DETECTION OF FRUIT TREE WATER STATUS IN ORCHARDS FROM REMOTE SENSING THERMAL IMAGERY

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ABSTRACT

Remotely sensed crop water stress index (CWSI) can be used to depict fruit tree water status. The aim of this study was: i) to develop an empirical approach for assessing the CWSI of peach trees throughout a growing season and validate it with ground-based leaf water potential (Ψ_{leaf}) measurements, and ii) to detect the spatial variability of fruit tree water status in a 2-ha peach orchard and throughout a complete growing season based on remotely estimates of leaf water potential (Ψ_{rem}) from airborne thermal imagery. Ψ_{rem} was estimated from the seasonal relationships with CWSI. This study was carried out during 2012 and 2013 growing seasons. CWSI and Ψ_{leaf} were significantly correlated both years indicating a similar tendency between years, but differences between phenological stages. Differences in the spatial variability of peach tree water status were successfully remotely detected, demonstrating that remote estimates of leaf water potential can be used for precise irrigation purposes.

Keywords: crop water stress index, leaf water potential, irrigation, peach, high resolution thermal imagery

INTRODUCTION

Water scarcity in irrigated agriculture is becoming an important issue in Mediterranean regions. Many approaches for monitoring plant water status can be used for scheduling irrigation in deciduous trees (Jones, 2004). For instance, leaf/stem water potential has demonstrated to be an excellent tool in irrigation scheduling and water stress assessment with orchard fruit trees (Garnier and Berger, 1985; McCutchan and Shackel, 1992; Shackel et al., 1997). However, this approach is time consuming and can only be performed at low spatial and temporal resolutions (Acevedo-Opazo et al., 2008). Due to high spatial variability in orchards, precise irrigation management requires a cost-efficient method capable of detecting plant water status at field scale, but with sufficient resolution to obtain information from vegetation, and with small mixing effects due to soil and shadows. Canopy temperature has been known to be useful for monitoring plant water status since the 1970s with the initiation of hand-held thermometers (Tanner et al., 1963; Fuchs and Tanner, 1966; Idso et al., 1978; Jackson et al., 1977). Canopy temperature led the development of the crop water stress index (CWSI) which is used to quantify water status from the difference of canopy and air temperature (T_c-T_a), normalized by the vapour pressure deficit (VPD) (Idso et al., 1981). By using infrared temperature sensors or thermal images, several studies have shown that the CWSI was well related with leaf water potential (Ψ_{leaf}) for several annual and woody crops, such as cotton (Cohen et al., 2005; Alchanatis et al., 2010), olive (Ben-Gal et al., 2009), pistachio (Testi et al., 2008), and grapevines (Möller et al., 2007, Bellvert et al., 2013a).

The development of remote sensing technologies have enabled the assessment of crop water status over large areas from high-resolution thermal cameras on board manned (Sepulcre-Cantó, 2006, 2007; Bellvert et al., 2013b) and unmanned aerial vehicles (Berni, Zarco-Tejada, 2009; Zarco-Tejada et al., 2013; Bellvert et al., 2013a). However, Bellvert et al. (2014) demonstrated in grapevines that the non-water stressed baselines (NWSB), required to compute the CWSI, and the relationship between remotely sensed CWSI and Ψ_{leaf} differed depending on variety and phenology. This information must be taken into account for precise irrigation purposes. The study reported here was conducted to evaluate the feasibility of detecting plant water status of a peach orchard at different phenological stages by using remotely sensed thermal imagery.

MATERIALS AND METHODS

This study was carried out during 2012 and 2013 growing seasons at a 2-ha commercial orchard of peach trees (*Prunus persica L. cv. Royal Glory*) located in Malpartit (Lleida, Spain). Peaches were planted in 1996 in a 3 m x 4 m grid. The orchard was divided into four irrigation sectors, ranging between 0.28 to 0.73 ha.

Irrigation treatments

The non-water stressed baselines (NWSB), required to compute the CWSI were established during 2012 and 2013 in a small area within one irrigation sector. The suitability of the CWSI for assessing water status was confirmed throughout the season by point measurements of leaf water potential (Ψ_{leaf}). Two contiguous rows of thirty-six trees each were selected and three irrigation treatments were set-up under different levels of water status. The treatments were: i) full-irrigation control, where irrigation replaced 100% ETc, ii) moderate deficit irrigation, where irrigation replaced around 50% ETc, and iii) deficit irrigation, where water was applied only when measured Ψ_{leaf} fell below -2.0 MPa. Each treatment was applied on 24 trees (12 per row).

The spatial variability of water status within the orchard was detected during 2013. Two irrigation treatments were adopted at orchard scale: i) Control, where irrigation was scheduled to satisfy full requirements throughout the growing season by using the water balance method, and ii) RDI

(Regulated Deficit Irrigation), where a moderated RDI strategy was applied during Stage II of fruit development and during postharvest. Each treatment was adopted in two irrigation sectors. In the RDI treatment, irrigation was withheld during Stage II and postharvest until averaged Ψ_{leaf} reached about -1.5 MPa and -2.0 MPa, respectively. Below this threshold, sectors were irrigated at 120% Control until Ψ_{leaf} was recovered.

Non-water stressed baselines of CWSI

Two infrared temperature sensors (IRT) (model PC151LT-0, Pyrocouple series, Calex electronics Limited, Bedfordshire, UK) were installed 1.5 meters above a peach tree of the full-irrigation control treatment. IRT were connected to a datalogger (CR200X, Campbell Scientific, USA) that registered canopy temperature (T_c) every 15 minutes. Recorded data of canopy temperature (T_c) were used to develop the non-water stressed baselines (NWSB) at different phenological stages, from the relationship between the difference of canopy and air temperature (T_c-T_a) and the vapour pressure deficit (VPD), and following the protocol previously defined by Bellvert et al. (2013a). Each point was obtained from half hourly averages of T_c, T_a and VPD from 11:00 to 16:00 hours. The CWSI was calculated according to Idso et al. (1981) as:

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{LL}}{(T_c - T_a)_{UL} - (T_c - T_a)_{LL}} \qquad (1)$$

where (T_c-T_a) is the difference between actual canopy temperature obtained from the thermal imagery and air temperature, $(T_c-T_a)_{LL}$ and $(T_c-T_a)_{UL}$ are the lower and upper limits, corresponding to a fully transpiring canopy with stomata completely opened and a non-transpiring canopy with closed stomata, respectively. $(T_c-T_a)_{LL}$ was obtained from the NWSB, for a given VPD. The $(T_c-T_a)_{UL}$ was obtained by solving the NWSB for VPD=0, and then correcting for vapour pressure differences caused by the difference in T_c-T_a (Idso et al., 1981). T_a and VPD were obtained from a portable weather station (Watchdog, model 2900ET, Spectrum Technologies, Inc. Plainfield, Illinois, USA) located on one side of the orchard.

Airborne campaign

Airborne campaigns were conducted in 2012 and 2013 using a thermal sensor (FLIR SC655, FLIR Systems, USA) on board an aircraft. A total of six and nine flights were conducted in 2012 and 2013, respectively, concurrently with field data collection. Flights of 2012 were used to validate remotely sensed CWSI with ground-based Ψ_{leaf} measurements at different phenological stages throughout the growing season. Flights of 2013 were also used to validate the CWSI at different phenological stages and for detecting the spatial variability of peach tree water status within the orchard. The flights were conducted at 12:00 hours (solar time) at 150 m altitude above ground level. The camera had a resolution of 640x480 pixels, equipped with a 13.1 mm optics focal length yielding an angular FOV of 45º that delivered approximate ground resolution of 0.30 m. The spectral response was in the range of 7.5-13 µm. Collected airborne thermal imagery were processed applying geometric, radiometric and atmospheric corrections (Berni et al. 2009b), to finally generate a thermal orthomosaic (Fig. 1).

Field measurements

During each flight, leaf water potential (Ψ_{leaf}) was measured in six trees of each treatment (full-irrigated, moderate deficit, and deficit) with the goal of comparing the aerial and ground-based stress indicators. A pressure chamber was used (3005-series portable plant water status console, Soil Moisture Equipment Corp., Santa Barbara, CA, USA) following the recommendations of Shackel et al. (1977). All measurements were taken in less than one hour, selecting one fully mature and sun-exposed leaf per tree. Additional measurements were carried out in 2013 to validate remotely sensed leaf water potential (Ψ_{rem}) with Ψ_{leaf} measurements at orchard scale. Ψ_{rem} was estimated from the seasonal relationships between CWSI and Ψ_{leaf} obtained during 2012. Ψ_{leaf} was measured in four to eight trees in the central rows of each irrigation sector at the time of flights.

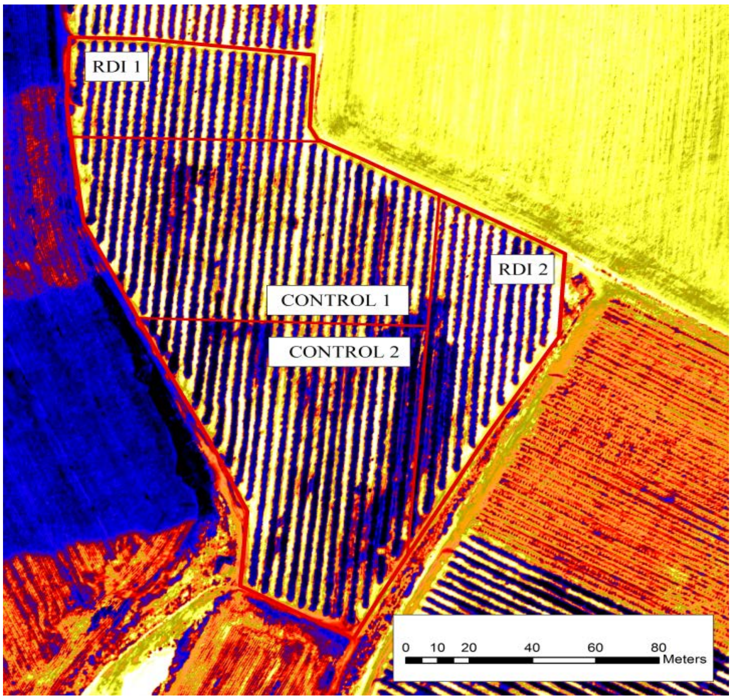

Fig. 1. Thermal mosaic of the 2-ha peach orchard correspondent with flight of day 31 July 2013. Thermal images had been obtained from an aircraft flying at 150 m altitude.

RESULTS AND DISCUSSION

Non-water-stressed baselines

The relationships between T_c-T_a and VPD for full-irrigated peach trees at different phenological stages, defining the seasonal non-water-stressed baselines (NWSB) did not show any significant difference between phenological stages. The regression displayed a negative slope, meaning that more transpirational cooling occurred for a given increase of VPD. The same NWSB was thereby used throughout the growing season to calculate CWSI in peach trees. NWSB equation was $y=0.13x^2-2.32x+4.5$.

Leaf water potential correlated significantly with CWSI at the different phenological stages and for both years of study (Fig. 2). The regressions at pre-harvest stages had a curvilinear shape and indicated a decrease in transpiration rate from a specific Ψ_{leaf} threshold until reaching complete stomatal closure. On the other hand, post-harvest stage had a linear regression. A different seasonal response was also detected in the CWSI-Ψ_{leaf} correlation. It seems that for a determinate level of CWSI, the values of Ψ_{leaf} were more negative as crop developed. This seasonal contrasted response may depend on seasonal changes in leaf turgor and hydraulic conductance. Bellvert et al. (2014) detected similar seasonal results in grapevines.

Estimated CWSI values in 2012 agreed with those of 2013 and following the same tendency at different phenological stages. Hence, both datasets confirmed that the developed methodology for calculating CWSI, based on the development of a NWSB could be implemented in different years with irrigation management.

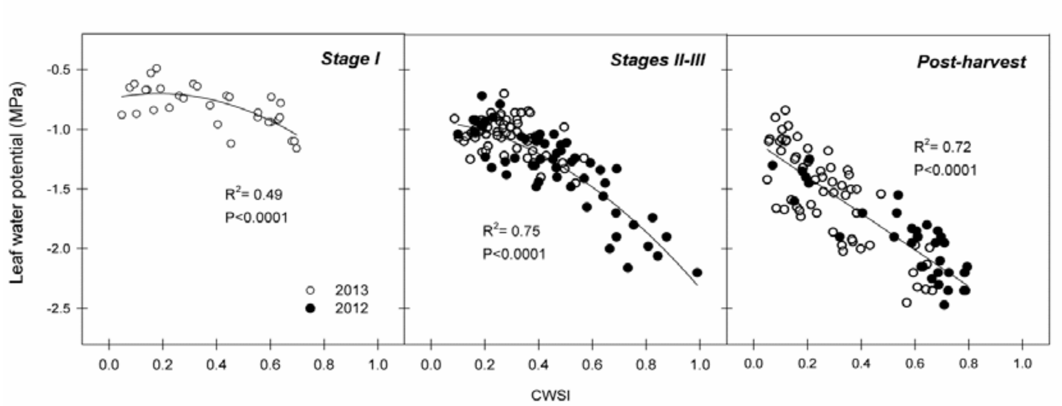

Fig. 2. Seasonal relationships between Crop Water Stress Index (CWSI) and leaf water potential (Ψ_{leaf}) in peach trees during 2012 and 2013 growing seasons, and showing in: a) stage I, b) stages II-III, and c) post-harvest.

Figure 3 illustrated the nine remotely sensed leaf water potential (Ψ_{rem}) maps of the peach tree orchard throughout the growing season. Ψ_{rem} was estimated according to the seasonal relationships with CWSI (Fig. 2). Maps characterized the spatial variability of crop water status, detecting differences between irrigation treatments. During Stage I, no differences were detected between Control and RDI

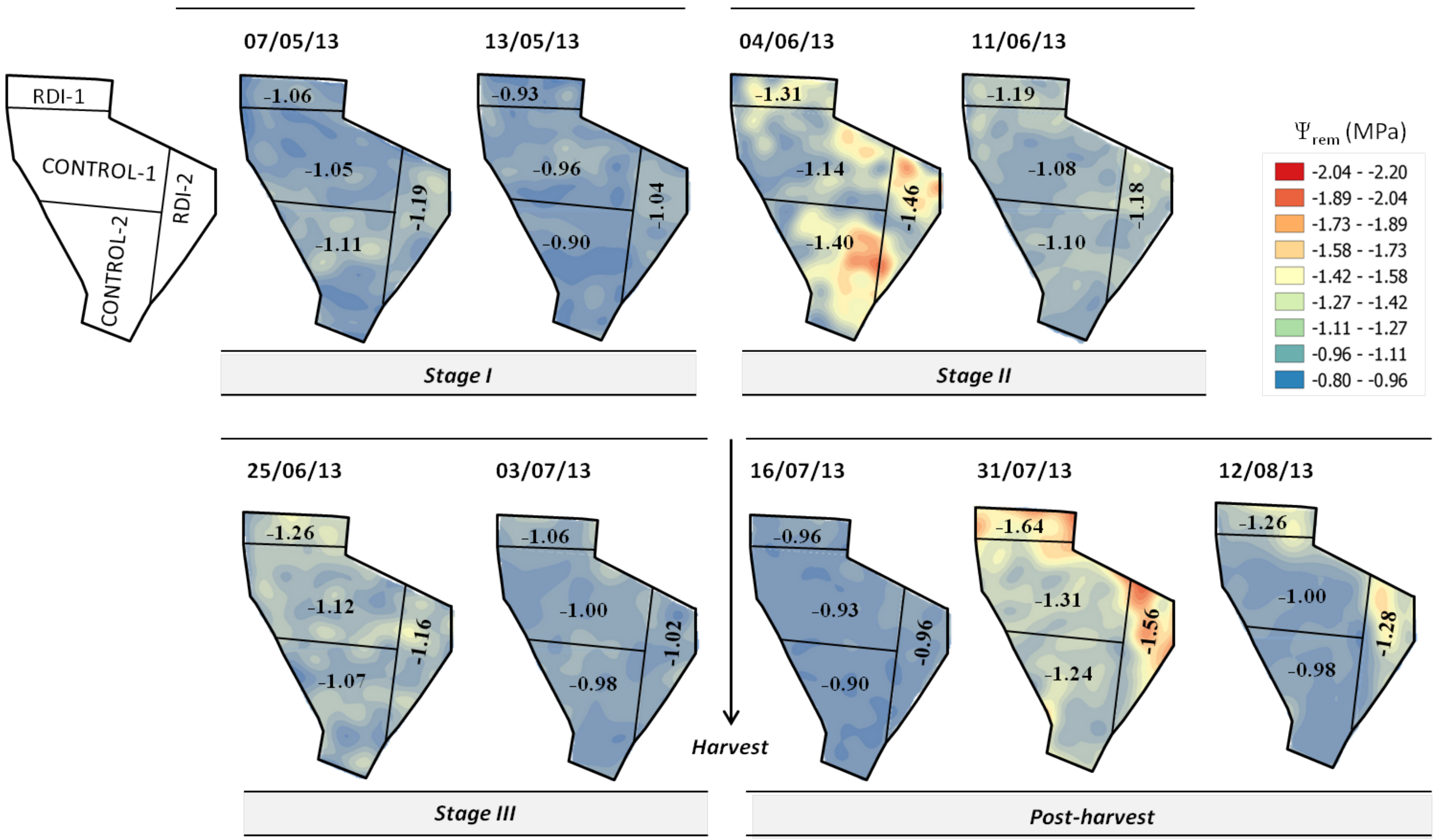

Fig. 3. Maps of remotely sensed leaf water potential (Ψ_{rem}) of a peach tree orchard of 2-ha obtained at different phenological stages from high resolution airborne thermal images. Averaged Ψ_{rem} for each irrigation sector are indicated.

treatments. Both treatments were fully-irrigated and averaged Ψ_{rem} values ranged between -0.90 to -1.19 MPa. During Stage II, Ψ_{rem} values considerably decreased for RDI treatments. The effect of deficit irrigation during Stage II was evident in the flight performed on day 4 June, as irrigation water supply for RDI treatment was stopped for the previous 13 days. Despite full irrigation in Control-2 at this time, there was a subzone within the sector that was moderately stressed. This could be explained because of differences in soil properties that may affect on plant water availability and may imply contrasted plant water needs to reach a similar water status. From the end of Stage II until harvest, both treatments were fully-irrigated again and Ψ_{rem} recovered to values above -1.5 MPa. A rainfall event of 32 mm during this period also contributed to the recovery of peach water status. Deficit irrigation adopted in RDI treatments during post-harvest period was evident in the flight on day 31 July. Averaged Ψ_{rem} of RDI treatments were -1.56 and -1.64 MPa, and -1.31 and -1.24 MPa for Control plots. Validations with Ψ_{leaf} measurements indicated no significant differences with Ψ_{rem} (p=0.29). Root mean square error (RMSE) between Ψ_{leaf} and Ψ_{rem} throughout the season were 0.13 and 0.15 MPa, for Control and RDI treatments, respectively.

CONCLUSIONS

The presented results demonstrated that remotely sensed Crop Water Stress Index (CWSI) was correlated successfully with leaf water potential (Ψ_{leaf}) for peach trees at different phenological stages. The relationship CWSI - Ψ_{leaf} pointed out phenological differences throughout the season, indicating a decrease of Ψ_{leaf} values for specific CWSI, as crop developed.

The study also demonstrated the feasibility of mapping spatial variability of remotely sensed leaf water potential (Ψ_{rem}) within a peach orchard and throughout a growing season. The implementation of this technology might represent a positive contribution for an efficient precise irrigation.

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