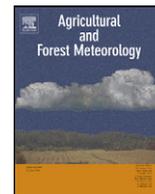




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Almond tree canopy temperature reveals intra-crown variability that is water stress-dependent

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ABSTRACT

Tree water status is often characterized by measuring a few leaves and it is not known to what extent such measurements represent the tree as a whole. We present an assessment of the intra-crown temperature variability and its relationship with water status in two almond cultivars. High-resolution imagery was acquired on 30 June 2009 at 11:30, 14:30, and 16:30 h (solar time) with a thermal camera on-board an aircraft over an almond orchard in Kern County, CA, USA. Ten irrigation levels were applied, ensuring a wide variability in water status, and each was replicated eight times. Stem water potential and stomatal conductance were measured on trees of various irrigation regimes at each flight. Significant variation in canopy temperature was found within each crown, probably reflecting differences in stomatal conductance in different parts of the tree crown. The intra-crown standard deviation of canopy temperature (intra-crown σT_c) increased from fully irrigated trees to intermediate irrigation levels, diminishing afterwards in the most stressed treatments. Mean canopy temperature was well correlated with stomatal conductance and stem water potential (R^2 above 0.65). In trees that had similar mean canopy temperature, intra-crown σT_c correlated well with tree water status. Our results quantified in detail the spatial variability in surface temperatures that exists within almond tree crowns and suggest that the intra-crown temperature variation may be a useful indicator of the onset of tree water stress.

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1. Introduction

Competition with other sectors of society is decreasing agricultural water supplies and/or increasing their costs which will undoubtedly result in growers facing periods of water scarcity in the future. To ensure that agricultural water is used most effectively, improved approaches to irrigation scheduling are needed and these will likely involve direct or indirect measurements of plant water status and their interpretation.

Most of the measurements that are currently used to characterize tree water relations are generally made at the leaf level. Leaf water potential, stomatal conductance and net photosynthesis are some examples of these measurements. Even though most of the current knowledge has been acquired by measurements at the leaf level, the scaling up to canopy level is necessary for field management. However, a large amount of time-consuming replication is required to adequately characterize even a single tree, for example, and description of an entire orchard is much more complex. The current state of the art in plant-based stress measurement at

the level of individual trees is the stem water potential (Ψ_x , Shackel et al., 1997). Since stem water potential measurements are manually taken, only a few leaves per tree are sampled and a very small percentage of the trees in a field can be monitored. Thus, it is nearly impossible with manual measurements to adequately characterize two important features of plant water status: mean values and spatial variability. Remote sensing promises this and stress indicators derived from thermal aerial imagery have been shown to accurately describe the spatial heterogeneity that is naturally found in orchards (Sepulcre-Cantó et al., 2006; Berni et al., 2009a,b). The most commonly used indicator – canopy temperature – is inversely related to transpiration and stomatal conductance (Jackson et al., 1981; Jones, 1999a,b; Sepulcre-Cantó et al., 2006; Berni et al., 2009a,b). Water stress induces stomatal closure, and hence, reduces evaporative cooling and increases leaf temperature.

The advantages of using thermal information for water stress monitoring were identified by a series of experiments on herbaceous crops conducted in the late 1970s by Jackson and co-workers (Idso et al., 1978; Jackson et al., 1981). Working with hand-held infrared thermometers, they developed the concept of the Crop Water Stress Index (CWSI), which became a popular thermally-based stress indicator. The CWSI is based on the normalization of the differences between canopy (T_c) and air temperatures (T_a) with

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evaporative demand (by means of vapor pressure deficit). However, adoption and use of the CWSI was limited, in part, due to the inability of manual, hand-held infrared thermometer measurements to adequately characterize entire fields and to the high variability of the measurements presumably due to the interference of surfaces other than vegetation in the measurements (Moran et al., 1994). The interference of non-vegetative surfaces in the T_c measurement, particularly important with perennial crops which cover less than 100% of the ground, has been addressed when using aerial images with various data-processing techniques that eliminate soil and other non-transpiring surfaces from the analysis (Leinonen and Jones, 2004).

Thermal imaging may reveal spatial heterogeneity within or between plant canopies, and can be acquired repeatedly over the same areas to monitor responses over time (Grant et al., 2007). Heterogeneity in T_c itself has long been proposed as an indicator of water stress (Gardner et al., 1981; Fuchs, 1990; Gonzalez-Dugo et al., 2006). In annual crops, it has been found that the canopy temperature variability is generally very low in well-watered plants and increases with increasing level of water stress (Gardner et al., 1981; Clawson and Blad, 1982). As the soil moisture reservoir nears full depletion and water stress becomes more severe, variability decreases (Gardner et al., 1981; Clawson and Blad, 1982; Gonzalez-Dugo et al., 2006). The analysis of the variability of T_c has not been extended to discontinuous canopies, such as those of tree crops, given the resolution needed to get accurate measurements of pure vegetation temperature (Leinonen and Jones, 2004; Moller et al., 2007). Limited studies in vineyards found no impact of different irrigation levels on thermal variability within individual canopies (Grant et al., 2007; Moller et al., 2007).

When analyzing canopy temperature measurements and their relationship with water status, one must recognize that variations in T_c can be due to many factors. At the individual tree level, differences in liquid-phase resistance to flow between the trunk base and the various parts of the top of the canopy determine variations in water supply that can influence stomatal conductance and T_c . Variability in current and previous radiation exposure can also generate T_c differences between various parts of the tree crown. Furthermore, changes in leaf angle distribution, leaf area density, and canopy architecture may affect T_c as well (Fuchs, 1990; Norman and Becker, 1995; Leinonen and Jones, 2004). Factors other than soil water deficits that may affect T_c also include nutrition, and the presence of insects/diseases (van de Vrie et al., 1972; Rodriguez et al., 2005; Lucena et al., 2009). Being able to not only characterize T_c spatial variability but to distinguish between its sources is of paramount importance to understand tree response and to use thermal imagery in on-farm water management.

Land in California's western San Joaquin Valley is rapidly being converted from relatively low value field and row crops, such as cotton, to higher value tree crops, such as almond and pistachio, due to higher profit margins. Almond is the largest tree nut crop produced in California (California Department of Food and Agriculture Highlights, 2010). Seasonal mature almond orchard evapotranspiration (ET_c) is at least 50% greater than cotton (Hake, 1996; Micke, 1996). Different strategies are being implemented in order to reduce water use by orchard crops, including regulated deficit irrigation (RDI, Goldhamer et al., 2006). Although almond is considered drought tolerant (Castel and Fereres, 1982; Fereres and Goldhamer, 1990), the physiology of the crop under water stress conditions must be well-known to develop deficit irrigation strategies that avoid reductions in yield and/or in nut quality (Girona et al., 1993; Goldhamer and Viveros, 2000).

The goal of this study was to determine the potential for using high-resolution thermal imagery acquired from an airborne platform over an almond orchard for water stress detection. The specific objectives of this work were aimed at: (i) the assessment of crown

temperature and its variability on almonds trees with increasing levels of water stress acquired with a high-resolution airborne thermal camera; (ii) the analysis of the diurnal evolution of crown temperature variability; and (iii) the relationships of canopy thermal features with tree water status.

2. Materials and methods

The work was conducted in a mature (1999 planting), commercial orchard (6.4 m × 7.3 m spacing) of almond (*Prunus dulcis* (Mill.) Webb, cvs. Non Pareil and Monterey), near Lost Hills in western Kern County, California (35°30'N, 119°41'W). The soil is a clay loam (Typic Torriorthens) with a rooting depth of about 2 m. The two cultivars were planted in alternate adjacent rows (one-to-one planting regime). An experiment was initiated in this orchard in 2006 that applied 10 irrigation levels (treatments, named from T1 to T10, ascending magnitude of irrigation levels), each replicated eight times (Fig. 1). The irrigation rates, which varied sequentially by about 4% between treatments, were originally chosen to ensure that the highest water application rate exceeded the maximum evapotranspiration (ET_c) of a mature orchard. Individual plots consisted of two rows (one of each cultivar) of five trees. There were one or two border trees adjacent to the ends of these five tree sets in each row. The within-tree-row microsprinkler irrigation system was modified by changing emission heads and adding drippers to accomplish the 10 irrigation rates, which were imposed only before harvest. The irrigation frequency (24 h operation one to three times per week depending on estimated, ET_c) was the same for all treatments as were the wetted surface areas.

2.1. Airborne imagery

A thermal camera (MIRACLE 640, Thermoteknix Systems Ltd, Cambridge, UK) was installed on an airborne platform, as described by Berni et al. (2009b) and flown over the experimental site on 30 June 2009 at 150 m above the ground level at three different times: 11:30, 14:30 and 16:30 (solar time). The camera had a resolution of 640 × 480 pixels with a field of view of 45° that delivered an approximate ground resolution (pixel size) of 12 cm. The images were stored on board in raw format with 16 bit radiometric resolution and were processed and atmospherically corrected following the method described by Berni et al. (2009b).

2.2. Field measurements

During each flight, water potential (Ψ_x) and stomatal conductance (g_s) were measured with the goal of comparing the aerial (thermal) and ground-based (Ψ_x and g_s) stress indicators on as many trees as possible. We assembled a team of eight pressure chambers (Model 3005, Soilmoisture Equipment Co., Santa Barbara, CA) and operators. In order to have the pressure chamber measurements coincide closely with the timing of the thermal assessment, we limited the number of measurements taken by each pressure chamber operator to that which could be comfortably taken within 1 h period. This resulted in 30 measurements per operator per flight; a total of 240 measurements per flight. The limitations on the number of Ψ_x measurements possible resulted in choosing five (of the existing 10) irrigation treatments to monitor—T1, T3, T5, T7 and T9; three trees per replicate in eight replications per treatment (total of 240 trees). A single, shaded leaf from the interior of the canopy was measured on each monitored tree using the procedure outlined by Goldhamer and Fereres (2001) who found that shaded leaf water potential in almond was well correlated with stem water potential ($R^2 = 0.94$).

Since there can be significant Ψ_x measurement differences even with operators given the same training (Goldhamer and Fereres,

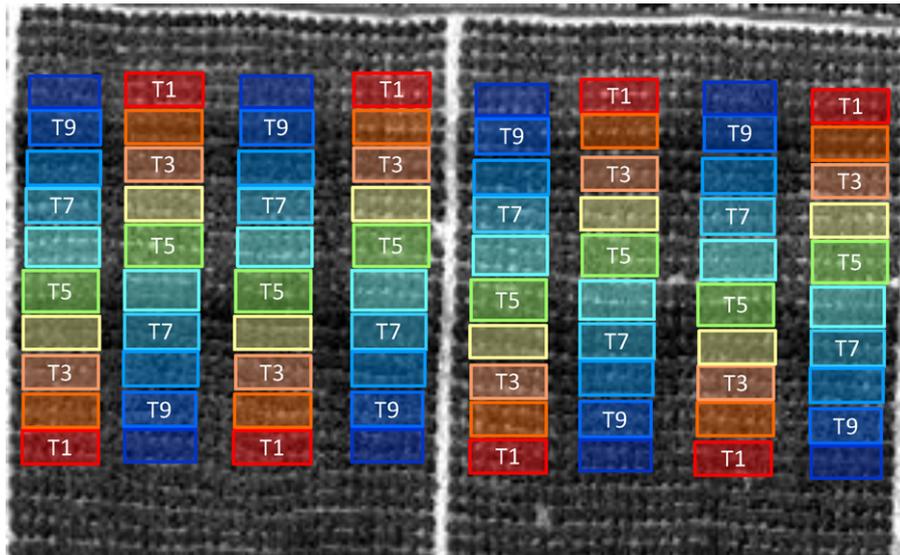


Fig. 1. Overview of the study site, showing the eight replicates of the treatments T1, T3, T5, T7 and T9 (named in ascending magnitude of irrigation level) considered in this work.

2001), we developed a normalization technique to minimize operator error. Immediately after the last flight, we had each pressure chamber operator take three measurements on selected single trees in each of the five monitored treatments (T1, T3, T5, T7, and T9); a total of 15 measurements for each operator. We then regressed mean treatment values for each operator with the mean values taken by the two most experienced and reliable operators. The resulting linear expressions were used to convert each Ψ_x measurement of each operator taken during the three flights to normalized values.

While Ψ_x was measured on three trees per plot on every replicate of treatments T1, T3, T5, T7 and T9, g_s was measured with a leaf porometer (SC-1, Decagon Devices, Pullman, WA, USA) on two trees on a single replicate of treatments T1, T3, T5 and T9.

A portable weather station (Model WXT510, Vaisala, Finland) located next to the experimental orchard was used to measure T_a and relative humidity (RH), which were used to calculate the atmospheric vapor pressure deficit (VPD).

2.3. Data analysis

The analysis of the temperature variability (measured as the standard deviation, σ) was made at two different levels, within each tree crown and between crowns of the same treatment, hereafter referred as intra- and inter-crown. Due to the high resolution of the images, we were able to exclude crown edges to insure that only pure vegetation pixels were used to characterize each tree.

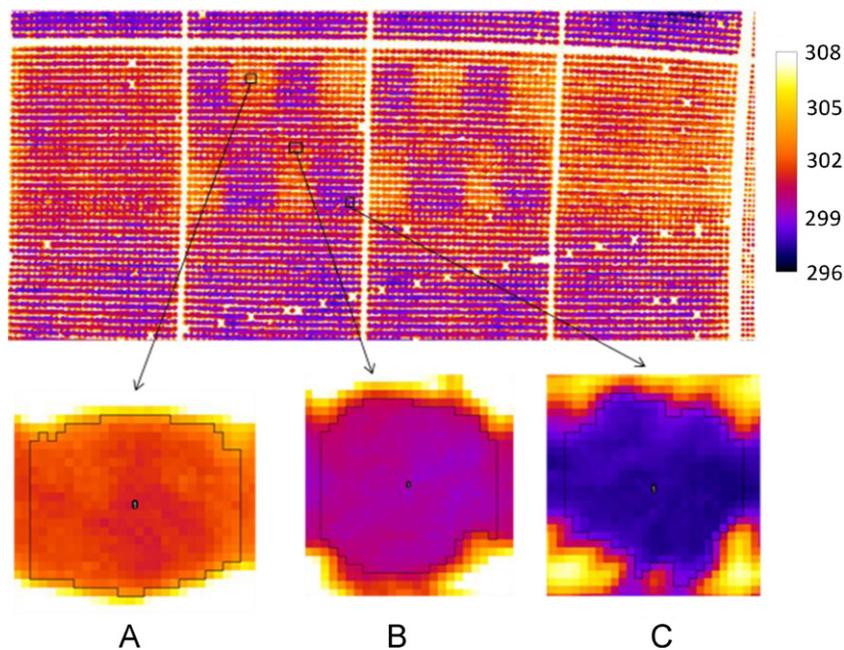


Fig. 2. Thermal mosaic of the field site and images for three individual trees representative of severe (A), mild water stress (B), and of full irrigation (C). Temperatures expressed in K on the upper right hand side.

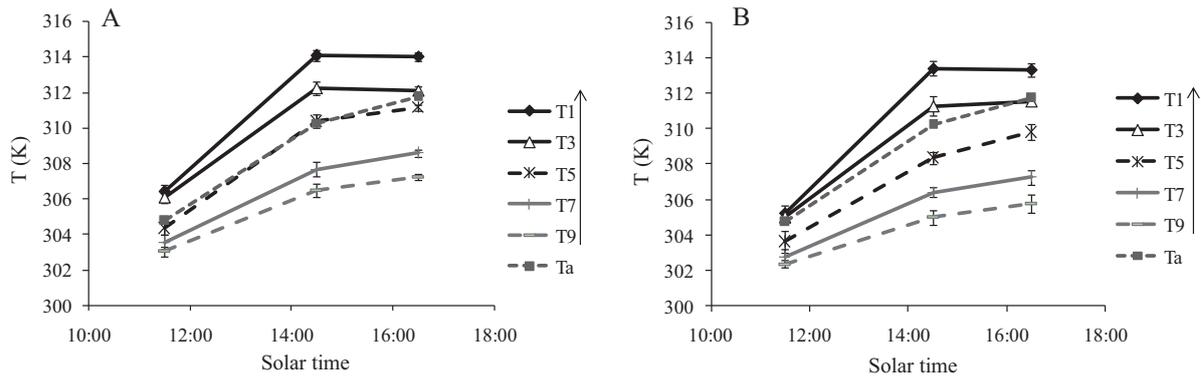


Fig. 3. Time course of T_c and T_a (in K) for cv. Non Pareil (A) and cv. Monterey (B). Vertical bars indicate \pm one standard error ($n=8$). Vertical arrow in the legend indicates the increasing level of water stress.

We manually extracted T_c from the 350 and 550 pixels per tree, depending on tree size, from the thermal imagery.

In addition to the mean canopy temperature, σ of individual tree crowns was calculated as in Eq. (1):

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{(N - 1)}} \quad (1)$$

where σ is the standard deviation, N is the number of pure vegetation pixels, x_i is the temperature value for a given pixel (K) and \bar{x} is the mean value for every pixel within the crown (K).

The analysis of shape and measure of the frequency distribution of T_c within individual crowns was performed by means of the indices Skewness and Kurtosis with the SPSS® software (IBM Corporation, Armonk, NY, USA).

3. Results

The T_c extracted from the airborne imagery (Fig. 2) clearly followed the pattern of the irrigation treatments layout described in Fig. 1. Although spatial variability in T_c existed in the orchard, as evidenced by T_c outside of the experimental plots, the different irrigation levels are clearly evident in the airborne images.

The time course of canopy temperature (Fig. 3) showed that T_c differences between treatments increased during the day. In cv. Non Pareil, the intermediate irrigation level (T5) followed T_a during the day. In cv. Monterey, the treatment that followed T_a was T3 which had a lower irrigation rate than T5. The maximum T_c for each treatment was attained at 16:30 for the treatments where T_c was below T_a , while the T_c was the same at 14:30 and 16:30 in the more stressed treatments where T_c was greater than T_a (Fig. 3).

In both cultivars, Ψ_x decreased during the day for every treatment (Fig. 4A and B). The cv. Non Pareil displayed consistently lower Ψ_x values as compared to cv. Monterey. These cultivar differences

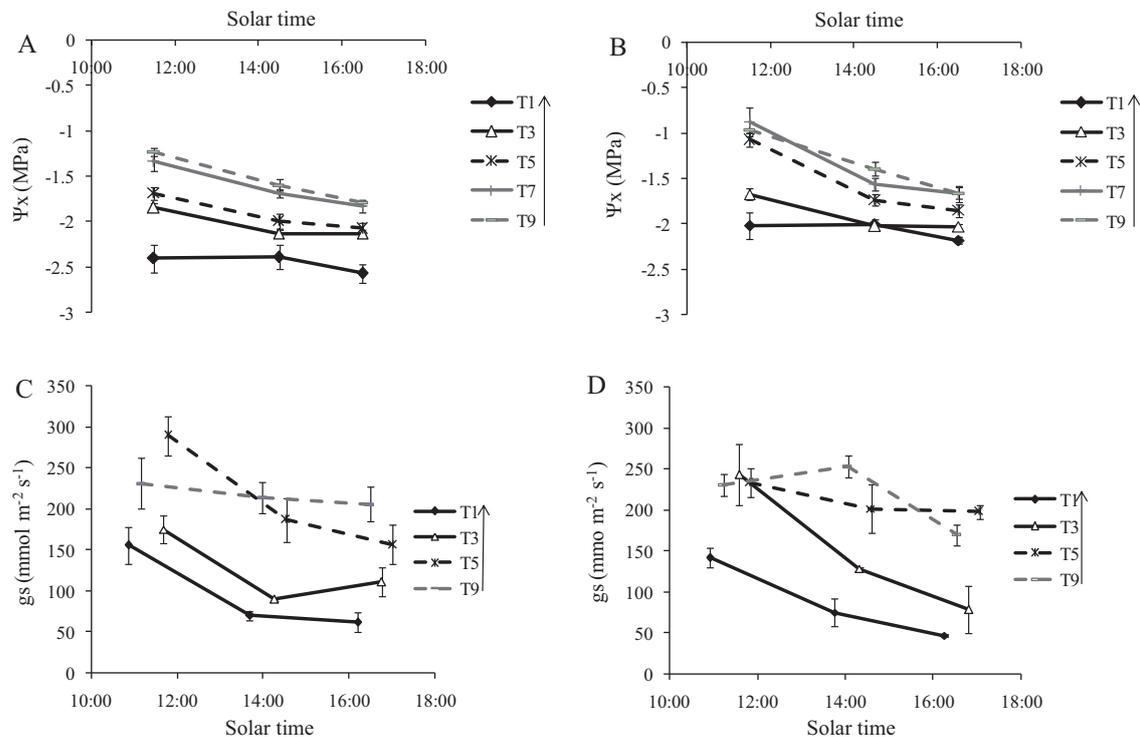


Fig. 4. Time course of midday shaded leaf water potential (A and B) and stomatal conductance (C and D) for cv. Non Pareil (A and C) and cv. Monterey (B and D). Vertical bars are \pm one standard error. Vertical arrow in the legend indicates the increasing level of water stress.

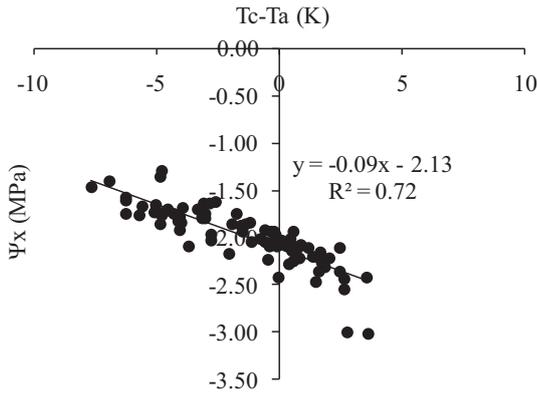


Fig. 5. Relationship between $T_c - T_a$ (K) and water potential (MPa) measured on both cultivars at 16:30 h.

in Ψ_x were not detected in g_s (Fig. 4C and D). The effect of the irrigation regime on the Ψ_x was evident in both cultivars with distinct separation among treatments (Fig. 4A and C). The magnitude of Ψ_x values generally reflected the amount of water deprivation of the irrigation regimes, with some exception for the cv. Monterey (Fig. 4B). The measurements of $T_c - T_a$ were plotted against Ψ_x , which is the established method of assessing tree water status. Fig. 5 shows that both variables correlated well for both cultivars ($R^2 = 0.72$). Stomatal conductance decreased significantly during the central hours of the day, with the exception of T9 that had a value of about $220 \text{ mmol m}^{-2} \text{ s}^{-1}$ at the three sampling times. The mild water stress applied to T5 resulted in a shift of maximum g_s to earlier in the morning, as compared to the well-watered treatment (Fig. 4B and D).

The diurnal evolution of intra-crown σT_c (Fig. 6) showed a maximum value of about 1.2 and 1.3 K, for Non-Pareil and Monterey respectively, at 14:30 for all treatments. At 16:30, intra-crown σT_c decreased in all treatments, as evaporative demand increased. Except for measurements taken at 11:30, the extreme treatments (T1 and T9) displayed the lowest σT_c values, while they were highest for the intermediate treatments. The relationship between intra-crown σT_c and $T_c - T_a$ measured at 14:30 is displayed in Fig. 7. In both cultivars, the intra-crown σT_c increased for intermediate irrigation levels, and then decreased for the most stressed treatments. Monterey displayed higher values of σT_c compared to Non Pareil for the well-watered treatments (T7 and T9). The maximum σT_c value was found for T3 in Non Pareil and for T5 and T7 in Monterey, both being intermediate irrigation treatments.

In Fig. 8, representative samples of temperature distribution within individual crowns of trees of T9, T5 and T1 are shown. The highest variability in T_c was found in T5 (Fig. 8E and F). Again, when the 3 h are compared, σT_c reached the highest value at 14:30

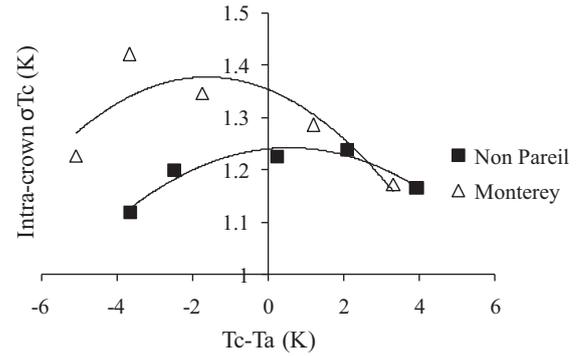


Fig. 7. Relationship between $T_c - T_a$ (K) and intra-crown σT_c (K), measured at 14:30 for cvs. Monterey and Non Pareil.

(Fig. 8B, F and H). The pattern of the temperature distribution within individual crowns seemed to differ depending on the irrigation regime. While the T_c values in the well-irrigated treatment (T9) were symmetrically distributed (according to skewness analysis, Table 1), those in the mild water stress treatment (T5) were not, especially at 14:30 and 16:30 (Fig. 8E and F). They showed a positive skew, with a higher number of pixels concentrated on higher temperatures, while it was closer to a normal distribution in well-watered and severely stressed trees. Moreover, Kurtosis was negative at 11:30 and 16:30, and positive at 14:30 for T5 and T9, indicating that the temperature distribution for these treatments around the mean was flatter than normal distribution at 14:30, and thus displayed a higher dispersion compared to those values found at 11:30 and at 16:30 (Table 1).

The inter-crown variability of canopy temperature (inter-crown σT_c) was smaller compared to the range observed within a crown (Fig. 9). The maximum values were 1 K and 0.8 K for Non-Pareil and Monterey, respectively. The well-watered treatment (T9) exhibited lower values for the three measurement times. As in the intra-crown measurements, in cv. Non Pareil the highest σT_c values were detected for intermediate irrigation levels, while in cv. Monterey, the decrease in inter-crown σT_c for the most stressed levels was only detectable at 16:30 (Fig. 9).

Stomatal conductance showed a gradual decrease concomitant with a decreasing water potential (Fig. 10A) and with an increasing $T_c - T_a$ for both cultivars (Fig. 10B). There were relatively good relationships between $T_c - T_a$ and Ψ_x , yielding R^2 between 0.65 and 0.82 for both cultivars at 14:30 and 16:30, as can be seen in Fig. 11, where both cultivars are shown separately. For cv. Non Pareil (Fig. 11A), the linear relationship found at 14:30 became closer to a second-order polynomial relationship at the time of maximum evaporative demand (at 16:30). The increase in $T_c - T_a$ for the most stressed treatments was smooth compared with the decline in Ψ_x . Monterey

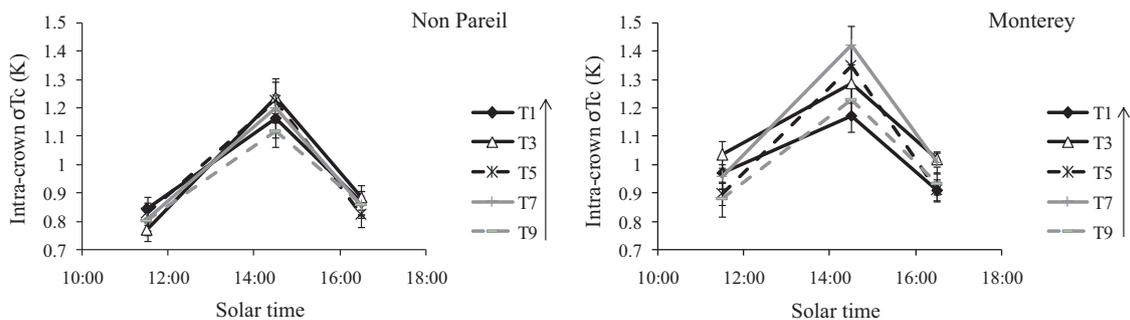


Fig. 6. Intra-crown standard deviation of T_c for cvs. Non Pareil and Monterey. Vertical bars showed the standard error ($n = 8$). Vertical arrow in the legend indicates the increasing level of water stress.

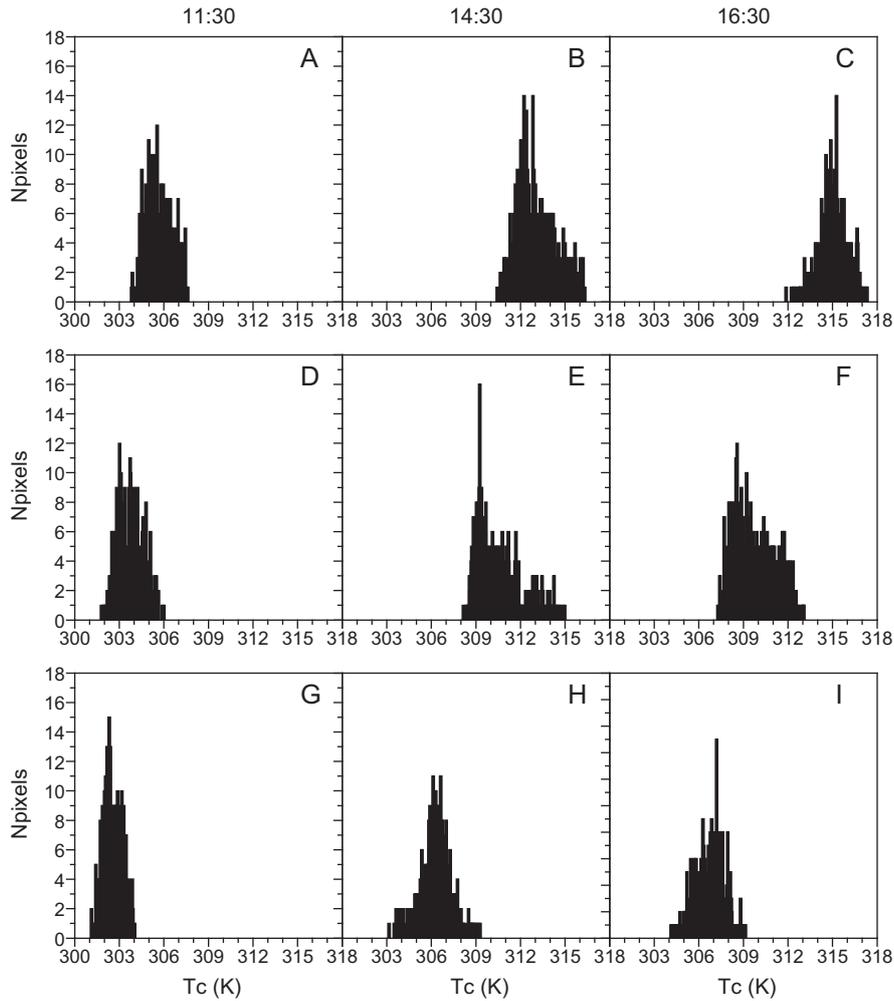


Fig. 8. Representative samples of the temperature distribution within individual crowns of trees subjected to T1 (A–C), T5 (D–F) and T9 (G–I).

showed the opposite for the most stressed treatments measured at 14:30, and fairly similar values of Ψ_x (around -2 MPa) corresponded with an ample range of $T_c - T_a$, from 0 to 5 K (Fig. 11B). Later on, at 16:30, the relationship between Ψ_x and $T_c - T_a$ became linear.

4. Discussion

4.1. Variability of canopy temperature within the crown

The results clearly indicate that crown temperature is a good indicator of water status in almond trees (Fig. 5) and that within

each tree crown, there is substantial variability in canopy temperature. While it is well documented that the canopy minus air temperature differential is a reliable indicator of plant water status (Idso et al., 1981; Jones, 1999a,b), the degree of variability in T_c offers additional options to quantify water stress levels via remote sensing. It is not known if the source of expected T_c variability in orchard trees is different from that in annual crops, where the variability is mainly caused by heterogeneity in soil properties and by lack of irrigation uniformity (Fuchs, 1990; Gonzalez-Dugo et al., 2006). This heterogeneity results in a higher variability in water capture capabilities. In tree orchard, the variability of intra-crown T_c is not well understood, as each tree has a single hydraulic

Table 1

Stem water potential (MPa), mean temperature (K), intra-crown standard deviation of canopy temperature (K) and distribution measures skewness and kurtosis for temperature distribution of trees shown in Fig. 8. Skewness and Kurtosis are mean values \pm its standard error. In treatment column, the corresponding histogram is shown in brackets.

Time	Treatment	SWP (MPa)	Mean T_c (K)	σT_c (K)	Skewness $\pm e_s$	Kurtosis $\pm e_s$
11:30	T1 (8A)	-2.89	305.6	0.87	306.470.300 \pm 0.117	-0.824 \pm 0.233
	T5 (8D)	-1.66	303.7	0.85	0.229 \pm 0.119	-0.626 \pm 0.237
	T9 (8G)	-1.15	302.5	0.61	0.138 \pm 0.116	-0.685 \pm 0.232
14:30	T1 (8B)	-2.89	313.1	1.25	0.558 \pm 0.099	-0.287 \pm 0.198
	T5 (8E)	-2.44	310.4	1.44	1.010 \pm 0.114	0.448 \pm 0.227
	T9 (8H)	-1.28	306.2	1.02	-0.065 \pm 0.120	0.830 \pm 0.239
16:30	T1 (8C)	-3.02	315.1	0.92	-0.197 \pm 0.116	0.263 \pm 0.232
	T5 (8F)	-2.43	309.7	1.34	0.421 \pm 0.096	-0.870 \pm 0.192
	T9 (8I)	-1.66	306.7	0.94	-0.219 \pm 0.117	-0.307 \pm 0.234

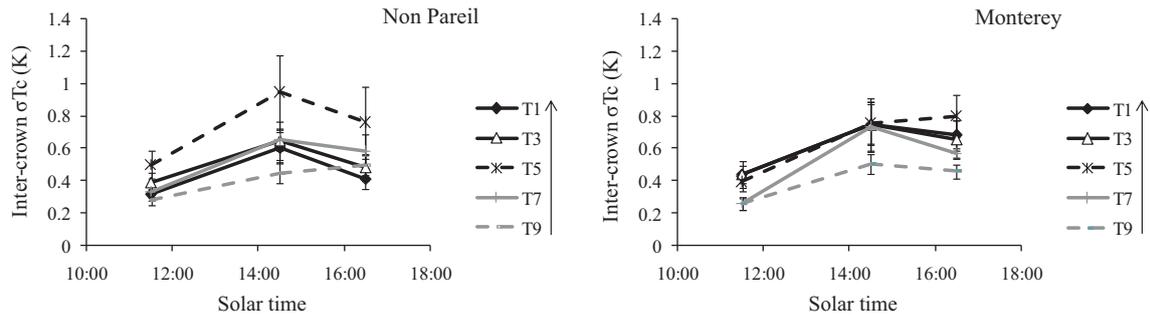


Fig. 9. Inter-crown standard deviation for cvs. Non Pareil and Monterey. Vertical bars showed the standard error ($n=8$). Vertical arrow in the legend indicates the increasing level of water stress.

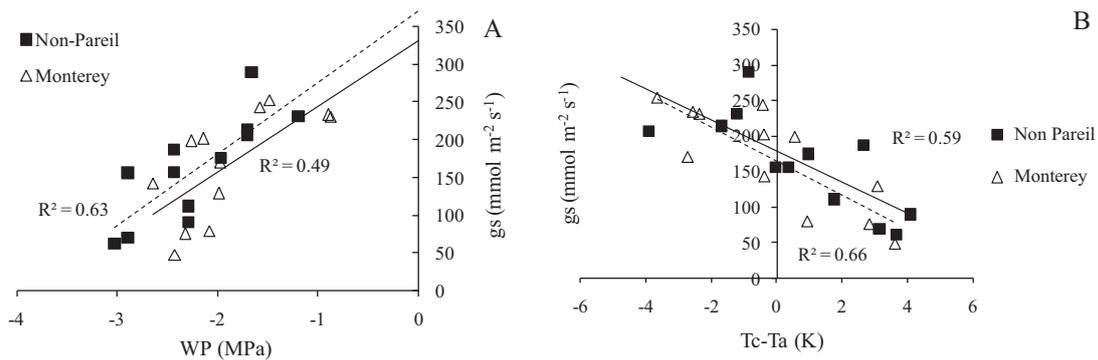


Fig. 10. Relationships between stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$) and water potential (MPa) (A); and, $T_c - T_a$ (K) (B) for cvs. Non Pareil and Monterey. Dashed and solid lines correspond to the adjusted regression to Non Pareil and Monterey, respectively.

architecture acquiring water from the root system that is transported to the leaves. Leaves are randomly distributed within tree crowns so that the shade history of individual leaves differs among them (Fereres et al., 2003) and, some time after being illuminated, some leaves will experience stomatal closure, while others, which have just been exposed, will have their stomata fully open. Simulating a cotton canopy with a spherical leaf angle distribution, Fuchs (1990) demonstrated that while water stress raises the temperature of the foliage, it also widens the range of temperature variation within the canopy. This increase in range was associated with leaf orientation, which plays an important role in the leaf energy budget, especially when stomatal aperture is small. In accordance with this result, we can expect a decrease in canopy temperature variability when leaves are non-randomly distributed, as in some vines. Indeed, some authors (Grant et al., 2007; Moller et al., 2007) have found that in vineyards using a trellis system, the range of

variability in canopy temperature was small, supporting the previous findings on the importance of leaf angle distribution on temperature variability.

There is little information that characterizes the water supply constraints to transpiration within tree crowns during the initial stages of water stress. In a series of experiments carried out in woody plants, Tyree and Sperry (1988) found that the xylem dysfunction related to cavitation occurred in a patchwork pattern throughout the minor twigs in the crown, *i.e.*, apparently some twigs were more hydraulically favored than others. Rood et al. (2000) demonstrated that some branches are subjected to die-back related to cavitation. Those zones where supply was more limited, and thus exhibit earlier stomatal closure, would influence the canopy temperature distribution. The hydraulic architecture is directly determined by the xylem vessels morphology and by the hydraulic resistance of stems and branches (Cruziat et al., 2002). Further information on the spatial distribution within tree crowns

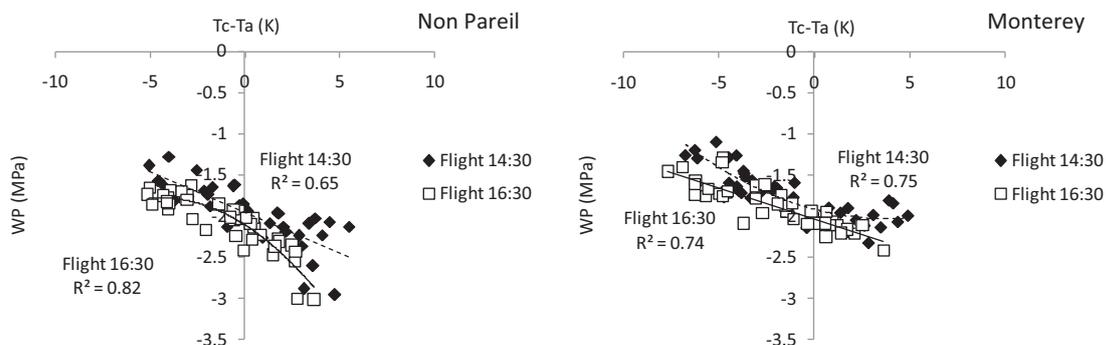


Fig. 11. Relationship between $T_c - T_a$ (K) and water potential (MPa) for Non Pareil and Monterey at 14:30 and 16:30. Dashed and solid lines correspond to the adjusted regression on measurements taken at 14:30 and 16:30, respectively.

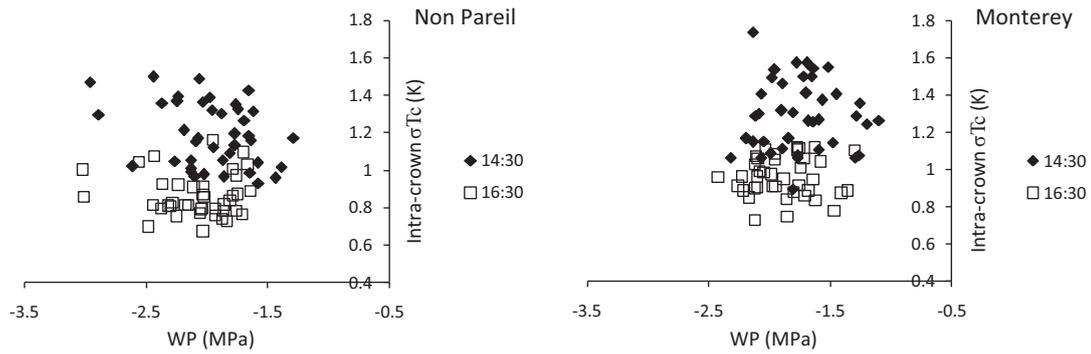


Fig. 12. Relationship between WP (MPa) and intra-crown σT_c (K) for Non Pareil and Monterey.

of the hydraulic conductance during the initial stages of water stress is needed.

The increase in the heterogeneity of the canopy temperature under mild water stress is supported by the pattern of distribution shown in Fig. 8. It suggests that at the onset of stress, a few areas within the crown have substantial stomatal closure while in the rest of the crown the stomata may still be open, given the T_c values observed.

The canopy minus air temperature differential has been considered an indicator of plant water status (Idso et al., 1981; Jones, 1999a,b), while only a few reports have focused on using σT_c as a water stress indicator (Gardner et al., 1981; Fuchs, 1990; Gonzalez-Dugo et al., 2006). When all the data collected in this experiment is pooled together, there is no relationship between intra-crown σT_c and Ψ_x , as shown in Fig. 12. However, Fig. 7 shows that trees displaying very dissimilar T_c could display similar values of intra-crown σT_c . Hence, intra-crown σT_c and Ψ_x cannot be clearly compared without taking absolute T_c into account. When trees having similar T_c (within a range of 1 K) but differing in Ψ_x

were assessed, clearcut relations between σT_c and Ψ_x emerged (Fig. 13). Two irrigation regimes were chosen, comprising trees with intermediate and severe levels of water stress. Fig. 13 shows that, in trees with similar values of crown temperature, σT_c was strongly related to Ψ_x , in particular for the intermediate levels of water stress. Therefore, intra-crown σT_c may be a useful indicator of the onset of water stress, when the mean crop temperature is yet to show a substantial difference from that of well-irrigated controls. If further work confirms that intra-crown σT_c is a sensitive indicator of the onset of tree water deficits, it could be used for close monitoring of precision irrigation management in intensive horticulture.

4.2. Variability of canopy temperature between crowns

The variability of inter-crown σT_c is mainly associated, among other factors, with differences in soil water content, rooting depth and irrigation distribution, as in annual crops (Gonzalez-Dugo et al., 2006). However, other factors such as root distribution, tree size,

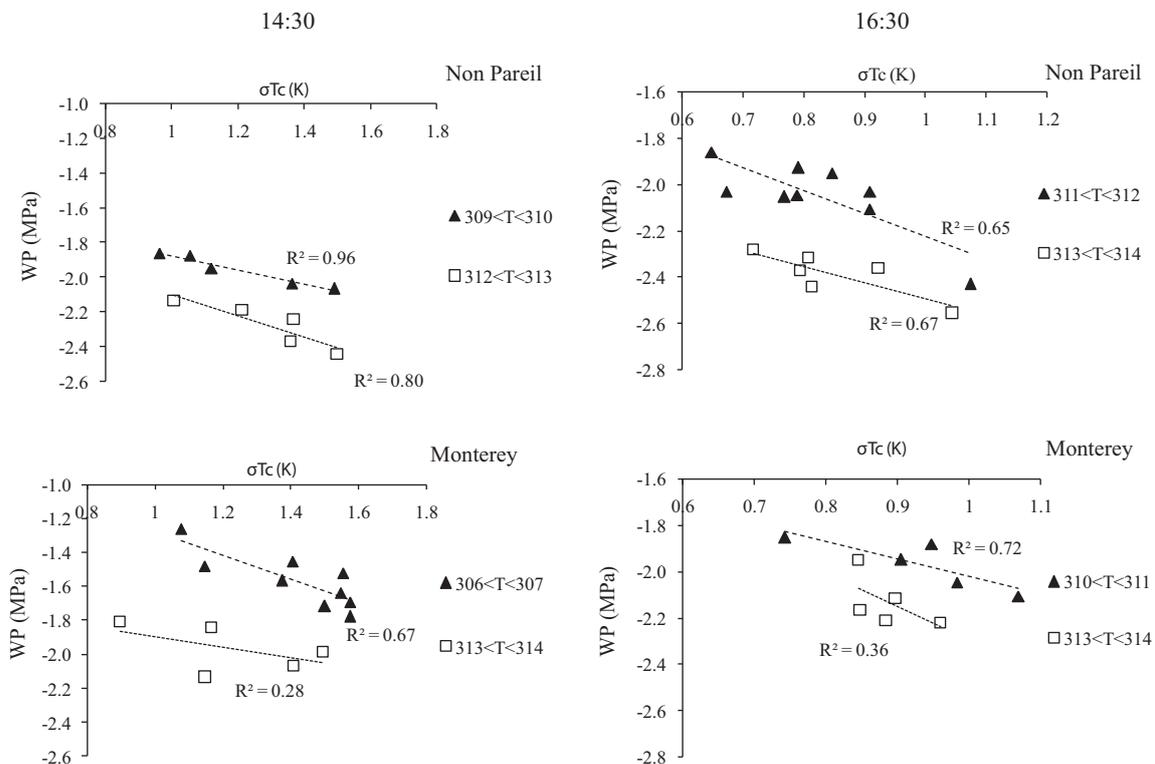


Fig. 13. Relationship between water potential and σT_c for both cultivars at 14:30 and 16:30 for trees within a range of T_c of 1 K.

crop load and tree health should also be taken into account when the variability of inter-crown T_c is considered. With high irrigation levels, as for T7 and T9, most of the plants can meet their potential ET_c . As water started to be deprived, there were some plants that became stressed first and this caused an increase in T_c variation. In Non Pareil, as the water deprivation period increased, more and more plants became stressed and the σT_c decreased. In Monterey, it was found only at 16:30. For intermediate levels, the inter-crown σT_c ranged from about 0.5 to 0.9 K.

Gardner et al. (1981) found an increase in the σT_c of temperature in maize, arising from 0.3 °C in well-watered treatment to 4.2 °C for stressed plots, while Gonzalez-Dugo et al. (2006), in cotton plots, found a maximum σT_c for intermediate levels of water stress around 1.5 °C. The lower values found in this study can be explained by the fact that we have separated the inter- and intra-crown variability. In these previous works, soil heterogeneity, irrigation distribution and canopy architecture effects are considered altogether, while here they are considered separately.

4.3. Differences among cultivars

The range of variation of the g_s and the Ψ_x was similar to that which was found previously in almonds by Castel and Fereres (1982) and Torrecillas et al. (1988). In both cultivars but more so in Monterey, there was an increase in variability in g_s for values of Ψ_x of about -2 to -2.3 MPa, similarly to what was observed by Castel and Fereres (1982) and Torrecillas et al. (1988). This can be ascribed to the feedback mechanism between stomatal closure and Ψ_x that has been observed in deciduous fruit trees (Fereres and Goldhamer, 1990). The interactions between g_s and Ψ_x in deciduous trees make it difficult to set an absolute Ψ_x threshold that would be indicative of the level of stress (Garnier and Berger, 1985; Jones, 1985). The cultivars exhibited different degrees of stomatal regulation, with cv. Non Pareil less able to maintain water status. On the contrary, for intermediate levels of water stress, this cultivar opened its stomata earlier in the morning, as was seen in Fig. 4. Similar behavior was reported by Romero and Botia (2006) in the almond cv. Cartagenera. When comparing different irrigation treatment during summertime, El-Sharkawi and El-Monayeri (1976) found that the maximum peak of transpiration for stressed almonds occurred earlier in the morning, while the well-watered treatment exhibited maximum g_s at around midday.

The relation between g_s and $T_c - T_a$ (Fig. 10B) was more robust than the one that related g_s to Ψ_x (Fig. 10A), because of the feedback mechanism that cause Ψ_x to increase when g_s decreases. Depending on the time of day and the climatic conditions during that day, the improved Ψ_x as a result of stomatal closure may induce partial opening in some tree areas, leading then to a decline in Ψ_x (Jones, 1985).

5. Conclusions

The observations of $T_c - T_a$ over almond trees correlated well with measurements of tree water status, paving the way to use such indicator as an alternative to Ψ_x monitoring. The intra-crown standard deviation of canopy temperature (intra-crown σT_c) varied with the level of water stress, increasing from fully irrigated trees to the intermediate irrigation levels, and diminishing in the severely stressed treatments. The pattern of the temperature distribution within individual crowns was also altered by the irrigation regime. The distribution of intra-crown T_c values suggests that, at the onset of water stress, the heterogeneity of stomatal closure within the crown increases, causing variations in T_c that could be detected remotely with high resolution thermal imagery. Compared to ground-based measurements, those derived from remote

sensing have the advantage of being capable of accounting for the spatial variability. The high resolution of the images acquired in this study enabled us to characterize the surface temperature distribution within individual tree crowns with a degree of accuracy that has not been previously achieved.

There were differences between the two cultivars studied that were related with the stomatal regulation and the water relations. Stomatal regulation in cv. Monterey better maintained water status than cv. Non Pareil, which was evident from the differences in the g_s vs. Ψ_x and g_s vs. $T_c - T_a$ relationships. Given the differential behavior of both cultivars, it would be important to consider the feedback of stomatal closure on tree water status when quantifying the level of water stress.

The consideration of the intra-crown standard deviation, in addition to mean temperature, should increase the performance of crown temperature as an indicator of water stress. This is especially significant for intermediate levels of water stress, suggesting that intra-crown σT_c is a good indicator of water stress in the early stages and a promising tool for irrigation management. The variability of T_c increased during the early stages of water stress and diminished afterwards when water stress was severe. The main factors controlling the source of variation remain unknown. Although previous works highlighted the importance of leaf angle distribution, there is a need to investigate the source of variation in order to acquire a better understanding of the variability in canopy temperature. Finally, it appears that the spatial heterogeneity in surface temperatures within tree crowns may be an important source of error when leaf level-measurements are used to assess water status in tree crops.

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