Using high resolution UAV thermal imagery to assess the variability in the water status of five fruit tree species within a commercial orchard

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Abstract This paper deals with the assessment of heterogeneity in water status in a commercial orchard, as a prerequisite for precision irrigation management. Remote sensing-derived indicators could be suitable for mapping water stress over large areas, and recent studies have demonstrated that high resolution airborne thermal imagery enables the assessment of discontinuous canopies as pure tree crowns can be targeted, thus eliminating the background effects. Airborne campaigns were conducted over a drip-irrigated commercial orchard in Southwestern Spain composed of five different orchard tree crops. An unmanned aerial vehicle with a thermal camera onboard was flown three times during the day on 8 July 2010, at 9, 11 and 13 h (local time). Stem water potential was measured at the same time of the flights. In some irrigation units, irrigation was stopped prior to the measurement date to induce water deficits for comparative purposes. Several approaches for using the thermal data were proposed. Daily evolution of the differential between canopy and air temperature ($T_c - T_a$) was compared to tree water status. The slope of the evolution of $T_c - T_a$ with time was well correlated with water status and is proposed as a novel indicator linked with the stomatal behavior. The Crop Water Stress Index (CWSI) was calculated with the temperature data from the 13.00 h flight using an empirical approach for defining the upper and lower limits of $T_c - T_a$. The assessment of variability

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in water status was also performed using differences in relative canopy temperatures. Ample variability was detected among and within irrigation units, demonstrating that the approach proposed was viable for precision irrigation management. The assessment led to the identification of water-stressed areas, and to the definition of threshold CWSI values and associated risks. Such thresholds may be used by growers for irrigation management based on crop developmental stages and economic considerations.

Introduction

Irrigated agriculture is the primary water user in the world, consuming about 85 % of the total water diverted for various uses worldwide (Jury and Vaux 2007). Although irrigation is only applied to 18 % of the total cultivated area, it is responsible for 45 % of agricultural production worldwide, highlighting the importance that irrigation has for food production. Nevertheless, the competition with other sectors of society and the fluctuations in fresh-water availability, combined with the expansion of irrigation in recent decades are all factors that are likely to diminish the share of water that is diverted to agriculture. Fore-casts provide a scenario where water resources will be even more limiting to irrigated agriculture (Molden 2007), while the demand for food will increase as a result of increasing population and dietary changes (Fereres et al. 2011). Hence, looking at the future, the need to manage irrigation efficiently is of paramount importance, and new tools enabling the optimization of water productivity will be sought and should be developed.

High-value crops, such as most fruit trees, are very sensitive to water deficits, so their performance in semi-arid environments is closely related to the irrigation supply. When water is limited to these crops, irrigation must be monitored in order to optimize water productivity while maintaining yield and economic return to growers. Knowledge of field heterogeneity (related to either spatial variability of soil water properties or caused by non-uniform distribution of irrigation water) becomes a critical issue when water supply for irrigation is limited. This was outlined in the analysis performed by Fereres and Soriano (2007) who showed that low uniformity of distribution increases substantially the risks of developing excessive stress under deficit irrigation. Therefore, assessing the performance of irrigation systems and quantifying the impact on crop water status of the variability in water application, are important features to enhance water management in the realm of precision agriculture. The assessment of variations in tree water status within a well-irrigated "uniform" field is not an easy task, and requires either many point observations or adapted tools enabling the characterization of entire fields via appropriate indicators. Such tools that would allow the monitoring of crop water status over large areas and at low cost are urgently needed.

Indicators derived from high-resolution airborne thermal imagery have been shown to accurately describe the spatial heterogeneity of water status that is naturally found in orchards when single tree crowns were targeted, both using manned platforms (Sepulcre-Cantó et al. 2006) and from unmanned aerial vehicles (UAV) (Berni et al. 2009b; Gonzalez-Dugo et al. 2012; Zarco-Tejada et al. 2012). Canopy temperature has been known to be a proxy for monitoring crop water status since the late 1970s (Idso et al. 1978; Jackson et al. 1981). Jackson and coworkers proposed the concept of Crop Water Stress Index (CWSI), defined as the difference between air (T_a) and canopy temperature (T_c),

normalized for the evaporative demand as determined by means of a lower limit (the case of a canopy transpiring at its potential rate) and an upper limit (a non-transpiring canopy), as shown in Eq. (1):

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

where UL and LL are the upper and lower limits, respectively.

Crop Water Stress Index has been derived from infrared thermometers or thermal images, either manually handled (Jackson et al. 1981), mounted on a mast or a crane (Testi et al. 2008a; Wang and Gartung 2010), over an aerial platform (Berni et al. 2009a) or on a satellite (Barbagallo et al. 2009). Each scale has a different resolution and is useful for specific purposes. Using thermal information for irrigation management of orchards would require assessing the trade-offs between high resolution (enabling the identification of pure crowns and the separation of mixed soil/vegetation pixels) and spatial characterization of many trees. Cameras mounted on UAV have shown promise in meeting the requirements needed for orchard irrigation management (Berni et al. 2009b; Zarco-Tejada et al. 2012). Nevertheless, further research is needed in order to optimize the use of this information for assessing field heterogeneity, such as determining the optimal spatial resolution required and the appropriate time of day for image acquisition.

Stagakis et al. (2012) have recently shown that the applicability of spectrally-derived indices is questionable when image resolution exceeds crown size. Testi et al. (2008a) obtained baselines for the CWSI in pistachio using infrared thermometers (IRTs) at different times of the day and showed that measurements around midday were most sensitive, while Sepulcre-Cantó et al. (2006) found that temperature obtained from airborne thermal imagery earlier in the morning was less affected by background effects than that measured at noon. Thermal-derived indicators were firstly developed using hand held thermometers. If airborne thermal imagery is applied, they may require adaptation to be applied accurately.

Information on the regulating effects of stomatal aperture daily patterns, which is species-dependant, is necessary to understand the fluctuations in canopy temperatures. Stomatal response to environmental conditions varies among species and must be taken into consideration when canopy temperature is proposed as a proxy for plant water status (Ballester et al. 2012b). Some species such as olive and *Citrus* have a conservative behavior and display significant stomatal closure at midday, even under well watered conditions (Testi et al. 2008b; Moriana et al. 2002). Other crops, such as sunflower, display dehydration tolerance mechanisms that enable the maintenance of stomatal aperture and a fluctuating water potential in response to evaporative demand (Fereres 1984). In almond spp., the stomatal behavior varies between cultivars (Gonzalez-Dugo et al. 2012). Partial stomatal closure feeds back on leaf temperatures, but it is not known if indicators derived from airborne thermal imagery have sufficient resolution and are capable of remotely detecting and differentiating between the behavior of contrasting species.

Following developments of high-resolution thermal imagery using a UAV, (Berni et al. 2009b), the hypothesis under study is that it would be possible to develop tools to accurately assess tree water status in commercial orchards derived from airborne thermal imagery for irrigation management purposes. The requirements for such an objective include: (i) establishing a tight relationship with tree water status, (ii) sufficient spatial resolution to enable targeting pure crowns, avoiding mixed soil/vegetation pixels, (iii) ability to assess entire commercial orchards in single flights, and (iv) quick

turn-around times for data acquisition and processing to provide real-time water status maps to aid in decision making.

The work reported here sought to assess the precision and usefulness of thermal aerial imagery acquired from a UAV in diurnal airborne campaigns carried out at three times over the course of the day. The goal was to characterize the spatial variations in tree water status among areas within a commercial orchard where five different fruit tree species were grown, and to assess the variability in tree water status within irrigated management units that could be deduced via precision irrigation in the future.

Materials and methods

Field description

The study was carried out in a 42 ha commercial orchard located in Mula Valley, Murcia, Spain (37°55′N, 1°26′W). The soil is of clay loam texture and classified as Xeric Torriorthent. Additional information on the site has been recently reported by Perez-Sarmiento et al. (2010). The climate is semi-arid mediterranean, with hot and dry summers; annual reference evapotranspiration (ETo) and rainfall in 2010 were 1 182 and 445 mm, respectively. The orchard is composed of fields planted in 1999 of five different tree crop species: almond (Al; *Prunus dulcis* cv. Garrigues and cv. Ramillete); apricot (Ap; *Prunus armeniaca* cv. Bulida); peach (Pe; *Prunus persica* cv. Catherine); lemon (Le; *Citrus x limon* cv. Fino 49); and orange (Or; *Citrus sinensis* cv. Lanelate). A layout of the orchard with the different irrigation units is shown in Fig. 1, and some specific orchard features are described in Table 1.

Trees were daily irrigated using an automated drip system with five emitters at 4 l h^{-1} per tree in almond, apricot and lemon, and three emitters at 4 l h^{-1} per tree in peach and orange. Within the areas devoted to almond, peach and lemon production, irrigation was stopped in a single management unit 8 days prior to the measurement date to induce some water deficits for comparative purposes. In the case of apricot, the crop had been harvested prior to the measurement date and water applications were limited for the previous 24 days, thus some water stress had developed throughout the whole apricot area. Irrigation was also interrupted for 8 days in an orange plot (Or-ww2), but water stress developed was very mild and no differences were found relating to the other orange plots.

Airborne imagery

A thermal camera (MIRICLE 307, Thermoteknix Systems Ldt., Cambridge, UK) was installed on a 2 m wingspan fixed–wing UAV platform, giving up to 1 h flight at 5.8 kg take-off weight (TOW) (mX-SIGHT, UAV Services and Systems, Germany). The UAV platform was controlled by an autopilot for autonomous flying (AP04, UAV Navigation, Madrid, Spain) and followed a flight plan using waypoints to acquire imagery from the entire orchard under study. The autopilot had a dual CPU controlling an integrated Attitude Heading Reference System (AHRS) based on a L1 GPS board, 3-axis accelerometers, gyros and a 3-axis magnetometer (Berni et al. 2009b). The ground control station and the UAV were radio-linked, transmitting position, altitude and status data at 20 Hz frequency; this tunneling transmission link was used for the operation of the thermal imager from the ground station deployed near the study site. The UAV was flown over the commercial orchard on 8 July 2010 three times during the day; at 09.00, 11.00 and 13.00 h (local time;
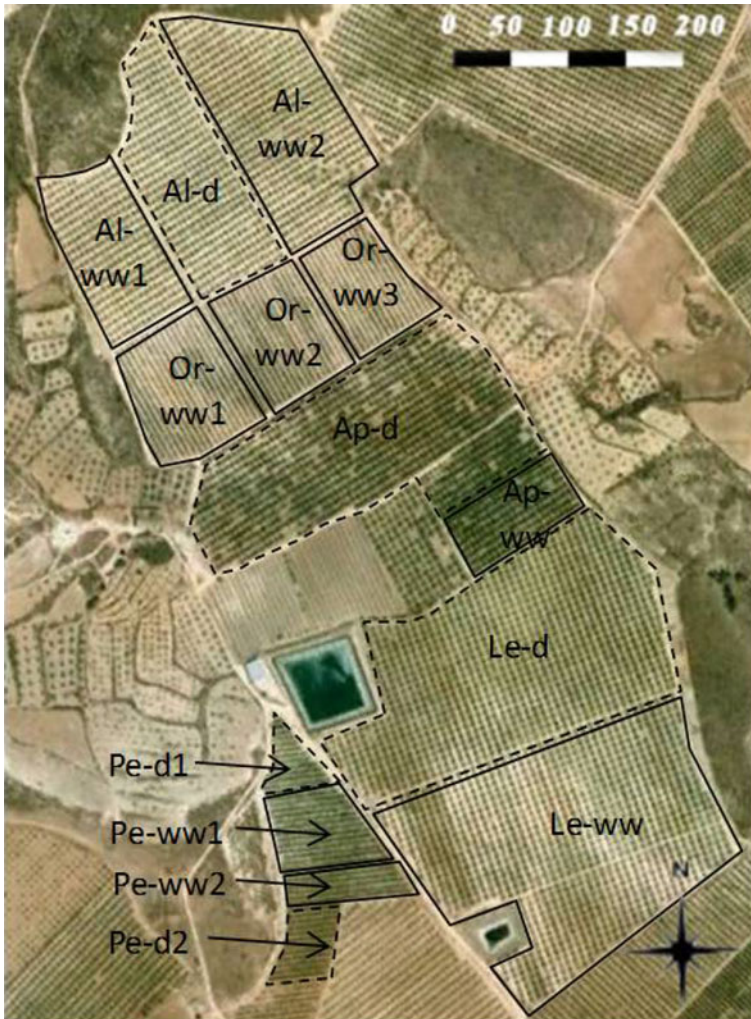
Fig. 1 Aerial view of the orchard and its irrigation management units. *Al*, *Or*, *Ap*, *Le* and *Pe* correspond to almond, orange, apricot, lemon and peach, respectively. *Solid line* indicate the plots that were fully irrigated (*-ww* plots), *while dotted lines* correspond with the plots where irrigation was withheld prior to the flights (*-d* plots)

Table 1 Orchard characteristics and irrigation units	Species	Planting grid (m)	Ground cover	Number irrigation units
	Almond cvs. *Garrigues* and *Ramillete*	6 × 8	0.40	3 (1)
	Apricot cv. *Bulida*	6 × 8	0.65	2 (1)
In number irrigation units column, the number of IU where water was withheld is shown in brackets	Peach cv. *Catherine*	4 × 6	0.48	4 (2)
	Lemon cv. *Fino 49*	6 × 8	0.41	2 (1)
	Orange cv. *Lanelate*	4 × 6	0.51	3 (0)

UTC + 1 h). Flight elevation was 370 m above the ground. In the afternoon of the previous day, a flight was carried out over the orchard and the thermal images acquired were processed in the following hours to identify the areas best suited for ground monitoring of tree water status. This flight was identical to the flights made on 8 July, the flight plan and altitude were as the others described above. The camera has a resolution of 640×480 pixels with a field of view of $45°$ that delivered an approximate ground resolution (pixel size) of 0.49 m. The camera acquired imagery in the 8–12 μm spectral region at a sensitivity ≤50 mK. Although a calibration/validation study has not been published yet regarding the accuracy of this camera, another study already demonstrated acceptable results obtained with this camera for water stress detection (Zarco-Tejada et al. 2012), where a coefficient of determination of $r^2 = 0.78$ was found between camera-derived surface temperature and leaf stomatal conductance measured in the field at the time of the flights.

Image processing

Surface temperature was retrieved from the airborne thermal imagery as in Zarco-Tejada et al. (2012). Single tree crown temperature was extracted from the imagery using an automated object-based method for conducting the image segmentation. An algorithm was applied afterwards to restrict the shape of the regions of interest for each tree crown excluding crown edges and avoiding mixed pixels of soil and vegetation. Only the central parts of the imagery were used to avoid border effects on the image-derived temperature. Due to the large along- and cross-track overlapping achieved during the flight (>70 %), the resulting thermal mosaics were not affected by pixels falling on the edge of the imagery. These procedures were conducted using algorithms developed at the QuantaLab/IAS–CSIC to ensure that the large thermal mosaics were not affected by off-nadir pixels acquired on each single frame. In addition, the automatic segmentation method used in this study selected only 50 % of the central pixels from each tree crown, ensuring that only pure-vegetation tree crown pixels were chosen, thus avoiding edge effects caused by soil temperature and shadows.

Field measurements

A team of five pressure chambers and operators was assembled to measure the water status of selected trees of the five species. Those trees were selected based on the information obtained from a preliminary flight the day before. This flight (with the same characteristics as those described above) was carried out to assess the degree of variability in thermal imaging across the orchard in order to locate the ground observations to adequately cover the range of differences detected. Table 2 presents the characteristics of each IU of each crop, the total number of trees and the number of trees used for measuring stem water potential (SWP) to assess tree water status. To measure SWP, shadowed leaves located near the tree trunk were covered with aluminum foil for at least 90 min before measurement. Measurements were made simultaneously with five different pressure bombs (Soil Moisture Equipment Corp, CA, USA) around the time of flights. Weather conditions at the time of flights were recorded with a portable weather station (Model WXT510, Vaisala, Finland) placed just outside the orchard. Mean values for the weather parameters at the times of flight are shown in Table 3. These values fell into the averages for the region and the time of the year.

Table 2 Characteristics of IUs, number of total trees and trees where SWP was measured

Species	I.U.	Withholding irrigation	Area (ha)	Total trees	Monitored trees
Almond	Al-ww1	No	1.48	298	11
	Al-ww2	No	2.62	540	–
	Al-d	Yes	2.06	441	12
Apricot	Ap-ww	No	0.91	137	6
	Ap-d	Yes	4.85	734	4
Peach	Pe-ww1	No	0.77	306	–
	Pe-ww2	No	0.37	147	8
	Pe-d1	Yes	0.39	143	–
	Pe-d2	Yes	0.41	142	7
Lemon	Le-ww	No	5.72	1 039	9
	Le-d	Yes	5.74	1 073	9
Orange	Or-ww1	No	1.26	421	12
	Or-ww2	No	1.14	470	6
	Or-ww3	No	1.15	530	–

Table 3 Weather conditions at the times of flight

Time flight	Air temperature (K)	VPD (kPa)	Wind speed (m s^{-1})
09.00	295.7	1.34	0.1
11.00	302.2	2.63	1.7
13.00	305.7	3.76	1.9

CWSI determinations

Crop Water Stress Index was estimated at 13.00 for the five species considered according to Eq. 1. The following empirical approach was followed to estimate the upper and lower baseline temperature limits needed to compute the CWSI. We hypothesized that the coolest 5 % of the tree crowns extracted from the well irrigated areas were transpiring at a rate determined only by the evaporative demand, and thus their canopy temperatures (T_c) were assumed to be at the lower limit (LL). This methodology has already been described by Rud et al. (2012) and Alchanatis et al. (2010), although the former used the lowest decile. This determination was carried out separately for each of the five species. The upper limit (UL) was established for the different species assuming a fixed value related to T_a, as in Cohen et al. (2005). Specifically, in our experiment, UL was defined as $T_a + 2$ for the *Prunus* sp. and $T_a + 4$ for the *Citrus* sp. These fixed values were established in accordance with the methodology originally proposed by Idso et al. (1981), where the UL is related to the intercept of the non-water stressed baselines (NWSB) corrected for T_a. To our knowledge, no NWSB has been published for trees of the *Prunus* genus that can be used to establish the UL. Hence, the value used in this study was based on data available for pistachio (Testi et al. 2008a) and olive (Berni et al. 2009a). For *Citrus*, the fixed value has been adapted from lime (Sepaskhah and Kashefipour 1994) and from data obtained in an orange orchard in Andalusia (unpublished).

Statistical analysis

The coefficient of variation (CV) of the T_c was calculated for each irrigation unit and each flying time as the ratio between standard deviation and mean value. Given that $T_c - T_a$ could achieve positive and negative values, the CV calculations were performed solely on crown T_c values.

The normality of the frequency distribution of CWSI within each field was checked by the Kolmogorov–Smirnov test. The analysis of shape and measure of the distribution was performed by means of the Skewness and Kurtosis indices with the SPSS ® software (IBM Corporation, Armonk, NY, USA).

Results

The average canopy-air temperature differentials for the three flights and all five species are presented in Fig. 2. In the *Prunus* spp., there were clear cut $T_c - T_a$ differences between the well-watered and the stressed fields for the three measurement times, with the differences increasing as time of day progressed (Fig. 2). There was a considerable change in $T_c - T_a$ from morning to midday; at 09.00 h the values were positive (the canopy being warmer than the air) but they became negative for both the well-watered and stressed irrigation units, although the fully irrigated canopies were cooler and consequently, $T_c - T_a$ was more negative than in the stressed plots (Fig. 2). The IU Pe-d2 displayed the highest T_c values at every temperature measurement.

The $T_c - T_a$ of well-watered plots of the three *Prunus* species behaved similarly, i.e., T_c becoming more negative than T_a as time went on. The $T_c - T_a$ of *Citrus*, changed between 09.00 and 11.00 h from positive to negative, but contrary to the three *Prunus* species, the $T_c - T_a$ either stayed constant or even increased in the third flight around midday (Fig. 2).

Figure 3 presents the relationship between $T_c - T_a$ and SWP for each of the species and at the three times of flight. At 09.00, although the two parameters were highly correlated in *Citrus*, apricot and peach, the $T_c - T_a$ generally displayed positive values in all species and changed little in response to variations in SWP (Fig. 3). Canopy temperatures measured at 11.00 and 13.00 h were better correlated to SWP in all species, although there were some differences among them. In apricot and peach, the regression lines became steeper as the morning advanced while, in almond, the regressions maintained similar slopes (Fig. 3). In *Citrus*, the low range of variation in water status hindered assessment of the tendency. Values of SWP ranged between −0.5 and −1.0 MPa, which correspond to well-watered situations (Ballester et al. 2012a). The coefficient of determination of each relationship and the significance level are shown in Table 4.

On a typical summer day, evaporative demand increases as the day advances and transpiration rate would increase too, leading to cooler canopies. Figure 4 relates the change of $T_c - T_a$ between 11.00 and 13.00 h to the tree water status quantified and the average SWP measured around the two flights. There is a clear relationship for the three *Prunus* which approximated a second order polynomial regression, with a correlation coefficient of 0.65. In contrast, there is no apparent relationship for *Citrus*, probably due to the small range of variation in tree water status (Fig. 4).

Analysis of the variability in canopy temperatures

The degree of variation in T_c among trees within the same irrigation management unit is not generally known. To characterize such variability, the CV of T_c was determined for
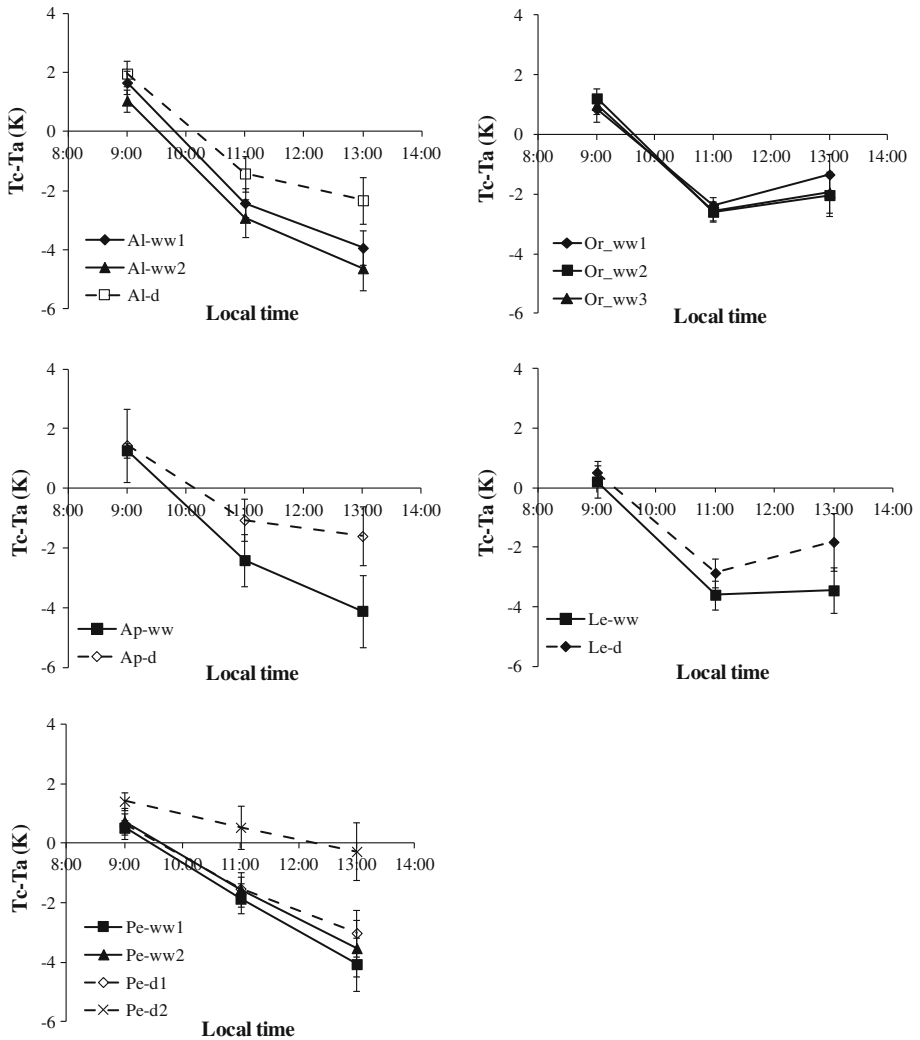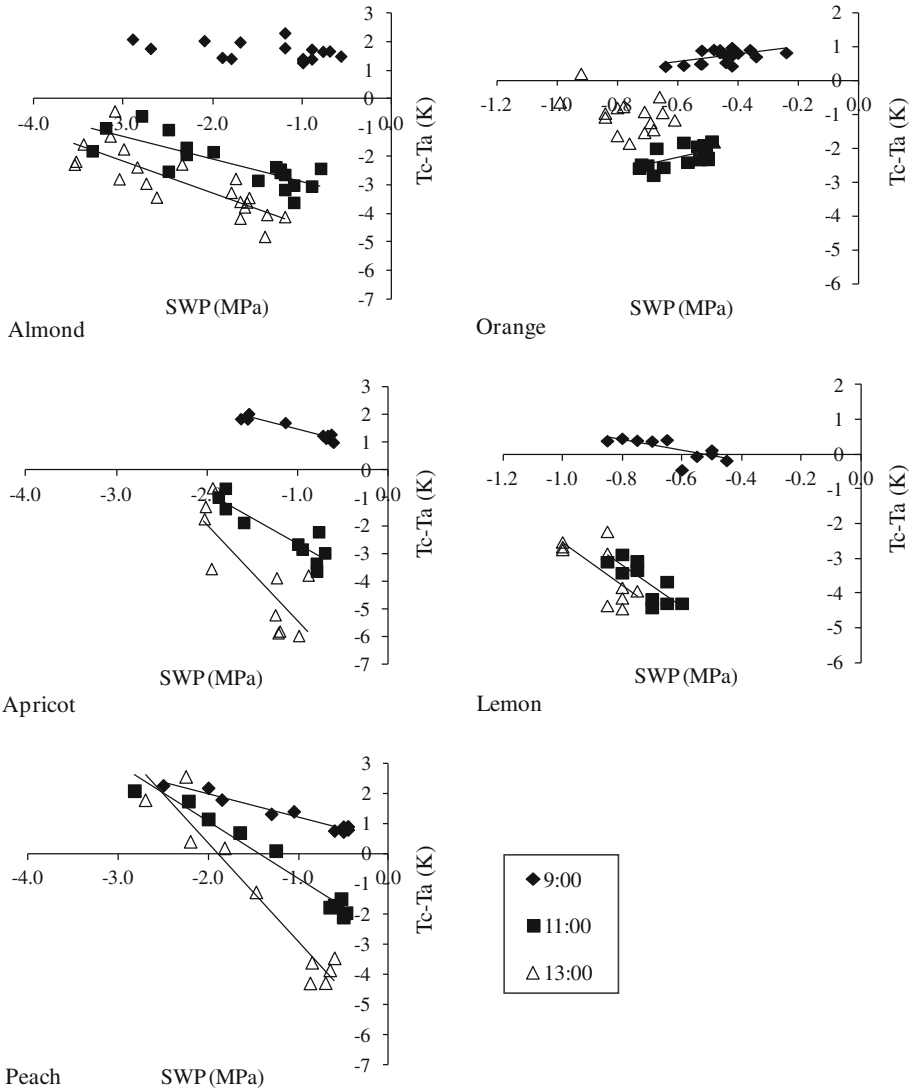
Fig. 2 Evolution of canopy minus air temperatures ($T_c - T_a$; K) at three times of the day. *Left column* almond (*Al*), apricot (*Ap*) and peach (*Pe*), *right column* orange (*Or*) and lemon (*Le*). Data from the plots where the irrigation was withheld are shown in *dotted lines*. *Vertical bars* indicate the standard deviation

each IU and for the three measurement times (Table 5). All CV values were between 0.010 and 0.051, which are quite low, and the extremes (minimum and maximum) were found in apricot. With the one exception of the Ap-d IU, the maximum CV values were found at 13.00 h. No difference in CV values was found between well-watered and stressed plots.

Determination of the CWSI

The calculation of the CWSI was inaccurate at 9:00, because the low range of VPD and air temperature resulted in a small range of temperature differences between the limits, of only around 2 K. This value was too close to the thermal resolution of the images, estimated

Fig. 3 Relationships between canopy minus air temperature ($T_c - T_a$; K) measured at three times of the day and the stem water potential (SWP; MPa) for the five tree species. Each point represented data from an individual tree

Table 4 Coefficient of determination for the relationships plotted in Fig. 3

	Almond (n = 20)	Apricot (n = 10)	Peach (n = 10)	Lemon (n = 10)	Orange (n = 18)
9:00	0.18 (n.s.)	0.91**	0.96**	0.5*	0.24*
11:00	0.63**	0.82**	0.96**	0.63*	0.37*
13:00	0.67**	0.64**	0.92**	0.48*	0.27*

The asterisks indicate the level of significance (* $p < 0.05$, ** $p < 0.001$, n.s. not significant)

Fig. 4 Relationship between the change in $T_c - T_a$ between 11.00 and 13.00 (K) and the stem water potential (SWP; MPa) for the five species grown in the orchard. The *regression line* was fitted only to the data of the three *Prunus* species ($p < 0.001$)
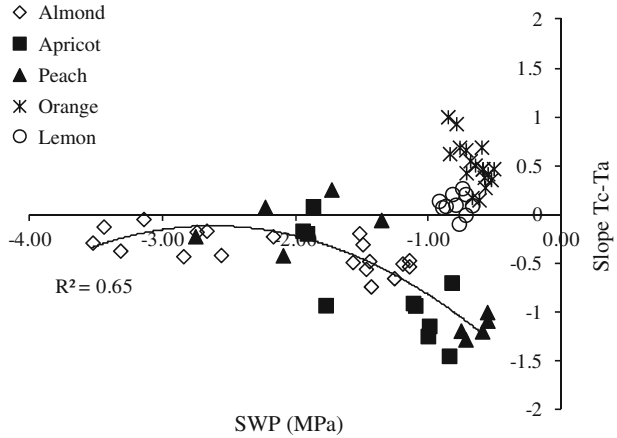

Table 5 Coefficient of variation of T_c for each IU and for each flight

	Flights		
	9.00	11.00	13.00
Almond			
Al-ww1	0.016	0.018	**0.020**
Al-ww2	0.016	0.024	**0.027**
Al-d	0.018	0.022	**0.026**
Apricot			
Ap-ww	0.010	0.033	**0.043**
Ap-d	**0.051**	0.025	0.032
Peach			
Pe-ww1	0.011	0.018	**0.031**
Pe-ww2	0.011	0.021	**0.032**
Pe-d1	0.023	0.015	**0.027**
Pe-d2	0.013	0.024	**0.030**
Lemon			
Le-ww	0.024	0.019	**0.027**
Le-d	0.016	0.019	**0.031**
Orange			
Or-ww1	0.018	0.010	**0.023**
Or-ww2	0.014	0.013	**0.023**
Or-ww3	0.013	0.012	**0.022**

For each IU, maximum value is showed in bold

around 1 K. The CWSI was calculated using the $T_c - T_a$ values measured at 13.00 h for every tree crown in the field. The value of the coolest 5 % was lower for the *Prunus* species, than in *Citrus*. The values were 300, 300.5 and 300.6 K for almond, apricot and peach, and 302.5 and 301.3 K for orange and lemon, respectively. The relationship between the SWP and the CWSI calculated for the monitored trees is depicted in Fig. 5. These values of CWSI varied between near zero up to 0.6 for almond and apricot, while the CWSI approached its maximum value (1.0) in some areas of the peach field. In *Citrus*, the
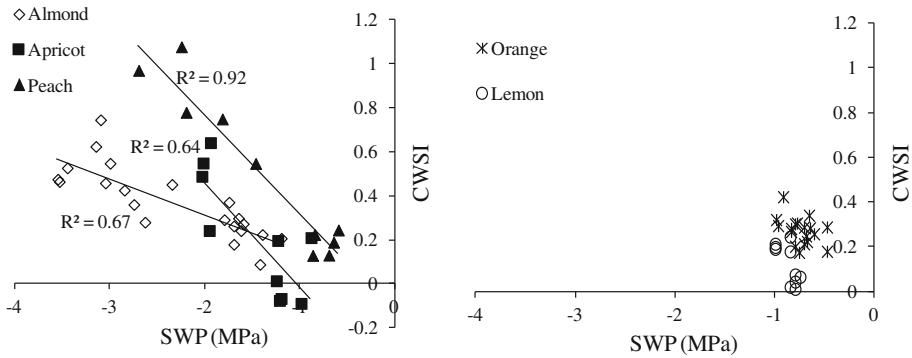
Fig. 5 Plots of crop water stress index (CWSI) as a function of stem water potential for the five tree species. *Regression lines* are fitted to the data of the three *Prunus* sp. in (**a**), while **b** the data for the two *Citrus* sp. where no significant relationships were found

CWSI values were lower, staying below 0.4, with a few reaching as high as 0.5. The regression lines are similar to those described for the $T_c - T_a$ vs. SWP relationships of Fig. 3 for the deciduous tree species. No correlation was found between CWSI and SWP in *Citrus*.

The thermal images for the whole orchard were used to compute the CWSI for every tree crown to develop a map of CWSI. Pure tree crown regions of interest (avoiding soil background effects) were interpolated by krigging to obtain a map of CWSI, and the results are shown in Fig. 6. It can be observed that *Citrus* IUs were generally more uniform than the *Prunus* IUs, with the Ap-d and Pe-d2 IUs the most variable, with CWSI ranging between 0.5 and 1.0.

From the complete CWSI map of the farm, the frequency distribution and the cumulative frequency of CWSI for each IU were derived (Fig. 7). The frequency distributions for the Pe-d2, Or-ww2, Or-ww3 and Ap-d IUs followed a normal distribution. CWSI values for the stressed IUs were substantially displaced to higher CWSI values, as compared to those of the well-watered IUs. Even plots that were well-irrigated showed a wide range in CWSI that demonstrated substantial spatial variability in tree water status within the irrigation units, as can be seen in the almond, peach and orange fields (Fig. 6). Comparing well-irrigated IUs, it can be observed that the peach, apricot and lemon distributions departed from normal, as shown by the extreme values to the right of the average CWSI (Fig. 6 b, c, e). This was corroborated by the statistical analysis. Skewness was not statistically different from 0 in the Al-ww1, Or-ww2 and Or-ww3 IUs (Table 6). The other -ww IUs were significantly different from 0 and positive. Kurtosis analysis showed that most of the plots (those with a positive coefficient) displayed a distribution flatter than the normal distribution, highlighting the significant variability in CWSI that occurred naturally within management units in this orchard.

Discussion

Under water scarcity, suitable indicators of crop water status are becoming even more relevant to assist in precision irrigation management. Indicators suitable for tracking crop water status exist (e.g., Fernandez and Cuevas 2010) but they reflect a single plant behavior
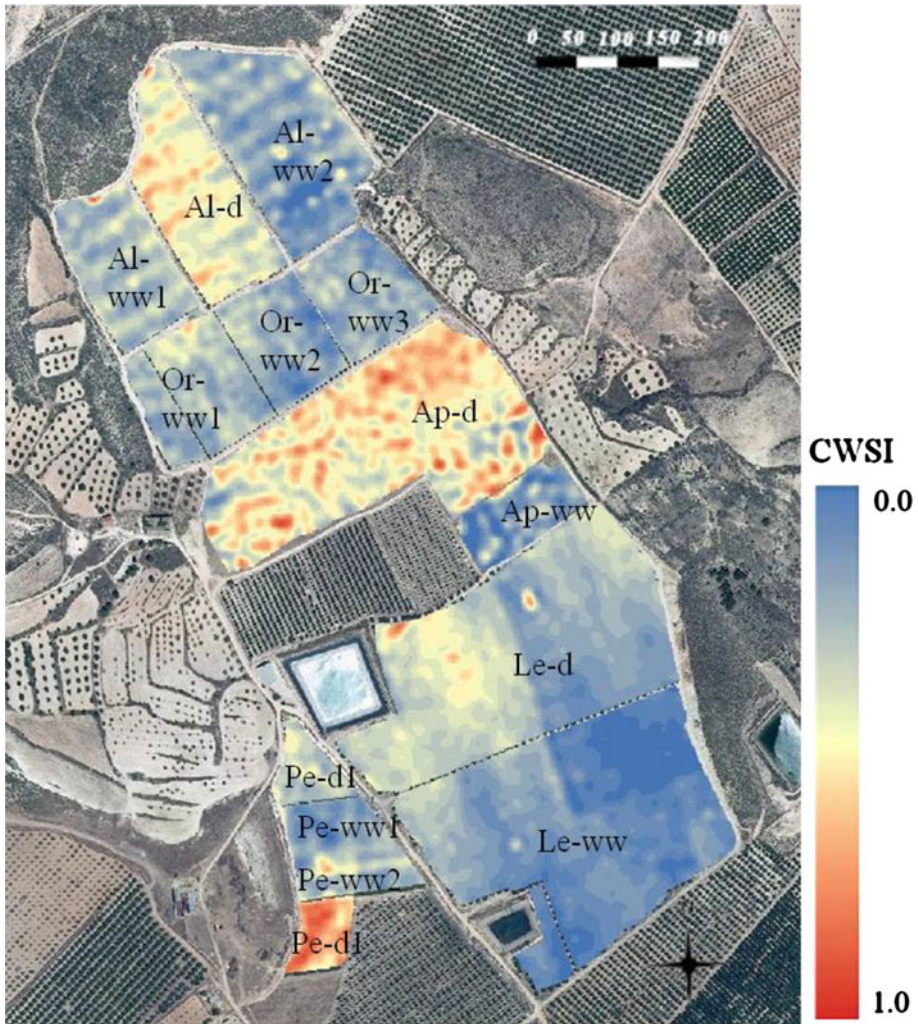
Fig. 6 Map of the CWSI of the orchard, showing the scale from minimum to maximum CWSI

and their representativeness is always in question. Given that deficit irrigation increases the risks of developing excessive water deficits in some parts of the orchard (Fereres and Soriano 2007), it is important to have access to tools that can account for the spatial variability in water status, without resorting to installing an unreasonable number of sensors that would be needed to characterize it. Thermal imagery acquired remotely provides a means of characterizing orchard variability and can assist in making decisions concerning irrigation management in precision agriculture (Alchanatis et al. 2010; Gonzalez-Dugo et al. 2006; Gonzalez-Dugo et al. 2012). In this work, several approaches are proposed to apply the thermal information obtained in three flights in a single day to analyze the spatial variability within irrigation management units.
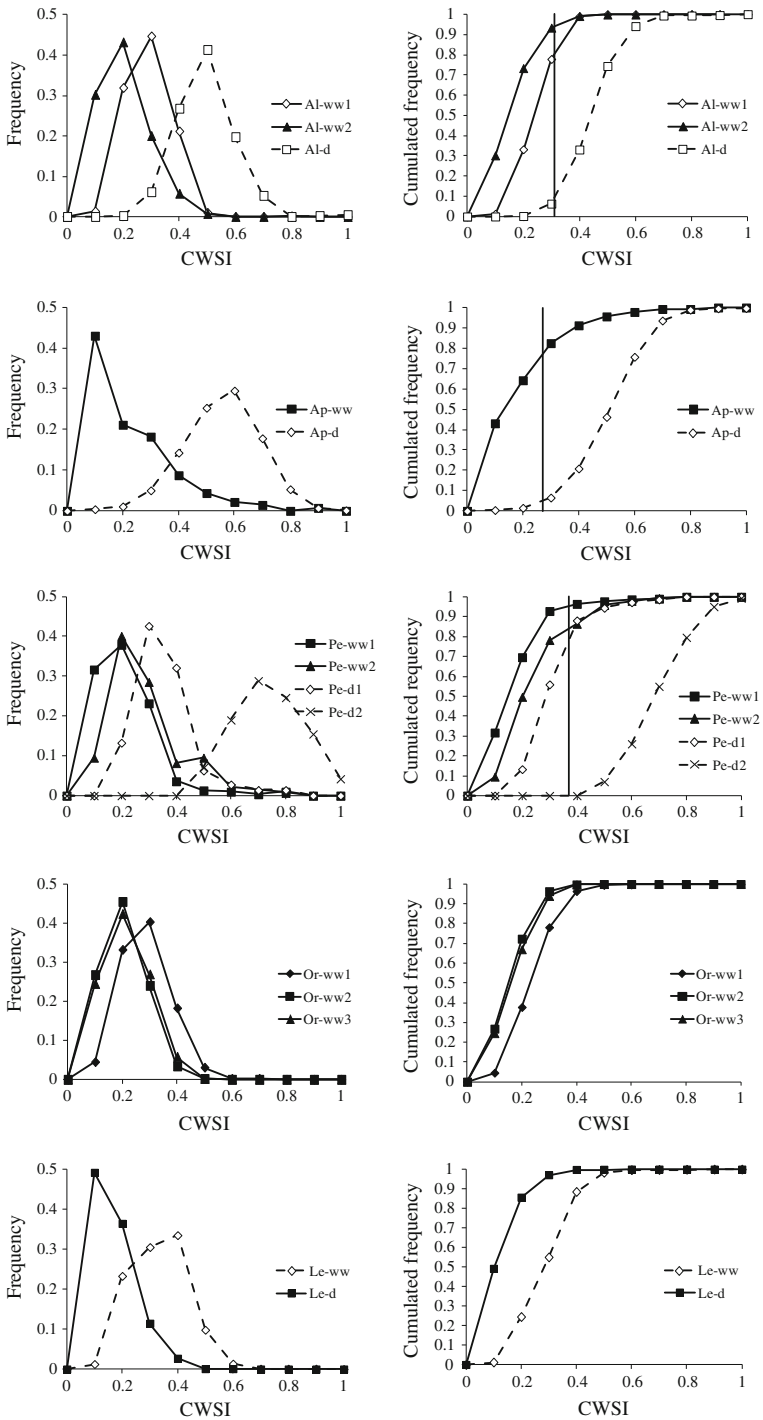
Fig. 7 *Left column* distribution of the frequency of CWSI values for each species. *Right column* cumulative frequency distribution. *Vertical lines* correspond to the established thresholds

Table 6 Main features of the frequency distribution of CWSI values within each IU

		SWP	CWSI				
		Mean	Mean	SD	CV	Skewness	Kurtosis
Almond	Al-ww1	−1.59	0.24	0.073	0.310	0.293 (±0.141)	−0.295 (±0.281)
	Al-ww2	N/A	0.15	0.098	0.650	0.507 (±0.105)	3.748 (±0.210)
	Al-d	−3.04	0.45	0.101	0.230	0.721 (±0.116)	2.559 (±0.232)
Apricot	Ap-ww	−1.13	0.16	0.166	1.020	1.093 (±0.207)	1.512 (±0.411)
	Ap-d	−1.99	0.51	0.135	0.268	0.022 (±0.090)	0.974 (±0.180)
Peach	Pe-ww1	N/A	0.16	0.123	0.770	1.786 (±0.139)	6.511 (±0.278)
	Pe-ww2	−0.73	0.23	0.130	0.555	1.342 (±0.200)	1.646 (±0.397)
	Pe-d1	N/A	0.31	0.109	0.370	1.457 (±0.203)	3.247 (±0.403)
	Pe-d2	−2.09	0.69	0.129	0.188	0.216 (±0.203)	−0.291 (±0.404)
Lemon	Le-ww	−0.80	0.11	0.081	0.715	0.795 (±0.077)	0.587 (±0.154)
	Le-d	−0.94	0.28	0.101	0.355	0.369 (±0.076)	0.503 (±0.152)
Orange	Or-ww1	−0.67	0.23	0.086	0.365	0.521 (±0.119)	0.585 (±0.237)
	Or-ww2	−0.88	0.15	0.084	0.560	0.044 (±0.113)	−0.019 (±0.225)
	Or-ww3	N/A	0.16	0.083	0.514	0.095 (±0.106)	−0.293 (±0.212)

Daily evolution of canopy temperature in orchard crops

The close relationship encountered between $T_c - T_a$ and SWP confirmed the previous findings on the use of canopy temperature as crop water status indicator in most orchards (Jackson et al. 1981; Moran et al. 1994; Sepulcre-Cantó et al. 2006; Berni et al. 2009a). The correlation coefficient of the relationship between $T_c - T_a$ and SWP at 13.00 h yielded high values for *Prunus* (R^2 between 0.64 and 0.92). The lower values displayed in *Citrus* were related to the narrow range of SWP measured in the two *Citrus* species, which was indicative of very mild water stress (Ballester et al. 2012a).

Even though canopy temperature is commonly proposed as a proxy for water status (Idso et al. 1981; Jones 1999a, b), changes in T_c during the day are rarely proposed as an indicator. In *Prunus*, the change in $T_c - T_a$ between 11.00 and 13.00 h was found here to correlate well with the SWP (Fig. 4). In fact, there was a valid correlation in both time steps considered (from 9.00 to 11.00 and from 11.00 to 13.00). Time of acquisition of canopy temperature is essential when the slope of $T_c - T_a$ is calculated; more research is needed to assess the appropriate intervals for the slope calculation. The daily course of $T_c - T_a$ and its slopes are strongly related to water relations and other aspects of crop physiology. The regulation of stomatal aperture, either in well-watered and stressed conditions, will determine the $T_c - T_a$ course. The relevance of crop physiology can be clearly observed when *Prunus* and *Citrus* are compared. *Citrus* are known to be conservative in water use. The evapotranspiration from well-watered orchards is significantly lower than the potential evaporation (Goldhamer et al. 2012), and the leaf conductance of *Citrus* decreases with increasing vapor pressure deficits (Cohen and Cohen 1983). As stomata partially close, leaf temperature rises, and hence, $T_c - T_a$ increases, relative to the behavior of other tree species. This explains the higher values of $T_c - T_a$ encountered in *Citrus*, as compared to *Prunus,* especially at noon.

A positive feature of the analysis of the slopes compared with the absolute values of $T_c - T_a$, as a potential water stress indicator, was that it described the stomatal behavior

during the time considered. This would be an important feature when comparing crops that are more or less isohydric, and it can be proposed as an indicator of the dynamics of stomatal regulation.

Moreover, the data seemed to be grouped according to the genus; data from all three *Prunus* species fitted a second order polynomial adjustment. Nevertheless, although several species are compared in this study, and the data were gathered at a single site under the specific meteorological conditions typical of summer in semi-arid areas, further research under different conditions is needed to confirm the robustness of these results.

Use of CWSI as a tool for irrigation management

The analysis of the CV of T_c and the comparison between the three different times of the day demonstrated that data obtained around noon described best the spatial variability of this parameter. Measurements carried out at midday are generally used as a standard for the assessment of plant water status (Shackel et al. 1997). Testi et al. (2008a) also showed that the CWSI in pistachio obtained around midday was most sensitive. The comparison between $T_c - T_a$ in relation to the baselines needed to compute CWSI, was shown to be more accurate at 13.00 as compared to data collected at the two other times. Comparing values obtained at midday in sunny days with contrasting values of VPD, Testi et al. (2008a) stated that unreliable values of CWSI are obtained when VPD was lower than 2 kPa. In conclusion, CWSI was computed for dataset acquired at 13.00.

CWSI is an accurate indicator that has proven to be well correlated with plant water status, amply shown in annual crops (Irmak et al. 2000; Wanjura and Upchurch 2000), but not nearly as common in fruit trees (Sepaskhah and Kashefipour 1994; Testi et al. 2008a; Berni et al. 2009a). The establishment of this index offers a quantitative framework that facilitates the interpretation of thermal data of crop canopies. The empirical method used in this study involves several implications. On the one hand, CWSI enables the comparison of the species considered and the analysis of the variability within the IU, which is useful information for decision making concerning irrigation and overall management. On the other hand, the extrapolation of these results to other orchards or conditions remains unknown. The development of models enabling the calculation of canopy conductance of well-irrigated trees (as a method to theoretically assess the NWSB) should provide a physiological basis for the analytical solution of the limits.

The definition of CWSI and its assessment in the whole area of each irrigation unit allows quantification of the area that remains above setting thresholds. This analysis can be used to define irrigation applications. In this experiment, a threshold cannot be accurately established in *Citrus*, given the low range of variation that was displayed in both the lemon and orange IUs (Fig. 5). On that date, apricot was the only species that had been already harvested, so a suitable SWP threshold for the post-harvest period proposed here would be around −1.6 MPa (adapted from Naor 2006). It ensures that no damage would result in the subsequent years. Peach was at the rapid fruit development phase, and hence, water stress must be avoided (Naor 2006). Girona et al. (2006) proposed a threshold at this stage of −1.1 MPa. Almond was in the pre-harvest period, so some water stress is desirable in order to hasten fruit maturation (Goldhamer and Fereres 2004). Hence, the threshold was set at −2 MPa. According to these values and given the relationships between SWP and CWSI reported in Fig. 5, the CWSI thresholds to start irrigation would be 0.27, 0.37 and 0.31 for apricot, peach and almond, respectively. These thresholds are plotted in Fig. 7, where the intersection with the cumulative frequency distributions indicates the percentage of the IU that was already above this threshold on the day of the flight. The relationships

between CWSI and SWP used in this calculation were obtained on a single day. For practical purposes, it would be of interest to replicate the measurements several days (within the same phenological period) to assess its consistency. In apricot for example, 23 % of the area of Ap-ww was already above the threshold, while almost the totality of Ap-d (95 %) was already beyond the limit. Once the CWSI threshold has been set according to the crop and the phenological phase, it remains a management decision (mainly related to economic considerations) to determine the percentage of area that will be allowed beyond the limit before the irrigation event is launched. Looking at the future, if the existing irrigation systems could be manipulated to irrigate independently different areas of a field, it would be possible to conduct precision irrigation and to minimize tree stress and water waste.

In peach and almond, the comparison between ww plots sheds light on the water requirements needed to attain maximum yield in each IU and is closely related with the plot homogeneity. Pe-ww2 displayed a higher CWSI compared to Pe-ww1, although both were irrigated the same. It means that Pe-ww2 was more heterogeneous than Pe-ww1 and hence, the irrigation delivery might be increased. The same could be concluded when Al-ww1 and Al-ww2 are compared.

Conclusion

Indicators derived from thermal imagery acquired from an UAV over a commercial orchard have been shown to accurately describe the spatial variability in crop water status. While physiologically-based indicators can be measured in a limited number of trees, thermal imagery provides information for whole fields and if the resolution is sufficient, as shown in this study, it allows the mapping of an orchard on a tree by tree basis. It becomes thus a valuable tool for water management in precision agriculture and deficit irrigation strategies.

The daily course of thermal-derived indicators was also analyzed. The slope of the evolution of $T_c - T_a$ with time was well correlated with water status and is proposed as a promising indicator to track water status. Its main advantage relative to point measurements of temperature is that it encompasses the stomatal behavior for longer periods of time. Moreover, the indicator behaved similarly for the three *Prunus* species. More studies under different conditions are required to assess the robustness of this approach.

The analysis of the variability of T_c demonstrated that data obtained at 13.00 were the most suitable for describing the spatial variability of canopy temperature; thus, CWSI was calculated for this time. The methodology proposed here enabled the determination of CWSI for the whole orchard, tree by tree, based on images of individual flights performed over an orchard where five tree species were grown commercially. Future work should determine CWSI thresholds for different species and phenological stages leading to a quantitative framework suitable for assisting in irrigation management decisions. The CWSI thresholds would be set based not only on physiological and horticultural responses to water stress but on economic considerations as well.

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