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Applicability and limitations of using the crop water stress index as an indicator of water deficits in citrus orchards

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ABSTRACT

Accurate measurements of the crop water status are becoming essential in irrigated agriculture, as water resources are limited and its use must be optimized, especially in semi-arid conditions. Indicators derived from thermal information have shown to be closely related to water status in several fruit tree species, and have shown promise for assessing the spatial variations among and within whole orchards. Here, a methodology is proposed for assessing the Crop Water Stress Index (CWSI) of mandarin (*Citrus reticulata* Blanco cv. Clemenvilla) and navel orange (*Citrus sinensis* L cv. Powell) located in Southern Spain, taking into account the short-term fluctuations in canopy temperature observed in both species. Infrared thermal sensors were installed above trees to record canopy temperature (T_c) continuously for three seasons from 2009 to 2011. The Non Water Stress Baseline (NWSB) was calculated using T_c of well irrigated trees on cloudless days during summertime. The NWSB was affected by flushes of growth that occurred periodically, depending on the crop load of a given year. Nevertheless, the close relationship observed between CWSI and stem water potential (R^2 ranging between 0.59 and 0.66; $p < 0.001$) demonstrated that it is a suitable indicator of water status in citrus. The results showed that care must be taken when using CWSI in citrus to account for the presence of new growth at the top of the canopy, and for the short-term fluctuations in canopy temperature. The canopy temperature information acquired from point sensors was used in conjunction with high resolution airborne thermal imagery to derive CWSI maps. The approach presented here demonstrates that CWSI is a valuable method to assess the water status, and to quantify the spatial variability in water stress among and within citrus orchards using high-resolution airborne thermal imagery.

1. Introduction

It has long been known that canopy temperature and transpiration are closely related (Gates, 1964). Water stress induces stomatal closure, reduces evaporative cooling and increases leaf temperature (Hsiao, 1973). This feature was used by Jackson et al. (1977, 1981) in the development of water stress indicators based on canopy temperature. Working with hand-held infrared thermometers, Jackson and coworkers developed the concept of Crop Water Stress Index (CWSI; Jackson et al., 1981; Idso et al., 1978). This indicator is based on normalizing the difference between canopy (T_c) and air temperature (T_a) relative to the evaporative demand (by means of the vapor pressure deficit of the air, VPD). The normalization related to VPD considers the T_c–T_a difference of a canopy under two boundary conditions: (a) a lower limit when it transpires at its potential rate (i.e., under well watered conditions) and (b) an upper limit under no transpiration. The lower limit is described by a linear regression between T_c–T_a and VPD, which is known as the Non Water Stress Baseline (NWSB). There are several methods to calculate the upper limit (corresponding to the T_c–T_a of a canopy where transpiration is halted). The most widely used was proposed by Idso et al. (1981) and defines the upper limit as a horizontal line departing at the intercept of the NWSB corrected for air temperature. These two bounds are climate dependent and are used to calculate the CWSI when plotted as a function of VPD (Idso et al., 1981). Analytical solutions to assess the CWSI have also been developed (Jackson et al., 1981; Jones, 1999; Maes and Steppe, 2012) that enabled the calculation of CWSI at the canopy level, which is of paramount importance for irrigation management applications. The CWSI has been extensively used in annual crops (Idso et al., 1981; Wanjura et al., 1990; Irmak et al., 2000; González-Dugo et al., 2006; Kar and Kumar, 2007). Recently, it has also been applied to

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perennial crops, such as olive (Ben-Gal et al., 2009; Berni et al., 2009), pistachio (Testi et al., 2008) and peach (Wang and Gartung, 2010).

Judicious irrigation management is based on a precise estimate of the crop water requirements. The traditional use of reference evapotranspiration (ETo) and crop coefficients (K_c) proposed by Allen et al. (1998) is now being substituted, in the case of tree crops, by more accurate models to compute water use by trees (Rana et al., 2005; Fereres et al., 2012; Villalobos et al., 2013). In the case of citrus, maximum water requirements may be assessed with a simple model as function of ground cover (Villalobos et al., 2009). Often, the full water requirements cannot be satisfied and thus, deficit irrigation strategies are being imposed as water resource becomes increasingly limited. Deficit irrigation is also proposed as a strategy for increasing fruit quality (Ballester et al., 2011). Growers must decide how to use the water efficiently in order to maintain yields and enhance fruit quality. Accurate water status assessments become essential in order to manage irrigation in water scarcity situations (Naor, 2006), and the search for reliable indicators of tree water status has recently expanded at the individual tree (Fernandez and Cuevas, 2010) and at the field level (Bastiaanssen and Bos, 1999; Gonzalez-Dugo et al., 2013).

One of the main advantages of the thermal derived indicators is that they can be remotely acquired and thus adapted to operate at the field and farm scales by remote sensing. Point indicators, which are currently the state of the art, typically assess water status at the leaf level and extrapolate those values at the plant level. However, irrigation management (and especially when deficit irrigation strategies may be applied) requires the precise assessment of water status at the field scale, including within-field variability. Furthermore, field characterization by point indicators is time consuming and does not represent well field heterogeneity. Remotely-sensed derived indicators allow the characterization of an entire field while maintaining high resolution to enable a close relationship with individual plant performance and the underlying physiology (Berni et al., 2009; Gonzalez-Dugo et al., 2012; Zarco-Tejada et al., 2012). An issue that requires investigation is whether the thermal indicators obtained from ground sensors in citrus can be extrapolated to airborne or satellite thermal imagery, as previously proposed for olive (Sepulcre-Cantó et al., 2006).

World citrus production has increased in recent decades (Spreen, 2001) and is still increasing (FAOSTAT, 2012). Nowadays, the Mediterranean region accounts for more than 16% of the total world production of citrus equivalent to about one million hectares of land use (FAOSTAT, 2012). These data highlight the importance of citrus production in the region. Given the semi-arid climate of the Mediterranean basin, irrigation is essential for citrus production. Traditionally, citrus has been irrigated by flooding, although water scarcity and management reasons have led to a shift to drip irrigation in many production areas. Investments in irrigation hardware should be accompanied by more precise management of the scarce resource. Gonzalez-Dugo et al. (2013) have used the concept of CWSI to assess its potential for irrigation management in a commercial orchard with several tree crops. In the case of citrus, to our knowledge, there is only one published report on the use of CWSI in sweet lime (Sepaskhah and Kashefipour, 1994), which has a different pattern of water use from other citrus species (Sepaskhah and Kashefipour, 1995). Recent work with orange trees in the coastal area of Spain (Ballester et al., 2013a) was unable to characterize the CWSI under contrasting water regimes. Given the potential usefulness of the CWSI for remote sensing applications (Berni et al., 2009; Maes and Steppe, 2012), it would be important to establish if the CWSI can be quantified in citrus plantations, and what are its limitations that have prevented its determination until now.

This work was aimed at testing the hypothesis that the Crop Water Stress Index is a reliable water stress indicator in mandarin and orange trees. A methodology to quantify the CWSI was established and tested over three seasons, and the extrapolation from thermal point data to thermal imagery, remotely acquired by an airborne platform was carried out.

2. Materials and methods

2.1. Site description and experimental design

The study was carried out during three years (2009–2011) in two 0.6-ha plots of orange and mandarin trees in a commercial orchard located near La Campana, Seville (37.8° N, 5.4° W), Spain. The orange trees (*Citrus sinensis* L. cv. Powell) were planted in 1997 in a 7 m × 4 m grid (358 trees/ha) on a deep alluvial soil of loam to sandy-loam texture. The mandarin (*Citrus reticulata* Blanco cv. Clemenvilla) orchard was planted in 1997 in a 7 m × 3 m grid (476 trees/ha). Both cultivars were grafted onto Carrizo citrange (*C. sinensis* L. Osb. × *Poncirus trifoliata* L. Osb), and were around 3 m height. The climate in the area is Mediterranean, characterized by warm and dry summers and cool and wet winters, with an average annual rainfall and reference evapotranspiration (ETo; Penman-Monteith) around 550 and 1300 mm, respectively.

Four treatments were compared in a randomized block design with four replicates per treatment. The experimental design was similar for orange and mandarin. Each individual plot comprised 12 trees (three rows and four trees in each row), the two central trees being monitored. Trees were daily irrigated with an automated drip system, with ten pressure-compensated emitters ($1.6\,l\,h^{-1}$) per tree. The treatments were: (i) C, where water was supplied to satisfy the full water requirements throughout the season, (ii) RDI1, where water supply was reduced to 37% of C from mid-June to early September, (iii) RDI2, with the same schedule as RDI1, but with a milder water deficit during that period, established at 50% of C; and, (iv) F, the commercial irrigation management followed in the rest of the orchard (based on long-term average ETo and locally developed crop coefficients that includes an adjustment in canopy size). In the deficit treatments, irrigation was modified by using lower discharge emitters while maintaining the number of emitters and the application time. The starting date for the two RDI treatments varied among years, and occurred around the end of the physiological June fruit drop. Full water requirements were estimated based on the crop evapotranspiration, which was calculated following Goldhamer, 2012. ETo was obtained from an automated weather station located 10 km away from the study site. The farm mineral fertilization program included periodic applications through the irrigation system of about 220 kg/ha of N, 90 kg/ha of P_2O_5, and 110 kg/ha K_2O. To compensate for the differences in irrigation volumes applied in the RDI treatments, additional fertilizer was applied through the system to achieve the same level of fertility in all treatments.

2.2. Canopy temperature measurement and CWSI calculation

Eight trees (four orange and four mandarin trees) were instrumented with eight infrared temperature (IRT) sensors with an angular field of view of 44° (Apogee, Utah, USA) acquiring continuous thermal crown temperature data from June 2009 to September 2011 in the mandarin and orange orchards. Each sensor was installed 1 m over the targeted tree crown, on aluminum masts with a horizontal arm that ended up over the center of the canopy of two consecutive trees, being both monitored with one IRT sensors each. For each species, two trees of C treatment and two trees of RDI1 were monitored, and their canopy temperatures were averaged to obtain an hourly value per species and treatment. For additional information on sensor installation, see Berni et al. (2009). We consider that only pure tree crown temperatures were monitored by the sensors, given that a typical citrus tree has over 140 m^2 of leaf area (Turrell, 1961) and that is equivalent to a leaf area index of over 13 under the orchard spacing and canopy size of our experimental trees. The accuracy of the sensors yielded ±0.15 °C, according to the manufacturer. These sensors were connected to a datalogger (model CR1000, Campbell Scientific, Logan, UT) that recorded canopy temperature every minute and stored the 5-min averages. For each species, two trees from C and RDI1 treatments were monitored. During 2010, problems with the dataloggers disabled the registration of all the data in two periods in the mandarin, (from DOY 181 to 197 and from 227 to 235), and from DOY 174 to 202 in the orange.

Air temperature (T_a, K) and relative humidity (RH, %) were recorded continuously with a Vaisala Weather Transmitter (model WXT510, Vaisala Oyj, Helsinki, Finland) installed in the study site 1 m over the tree crowns in the mandarin experiment.

Canopy temperature (T_c) and air temperature (T_a) were used to calculate the Crop Water Stress Index (CWSI), according to Eq. (1):

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

Where $(T_c–T_a)_{LL}$ is the lower limit of the difference between canopy and air temperature. It corresponds with the $T_c–T_a$ value of a canopy transpiring at the potential rate. $(T_c–T_a)_{UL}$ corresponds with the difference of a canopy where transpiration is completely halted.

The relationship between $T_c–T_a$ and VPD for well irrigated trees was used to establish the Non-Water-Stressed Baseline (NWSB) which defines the lower limit ($(T_c–T_a)_{LL}$) for a given evaporative demand. $(T_c–T_a)_{UL}$ was calculated as the intercept of the NWSB corrected for air temperature, according to the methodology described by Idso et al. (1981). From the entire seasons, only cloudless days from mid June to end of August were selected for the calculation of the CWSI.

NWSB was calculated for $T_c–T_a$ values at solar noon. In mandarin in 2011, the period comprised between DOY 176 and 196 was discarded due to a failure in the irrigation system that altered the anticipated treatments.

2.3. Aerial imagery

An unmanned aerial vehicle (UAV) platform for remote sensing research was developed at the *Laboratory for Research Methods in Quantitative Remote Sensing* (QuantaLab, IAS-CSIC, Spain) to carry a payload with a thermal and a hyperspectral camera. Two UAV platforms were operated in this experiment. The first UAV consisted of a 2-m wingspan fixed-wing platform capable of one-hour endurance at 5.8 kg take-off weight (TOW) (mX-SIGHT, UAV Services and Systems, Germany). This platform was used to fly the thermal camera over the study sites in 2009. A second UAV platform was developed for hyperspectral imagery acquisition, consisting of a 5-m wingspan fixed-wing platform capable of three-hour endurance at 13.5 kg TOW (Viewer, ELIMCO, Seville, Spain). This larger platform enabled the image acquisition of both study sites in a single flight carrying both the micro-hyperspectral imager and the thermal camera concurrently. Platform characteristics are detailed in Zarco-Tejada et al. (2012).

On DOY 217 2009, images of the experimental plots were acquired with a thermal camera (MIRICLE 307, Thermoteknix Systems Ldt., Cambridge, UK) installed onboard the UAV. Flight altitude was 250 m above the ground, and spatial resolution was 35 cm (pixel size). Images were radiometrically and atmospherically calibrated as described in Zarco-Tejada et al. (2012). Canopy temperature (T_c) was extracted from the individual images for each tree of the experiment. An algorithm was applied to restrict the shape of the regions of interest considered and to exclude crown edges, thus avoiding soil/vegetation mixed pixels. Once the T_c of pure crowns was obtained, CWSI at the object level was calculated after Eq. (1).

A micro-hyperspectral camera (Micro-Hyperspec VNIR model, Headwall, Photonics, MA, USA) was flown over the orange experiment on DOY 257 2010 and DOY 263 2011. Information concerning radiometric calibration of the imager and atmospheric correction of the imagery can be found in Zarco-Tejada et al. (2012). Flight altitude was 550 m above the ground, yielding 35 cm resolution in 260 bands in the 400–900 nm spectral range. Similarly to what was described for the thermal imagery, pure crowns were targeted to avoid background effects on the spectra. The chlorophyll content of the tree crowns was estimated based on the data extracted from the hyperspectral images and the model developed by Zarco-Tejada et al. (2004) for open-canopy tree crops.

2.4. Tree measurements

Midday stem water potential (SWP) was monitored weekly in eight trees per treatment and per species throughout the seasons using a pressure chamber (Soil Moisture Equipment Corp. model 3000, Santa Barbara, CA, USA). Two shaded leaves located near the trunk per tree were used to obtain an estimate of SWP.

Crop load (#fruits $tree^{-1}$) and yield (kg $tree^{-1}$) were determined at harvest separately for each monitored tree.

In order to assess the spectral response of crowns displaying contrasted vegetation characteristics, a series of leaf-level measurements was made, including SPAD values obtained with a chlorophyll meter (SPAD-502, Minolta Corp., Ramsey, NJ) on ten sun-exposed fully-expanded young leaves recently developed from the current summer growth, and on ten over-wintered adult leaves (leaves that had appeared, at least, six months before), all sun-exposed. SPAD values were used to determine chlorophyll content (Cab) according to the model developed by Jifon et al. (2005). The assimilation (A) and transpiration rate (Tr) at the leaf level, as well as leaf temperature were also determined in these leaves with a portable photosynthesis measurement system (LCpro-SD, ADC BioScientific Ltd., Herts, England). Measurements were performed around noon.

3. Results

3.1. Diurnal evolution of $T_c–T_a$ in citrus and temperature oscillations

Fig. 1 illustrates the patterns of the daily evolution of T_c for mandarin in control and stressed trees, as well as the T_c differences between both treatments, before the onset of stress (Fig. 1A) and with increasing levels of water stress (Fig. 1B and C). We noted that T_c experienced large oscillations, especially around midday, with a variable period ranging between 20 and 60 min. Within these oscillations, T_c often varied more than 1 °C. On DOY 162 (Fig. 1A), trees in both treatments showed no T_c differences, reaching a maximum value of about 41.5 °C. In subsequent days, the difference between control and stressed trees became significant (Fig. 1B and C) and increased with time. Differences between treatments attained a value as high as 3.5 °C. The vapor pressure deficit (kPa) and incoming solar radiation (W m^{-2}) for the selected days did not explain these fluctuations in T_c (Fig. 1D–F). It can also be observed that, as the stress level increased, the T_c differences between treatments started earlier in the day. Differences between both treatments generally disappeared at around 17:00 (GMT), as a result of the decline in the

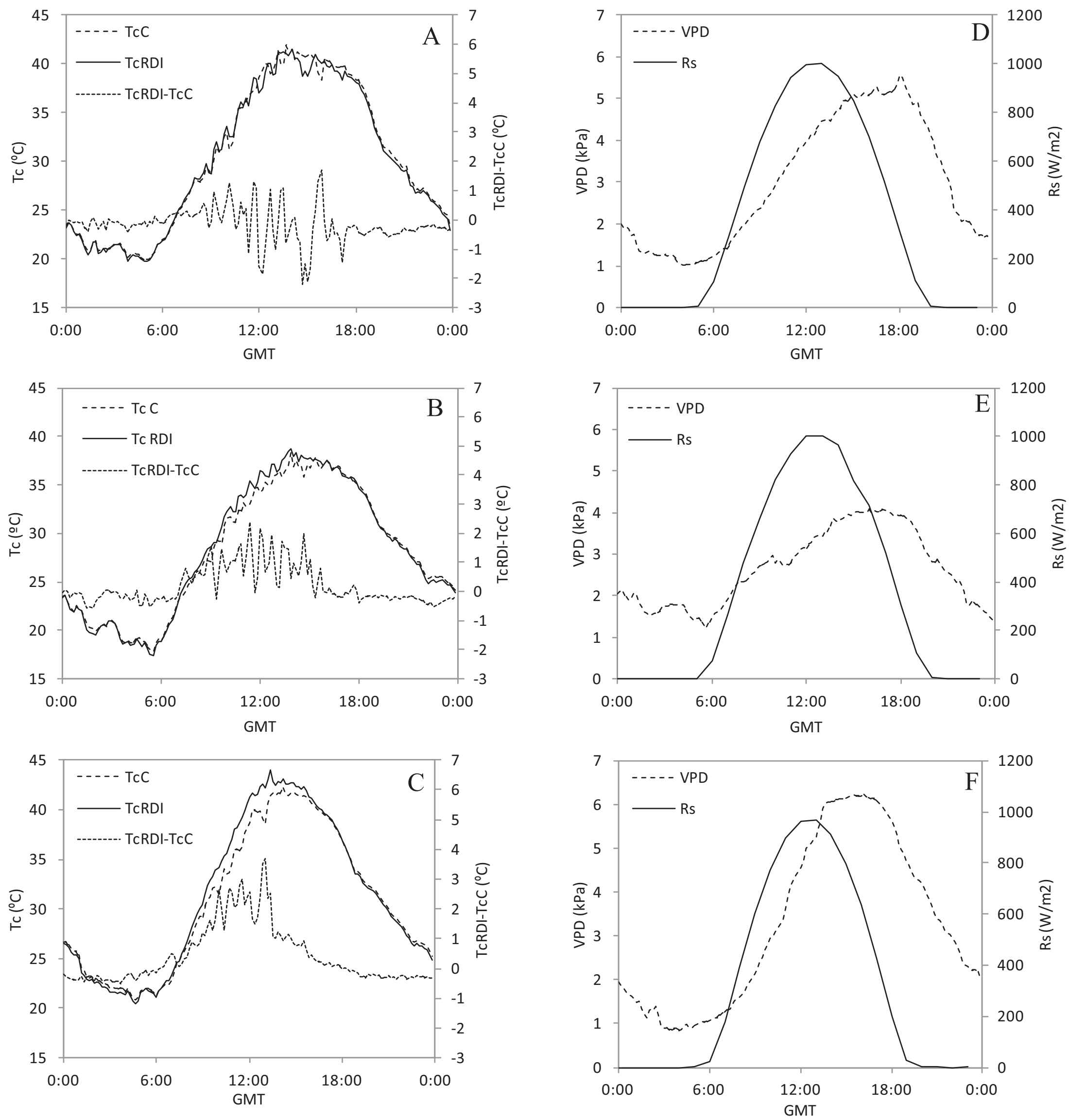

Fig. 1. Representative diurnal course patterns of canopy temperature, T_c (°C), and of its difference between treatments, for C and RDI1 in mandarin trees (left column; plots A–C) and evolution of vapor pressure deficit (kPa) and incoming solar radiation (W m^{-2}) (right column; plots D–F) on DOY 162 (A and D), DOY 199 (B and E) and DOY 234 (C and F), in 2009. For figures A–C, each reading corresponded to the averaged value from two trees of the same treatment.

evaporative demand and in the incoming solar radiation (Fig. 1D–F). The orange trees displayed similar results (*data not shown*).

3.2. Establishment of the NWSB

The ample, short-term fluctuations observed in T_c made the computation of the relationship between T_c–T_a and VPD difficult. We averaged the T_c values over several time periods to define accurately the optimum time interval for the establishment of the NWSB in these two cultivars. We tested different time intervals, ranging from 10 to 120 min (every 10 min) and centered at noon. Although the regression lines obtained for each of the intervals considered did not change by much, the best adjustment was observed for 60-min T_c averages (*data not shown*). Fig. 2 showed some examples of the regressions obtained for the mandarin site in 2009. Thus, for all the subsequent analyses, 60-min T_c–T_a and VPD averages were used for the CWSI calculations. Tests performed in the remaining datasets of both cultivars showed similar results.

The Non Water Stress Baseline (NWSB) was established using measurements of T_c–T_a of control trees in cloudless days, averaged

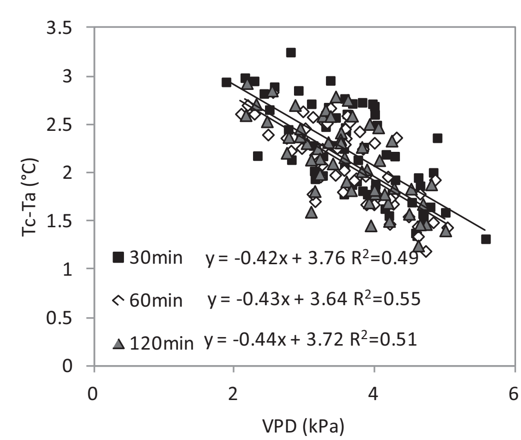

Fig. 2. Relationship between T_c–T_a (°C) and VPD (kPa), using 5 min observations averaged over 30, 60, and 120 min (centered at noon) obtained in two well-watered mandarin trees in 2009.

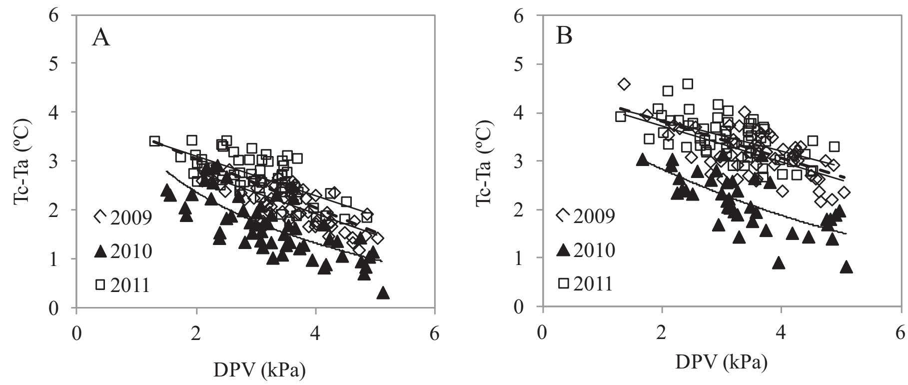

Fig. 3. Relationship between T_c–T_a (°C) and VPD (kPa) for well-watered mandarin (A) and orange (B) trees on clear sunny days. Measurements from mid June until the end of August were averaged between 11:30 and 12:30 (GMT). Regression lines for the dataset pooling 2009 and 2011 are shown in the graphs.

between 11:30 and 12:30 GMT, and the plots of T_c–T_a vs. VPD generated the NWSB lines (Fig. 3). This relationship was significant for both mandarin (Fig. 3A) and orange (Fig. 3B) trees, with moderate R^2 values, ranging between 0.33 and 0.56 ($p < 0.001$; Table 1). It can be observed that, although the slope of the regressions was more or less the same for each species during the three years, there were differences in the intercept among years (Fig. 3). The intercept varied from 3.3 °C to 3.9 °C in mandarin and from 3.6 °C to 4.5 °C in orange. The minimum value of the intercept was found in 2010 in both species; for the same range of VPD, T_c–T_a was about 1 °C lower as compared to the two other years. Data from 2009 and 2011 were pooled together, as the linear regression corresponding to both years was nearly identical to those computed for separate years (Table 1).

The moderate R^2 values of the NWSB may be attributed to the described fluctuations in canopy temperature. The examination of data obtained in different days displaying close values of T_a and VPD showed that such temperature variations were causing large part of the variability observed in Fig. 3. It can be thus expected that the deviation should be symmetrically distributed around a mean value, as, for the same VPD, T_c would vary above or below its mean value. Consequently, negative values of CWSI (corresponding to those observations lying below the NWSB; see Fig. 3) should be expected for control trees.

3.3. Variability among years

The differences observed in the intercept of the NWSB among years were analyzed. In contrast to the two other years, fruit yields in 2010 were very low (27 and 8 kg tree^{-1} for the targeted control trees in mandarin and orange, respectively). Yields in 2009 and 2011 averaged 64 and 82 kg tree^{-1} for mandarin and orange, respectively. If the variation in yield among years had an effect over the vegetation of the monitored tree areas located on the top of the canopy, it could influence their heat dissipation characteristics and thus, the temperature registered by the IRT sensors. We observed active flushes of new growth during the summer of 2010, the low yield year, mainly in the upper parts of the canopy. Newly formed leaves display a higher stomatal conductance, less pigment contents, and thus different water relations than mature leaves. These differences were assessed here with a series of measurements made at the leaf level, where gas exchange rate and chlorophyll content of ten young and ten over-wintered leaves were measured. Table 2 shows that young leaves displayed a higher transpiration rate than mature leaves (about 280% more), leading to a decrease of about 1 °C in mean leaf temperature. A lower value of chlorophyll content in the young leaves (28 μg cm^{-2}) was observed relative to that of mature leaves (Table 2).

The differences observed in the chlorophyll content at the leaf level were used to depict a change in vegetation pattern at the top of the canopy by the hyperspectral imagery remotely acquired over the orchard. The high resolution of the hyperspectral imagery enabled the analysis of pure-crown spectra, avoiding background effects (Fig. 4A). Crown spectra of the monitored trees were extracted for each tree of the experiment from the images acquired in 2010 and 2011. Fig. 4B shows the differences observed in the crown reflectance for the control trees between the two years. The chlorophyll content (Cab) calculated according to Zarco-Tejada et al. (2004) showed that the tree crown had a lower amount of Cab in 2010, the low yield year, as compared to 2011 (55.8 vs. 63.1 μg cm^{-2}). These differences in Cab may be related to an accelerated development of young leaves that displayed a lower content of Cab as compared to the mature leaves (Table 2). These young leaves in 2010 altered the exchange rate and heat dissipation relative to the other two years. Chlorophyll content was also estimated for the stressed trees but the mean chlorophyll values were nearly identical for 2010 and 2011 (64.9 and 65.9 μg cm^{-2}).

If the difference in the intercept of NWSB between 2010 and the other two years (Fig. 3) would be related to the increased vegetative growth, presumably activated by the low amount of assimilates demanded by the limited fruit number in 2010, one would expect a positive relationship between crop load and the intercept of the NWSB. Fig. 5 presents the relationship between crop load and the intercept of the NWSB for each year and the two species. The higher

Table 1
Parameters of the NWSB ($Tc\text{-}Ta = a \cdot VPD + b$) for orange and mandarin and for each experimental year, obtained between 13:30 and 12:30 GMT. The regression line for 2009 and 2011 data is also shown.

Species	Year	a	b	R^2	P
Mandarin	2009	−0.430	3.640	0.54	<0.001
	2010	−0.496	3.313	0.52	<0.001
	2011	−0.401	3.903	0.46	<0.001
	2009&2011	**−0.500**	**4.056**	**0.56**	**<0.001**
Orange	2009	−0.372	4.462	0.39	<0.001
	2010	−0.433	3.635	0.45	<0.001
	2011	−0.320	4.487	0.33	<0.001
	2009&2011	**−0.379**	**4.586**	**0.41**	**<0.001**

Table 2
Leaf temperature, gas exchange rate and chlorophyll content measured on ten young and mature (over-wintered) orange leaves. Leaf T: Leaf temperature, E: leaf transpiration, Gs: stomatal conductance, A: assimilation rate, Cab: chlorophyll content.

Leaf type	Leaf T (°C)	E (mol m^{-2} s^{-1})	Gs (mmol m^{-2} s^{-1})	A (mmol m^{-2} s^{-1})	Cab (μg cm^{-2})
Young	38.7	4.33	126	7.42	28
Mature	39.7	1.53	28	3.02	61

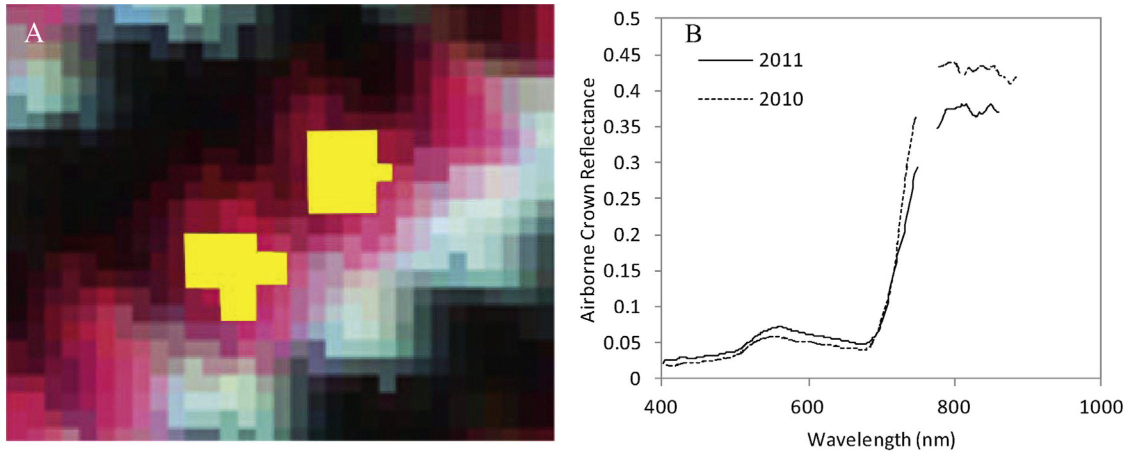

Fig. 4. (A) Detail of the imagery acquired with the hyperspectral camera, showing the identification of targeted tree crowns. (B) Tree crown reflectance extracted from the same well watered orange tree in 2010 and 2011, showing spectral differences between the two years.

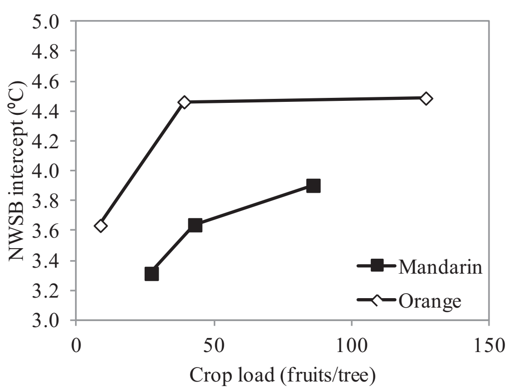

Fig. 5. Relationship between the NWSB intercept and the crop yield (fruit tree^{-1}) for orange and mandarin well-watered trees. Each point represents one year and corresponds to the averaged value of the two monitored trees.

the crop load, the higher the intercept, each value presumably corresponding to a lower level of vegetative growth. Even though there are only six data points in Fig. 5, the trend shown is consistent with the proposed hypothesis.

3.4. Seasonal evolution of T_c–T_a

The seasonal course of T_c–T_a showed differences between C and stressed (RDI1) trees, being these differences generally greater as the stress level increased during the season. Fig. 6 shows the time course of T_c–T_a measured at noon for mandarin and orange trees in 2009 (Fig. 6A and D), 2010 (Fig. 6B and E) and 2011 (Fig. 6C and F). Except for mandarin in 2011 (Fig. 6B), control trees maintained rather stable values, while T_c–T_a in stressed trees increased during the experiment. Maximum differences between control and stressed trees ranged between 1.5 and 2.5 °C. In 2011, stressed trees were rewatered following the achievement of severe water stress levels. Recovery was performed on DOY 180 for the orange plots and in DOY 190 for the mandarin plots. Once the water status of the trees was recovered to normal levels, the irrigation treatments resumed.

The relationship between T_c–T_a and the SWP measured both at noon showed a correlation when data were pooled together, with an R^2 of 0.56 and 0.55 for mandarin and orange, respectively (Fig. 7).

3.5. Assessment of CWSI

Given the differences on T_c–T_a observed in 2010, these datasets were discarded from the calculation of the CWSI. The NWSBs built with data from 2009 and 2011 (Table 1) were used as a lower limit to compute the CWSI (Fig. 8). The CWSI for control trees was consistently close to 0, except for the experiment of mandarin in 2011; a failure in the system stopped the irrigation for about two weeks and, as a consequence, the CWSI sharply increased. Once the irrigation was resumed, it attained normal values close to 0. In 2009, the stressed trees in both species showed a mean value of about 0.2 at the beginning of the experiment and increased during the stress period until it reached a maximum value of 0.85 (Fig. 8A and C). In 2011, both species showed a peak between DOY 180 and 190 with a maximum value near 0.8. Given the high level of water stress experienced, irrigation was increased in this treatment and that caused the CWSI values to approach 0. A second period of water deficits was imposed, and CWSI increased again to a maximum value of 0.8 (Fig. 8B and D). In 2011, the RDI1mandarin and orange trees were rewatered at the end of the August and mean CWSI values decreased to values similar to control trees.

The suitability of CWSI for assessing water status in both citrus species can be observed in its relationship with SWP (Fig. 9), where data from the two years were pooled together. CWSI showed good agreement ($p < 0.05$) with SWP, with R^2 yielding 0.66 and 0.59 for mandarin and orange, respectively. These R^2 values were similar for the orange trees and higher for mandarin than those obtained for the relationships between T_c–T_a and SWP (Fig. 5). For both species, the data followed an exponential relationship. A single relationship was observed for the two treatments, C and RDI1. For CWSI below 0.3 and 0.4 for mandarin and orange respectively, SWP maintained a constant value of about −1 MPa. Beyond these thresholds of CWSI, the SWP sharply decreased.

Once the NWSB had been established, a map of CWSI was derived from the airborne thermal imagery acquired on DOY 217, 2009, showing the spatial distribution of water status for every tree of the field (Fig. 10). It can be clearly observed that CWSI was related to the level of applied water, following the treatment distribution. In fact, while the average CWSI of the control plots was 0.35, the average CWSI of the RDI1 plots reached 0.66, despite the large variability encountered in the field. The RDI1 plots that were located uphill (northern part of the experimental field) were more stressed as compared to those plots located downhill.

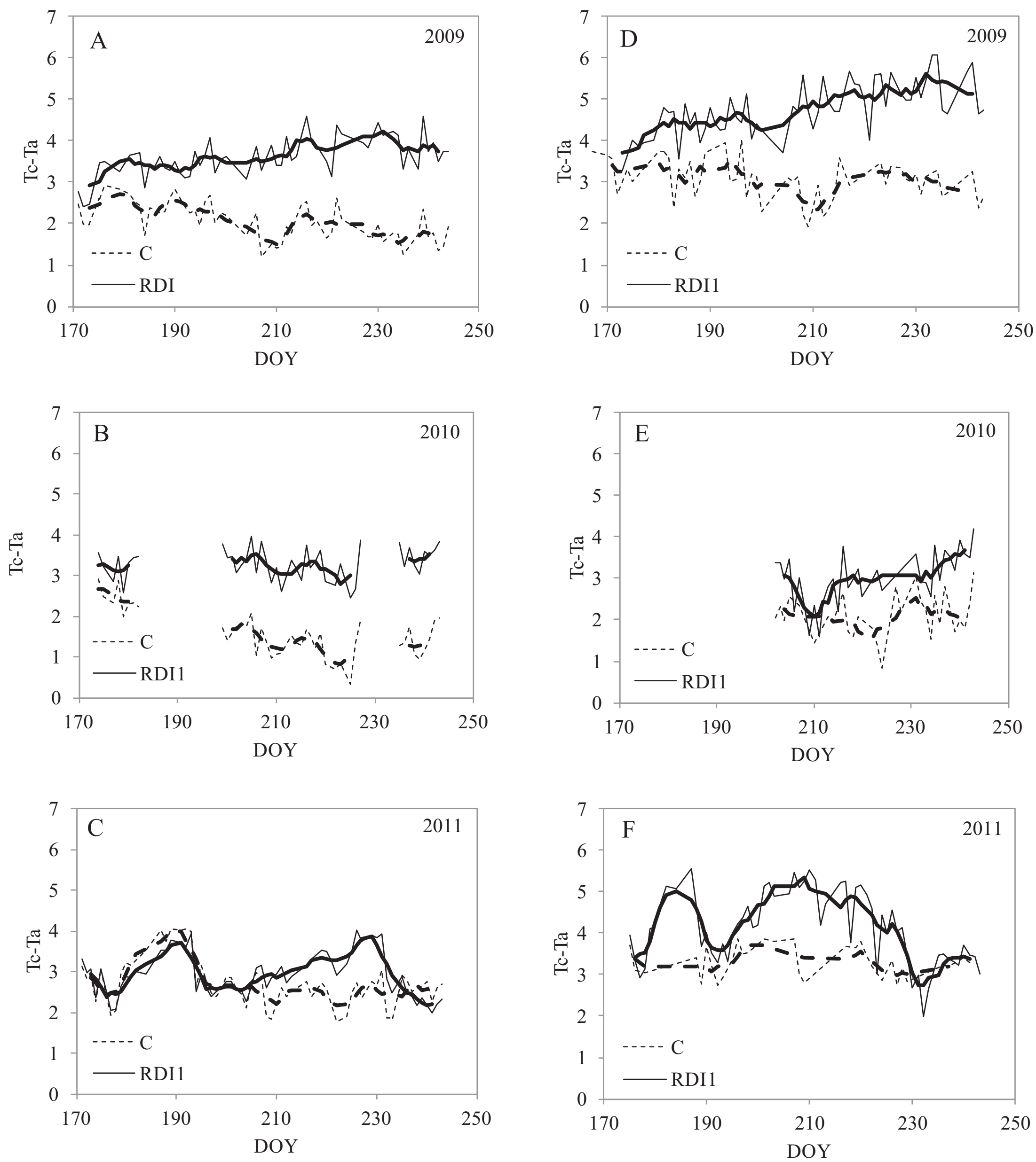

Fig. 6. Time evolution of the difference between canopy and air temperature (T_c–T_a, °C) for mandarin (Fig. 4A–C) and orange (Fig. 4D–F) for 2009, 2010 and 2011 measured at noon. The bold lines correspond to the five-day moving average for each treatment, C (dashed line) and RDI1 (solid line).

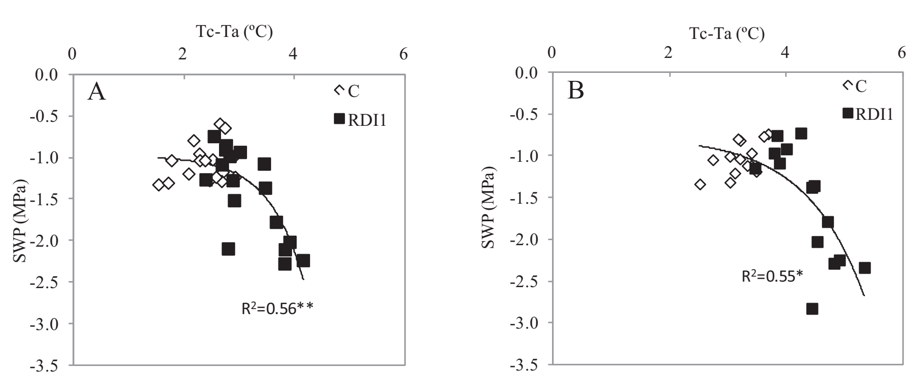

Fig. 7. Relationships between stem water potential (SWP; MPa) and T_c–T_a (°C) for mandarin (Fig. 5A) and orange plots (Fig. 5B). Data from 2009 and 2011 were pooled together. A negative exponential regression line was adjusted in both species. The correlation coefficient is shown in the graph. The level of significance is shown as: *($p < 0.01$), **($p < 0.001$).

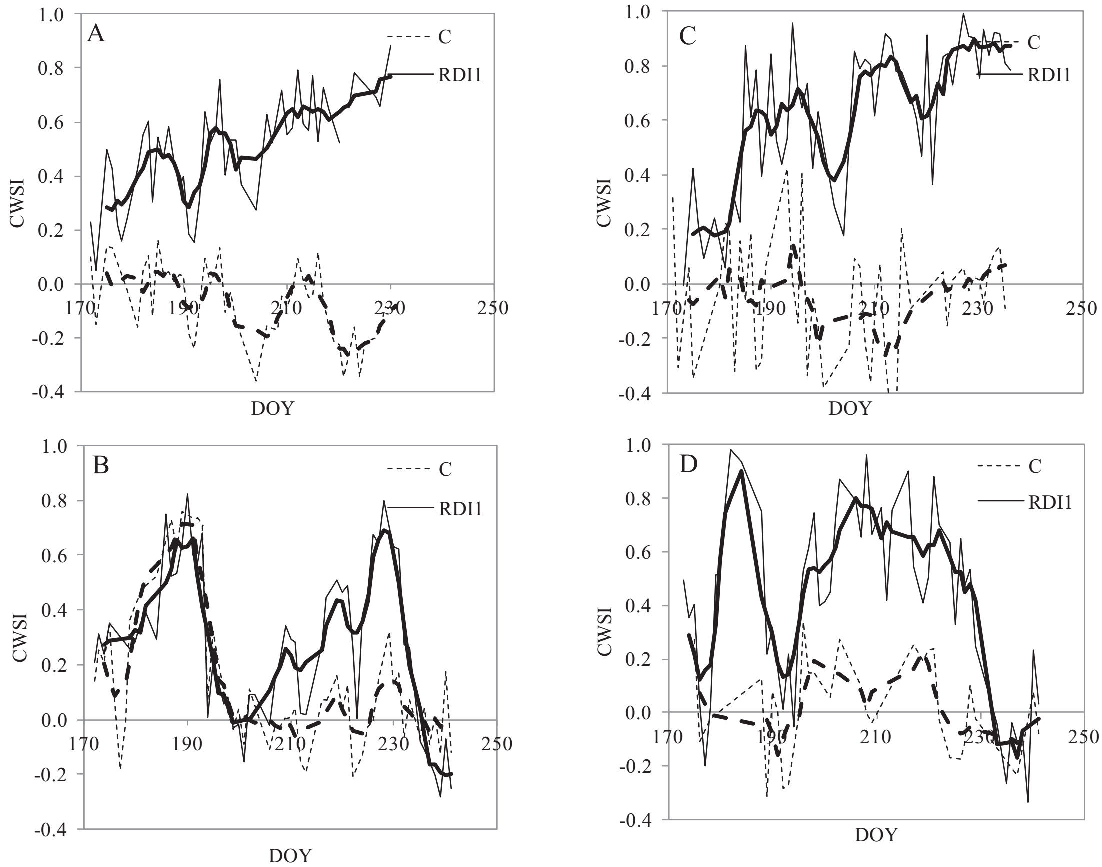

Fig. 8. Time evolution of the CWSI for mandarin (A and B) and orange (C and D) for 2009 and 2011. The bold lines correspond with five-day moving average for treatment C (dashed lines) and RDI1 (solid lines).

4. Discussion

This paper demonstrated that CWSI is a suitable indicator for the assessment of water status in citrus, although there are some specific features that deserve special attention, when compared to its use in annual crops (Moran, 1994) or in other orchard trees (e.g., Testi et al., 2008). Robust upper and lower limits are needed to characterize the CWSI with precision (Jackson, 1982). Even though the linear regressions representing the NWSB (Fig. 3) were always significant ($p < 0.05$), the data had more scattering than that of other tree crops where the NWSB had been assessed, such as pistachio (Testi et al., 2008) and sweet lime (Sepaskhah and Kashefipour, 1994). This is probably due to the fluctuations in canopy temperature shown in Fig. 1 that requires careful assessment of the time interval to estimate an average canopy temperature in relation to the air temperatures, as it was described in Fig. 2. Fluctuations in stomatal resistance in citrus have been described long ago (Levy and Kaufmann, 1976) and more recently, fluctuations in citrus canopy conductance have been described as well (Dzikiti et al., 2007). These special features may be at the origin of the difficulties encountered in the past to assess CWSI in citrus (e.g., Ballester et al., 2013a). We have also demonstrated that no unique NWSB can be ascribed to

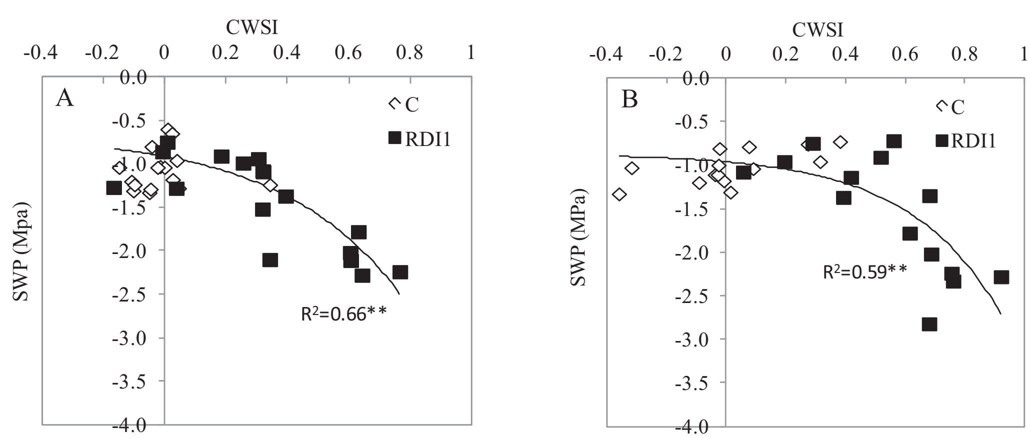

Fig. 9. Relationship between stem water potential (SWP; MPa) and CWSI for mandarin (Fig. 7A) and orange (Fig. 7B). Data from 2009 and 2011 were pooled together. A negative exponential regression line was adjusted in both species. The correlation coefficient is shown in the graph. The level of significance is shown as in Fig. 7.

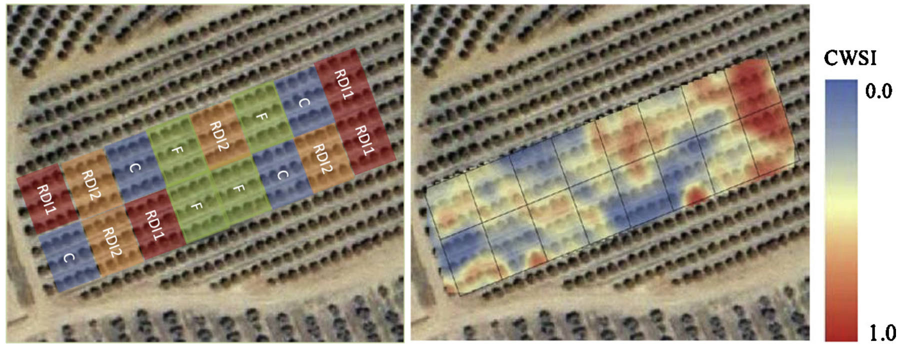

Fig. 10. Diagram of the experimental design of the orange experiment and its corresponding calculated CWSI map obtained at 35 cm resolution.

the citrus species, as the line for mandarin was different from that of orange (Fig. 3). The variability in the response to water deficits among citrus species was clearly depicted in the early review of Kriedemann and Barrs (1981) and more recently, research dealing with the optimization of deficit irrigation strategies has described the contrasting behavior of mandarin (cv. Clementina de Nules) and orange (cv. Navel Lane Late) in response to RDI strategies (Ballester et al., 2011, 2013b). Finally, we have also found that crop load has an influence on the NWSB (Fig. 7), although it appears that it is the absence of fruits that have the most effect on the intercept of the NWSB (Fig. 7). This may be a general phenomenon in other species, given the source–sink interactions in fruit trees and their effects on stomatal and canopy conductances (DeJong, 1986; Reyes et al., 2006), and therefore on canopy temperature.

CWSI would be considered for irrigation management purposes, as changes in the crop water status were translated into a proportional shift of the index (Fig. 9). When CWSI is compared to T_c–T_a as a proxy of water status (by comparing the R^2 and p value of the relationship of both indices to SWP, Figs. 5 and 9), it can be observed that CWSI represents more accurately the crop water status, especially for mandarin. Compared to T_c–T_a, the performance of the CWSI is improved by the consideration of the evaporative demand, as well as the species-specific response of water relations to VPD.

The NWSB of citrus found here is similar to that reported for olive (Berni et al., 2009), a tree crop well adapted to Mediterranean-type climatic conditions. In both species, T_c is generally higher than T_a for the usual values of VPD and their NWSB display a steeper slope compared with other tree crops, such as pistachio (Testi et al., 2008). As far as we know, the only NWSB that has been published in citrus was that presented by Sepaskhah and Kashefipour (1994) in sweet lime. Canopy temperature was measured with a hand-held infrared thermometer 2 m away from the tree, around 15° above the horizontal, a procedure that would not assess the T_c of the top of the canopy. This may be the reason why the values obtained by them were considerably different from what we have observed. In their case, T_c was lower than T_a for well watered conditions, resulting in negative values of T_c–T_a for a wide range of VPD. In our case, these values were always positive. Moreover, the same authors demonstrated that water use of sweet lime is quite different from other citrus (Sepaskhah and Kashefipour, 1995); it could also explain the differences encountered in the two studies. Other studies report that transpiration in citrus is less than that of other fruit tree species during summer, also under well watered conditions (Villalobos et al., 2013). The low transpiration rate agrees with a partial stomatal closure that results in an increase of canopy temperature. This characteristic of citrus grove is well known and has been characterized in the past (Veste et al., 2000; Villalobos et al., 2009).

The different behavior observed in T_c–T_a during 2010 as compared to the other two years was attributed above to the lack of fruit production in that year. The occurrence of vegetative flush growth that is enhanced in off-years (Lenz, 1967) could be at the origin of this behavior. In citrus, these flushes of growth take place from two to four times, depending on cultivar and climate (Monselise and Goldschmidt, 1982), and occur in spring, summer and autumn. We have shown (Table 2) that recently-formed leaves displayed a contrasted gas exchange as compared to over-wintered or older leaves. Syvertsen et al. (1981) found that the transpiration rate of summer leaves were 25% higher compared to spring leaves. Stuckens et al. (2011) obtained similar results in a study where canopy temperature was monitored during three seasons. The new shoots are mainly located in the upper part of the canopy, well within the field of view of the IRT sensors positioned above the tree crowns in a zenital view. In addition to our observations of Table 2, two different datasets supported the hypothesis that the summer new growth would have an effect on the crown temperature measured by the IRT sensors. The information acquired with the hyperspectral imager that was flown over the orchard in September 2010 and 2011 showed that the top of the crowns had a lower amount of chlorophyll in the low-crop year (2010) as compared to a normal year. We hypothesized that this difference was related to the newly formed leaves that had lower chlorophyll content than the older leaves. A possible effect of nutrient status on chlorophyll content would be discarded, as fertilizer application was managed similarly among years and treatments, and was never limiting. Furthermore, no pest or disease was detected during the experiment that would damage the canopy. The relationship between crop load and the intercept of the NWSB for each year also pointed out to a more extended vegetative growth in 2010. The lower the crop load, the higher the vegetative growth, and according to the results obtained here and elsewhere (Syvertsen et al., 1981) the higher the stomatal conductance. Spiegel-Roy and Goldschmidt, 1996 stated that stomatal regulation of water loss in the young leaves of citrus is not well developed. The effect of growth habit on the assessment of crop water status based on thermal information appears important for the quantification of indices such as the CWSI in citrus. Research is needed to investigate whether this effect may affect other evergreen species.

One of the shortcomings for the use of the CWSI in years that would have substantial vegetative growth in the summer due to a very low crop load is the lack of representativeness of control trees needed to develop the NWSB. Contrary to the case of olive, modern citrus cultivars have relatively low alternate bearing behavior and the situation we observe in 2010 of very low crop load is not common. Therefore, the CWSI approach is valid as an indicator of tree water deficits, given its correlation with established methods of measuring tree water status. Further research is needed to develop a methodology that integrates leaf age and enables the monitoring of the water status when vegetative flushes occur.

Knowledge of the natural variability generally observed in field (which is related to either soil and/or plant heterogeneity or to the lack of uniformity in irrigation water distribution) is essential for the correct application of deficit irrigation (DI). The commercial development of DI strategies requires the tree water status to be maintained within a narrow range in order to save water without reducing yield. In this context, high-resolution thermal imagery proposed in this work would be an ideal tool, as it enables the monitoring of large areas with the precision required to accurately manage DI. The robustness of this approach has already been demonstrated in several fruit tree species (Berni et al., 2009; Meron et al., 2010; Gonzalez-Dugo et al., 2013). The remote assessment of water status at the tree level for whole fields enables the economic analysis and risk evaluation of water application under different strategies (Gonzalez-Dugo et al., 2014). The large range of variability under plots that were similarly managed can be derived from the thermal image obtained over this experiment. This information could be used to monitor irrigation by a periodic assessment of field water status (regular flights), by establishing control points that characterize the variability of the orchard or, in high-value crops, by assessing the most sensitive area in order to monitor those trees displaying the lowest water status.

5. Conclusions

It can be concluded that CWSI is a suitable indicator for water status monitoring in citrus during summertime in semi-arid conditions, and also for manage irrigation in precision agriculture. Nevertheless, some specific considerations must be taken into account if the CWSI is to be used in citrus, namely, the short-term oscillations of canopy temperature and the vegetative flushes. The effect of the short-term oscillations could be avoided by adapting the interval considered for averaging thermal data to the oscillations. The flushes of new growth that occur mainly in spring and summer alter the water relation of the top view canopy and shift the NWSB. The main shortcoming is the inability of well-irrigated trees to serve as a control, as the development of these flushes would differ among trees with a contrasted water status. Further research will characterize this behavior and will propose adaptations to take leaf age into account.

In this work, the NWSB was obtained from point IRT sensors and the methods scaled up to high resolution aerial thermal imagery to obtain CWSI maps at 35 cm resolution. The utilities of such tool increases, as the water status of a whole field can be assessed and thus, studies related with spatial variability can be tackled.

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