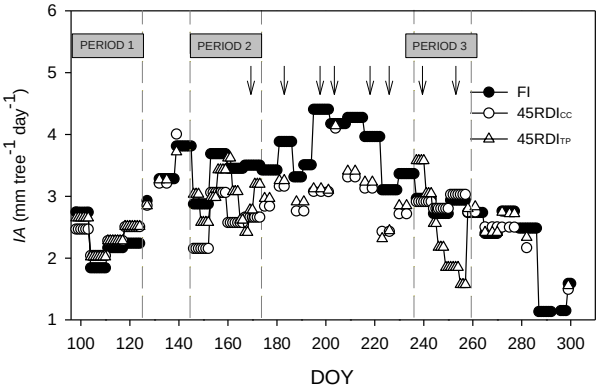

Figure 2. Irrigation applied (IA) in each irrigation treatment: full-irrigated (FI), crop-coefficient regulated deficit irrigation (45RDI$_{CC}$), regulated deficit irrigation based on turgor pressure related measurements (45RDI$_{TP}$). Arrows down show the days on which the thermal measurements were made..

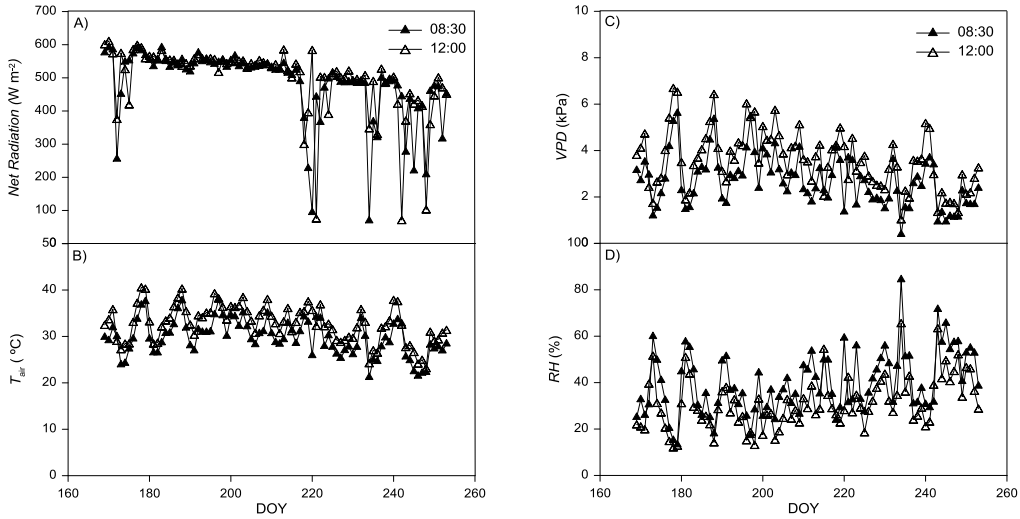

Figure 3. Seasonal course of net radiation (A), air temperature (B), vapour pressure deficit (C) and relative humidity (D), measured at 08:30 and 12:00 GMT.

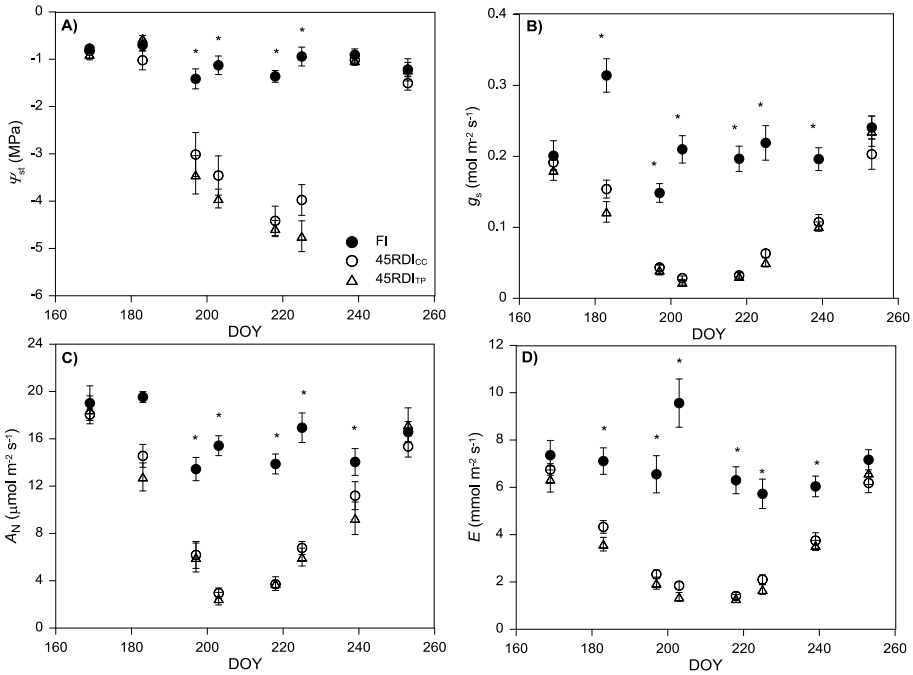

Figure 4. Seasonal course of stem water potential (Ψ_{st}) (a), stomatal conductance (g_s) (b), net CO_2 assimilation (A_N) (c), and transpiration (E) (d), measured in trees of the three irrigation treatments. * shows significant differences between FI and RDI trees (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

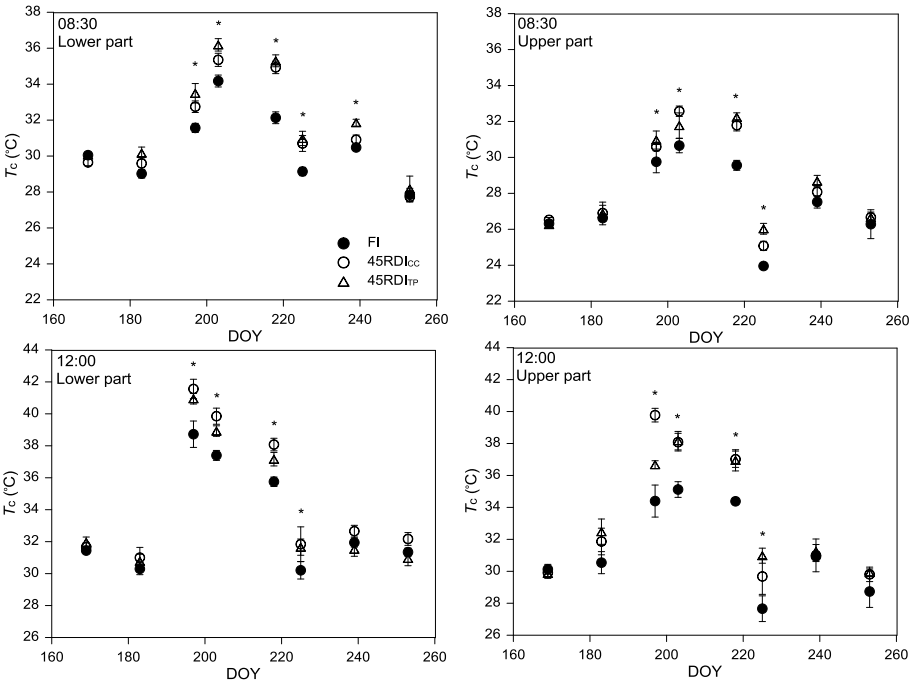

Figure 5. Seasonal evolution of the canopy temperature (T_C) measured at the two times (08:30 and 12:00 GTM) and sampling locations in the canopy (lower and upper part), in trees of the three irrigation treatments. * shows significant differences between FI and RDI treatments (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

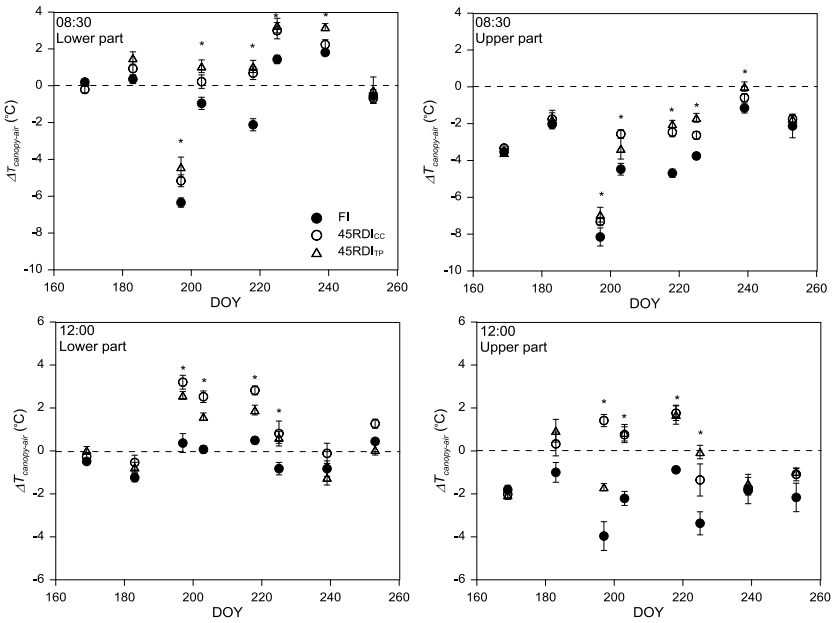

Figure 6. Seasonal evolution of the difference between canopy and air temperature ($\Delta T_{Canopy\text{-}air}$) measured at the two times (08:30 and 12:00 GTM) and sampling locations in the canopy (lower and upper part), in trees of the three irrigation treatments. * shows significant differences between FI and RDI treatments (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

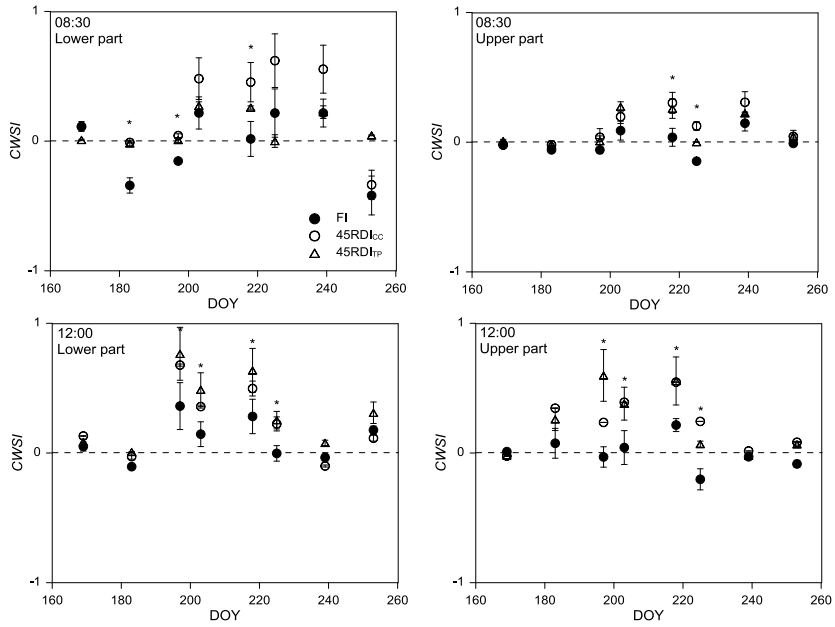

Figure 7. Seasonal evolution of the Crop Water Stress Index (*CWSI*) measured at the two times (08:30 and 12:00 GTM) and sampling locations in the canopy (lower and upper part), in trees of the three irrigation treatments. * shows significant differences between FI and RDI treatments (p<0.05). Each point corresponds to the average value for each treatment (n=8). Vertical bars represent the standard error of the mean.

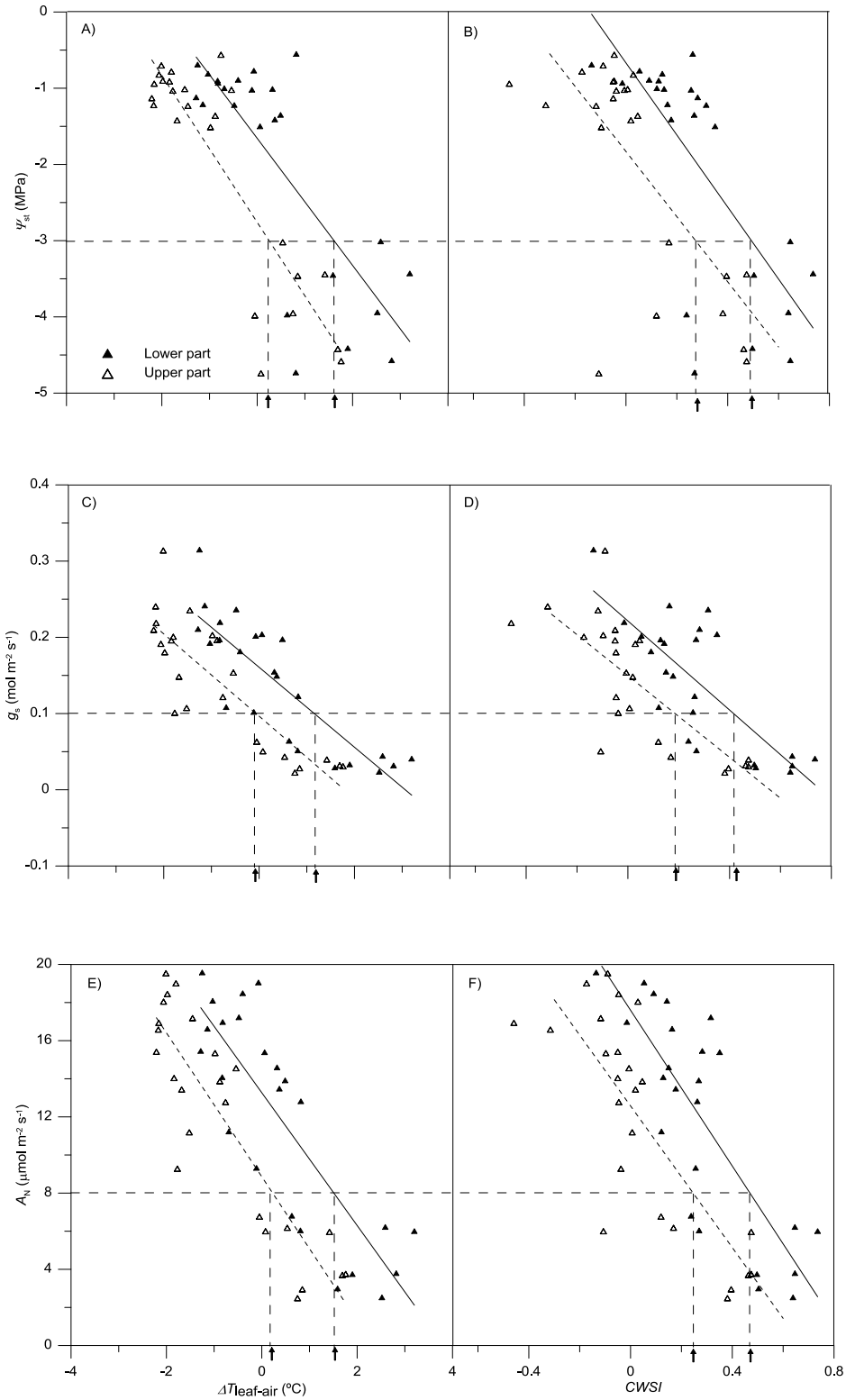

Figure 8. Linear regressions between the difference between canopy and air temperature ($\Delta T_{canopy\text{-}air}$) and the crop-water stress index (*CWSI*, dimensionless) with the stem-water potential (Ψ_{st}), stomatal conductance (g_s) and net CO_2 assimilation (A_n), using the readings taken at 12:00 in the lower part of the canopy (▲) and in the upper part (Δ).