Crop Water Stress Index is a Sensitive Water Stress Indicator in Pistachio Trees

Testi, L.^{(a)(*)}, Goldhamer D.A.^(b), Iniesta, F.^(a), Salinas M.^(b)

a) Instituto de Agricultura Sostenible, CSIC, Apdo. 4084, 14080 Córdoba, Spain

b) University of California, Kearney Agricultural Center, Dept. Land Air & Water
Resources, 9240 S. Riverbend Ave., Parlier, CA 93648, USA

Corresponding author:

Luca Testi

Instituto de Agricultura Sostenible, CSIC - Apdo. 4084, 14080 Córdoba, Spain.

Tel: +34957499231; Fax: +34957499252

Running Title: Crop Water Stress Index as a Stress Indicator in Pistachio

Keywords: Canopy Temperature, Water Stress, Regulated Deficit Irrigation, Remote
Sensing, Thermal Image

Abstract

Regulated Deficit Irrigation (RDI) strategies, often applied in tree crops, require precise monitoring methods of water stress. The Crop Water Stress Index (CWSI), based on canopy temperature measurements, has shown to be a good indicator of water deficits in field crops but has seldom been used in trees. The CWSI was measured on a continuous basis in a Central California mature pistachio orchard, under full and deficit irrigation. Two treatments – control, returning the full evapotranspiration (ET_c) and RDI, irrigated with 40% ET_c during the Stage two of fruit grow (shell hardening). During Stage two, the canopy temperature - measured continuously with infrared thermometers - of the RDI treatment was consistently higher than the control during the hours of active transpiration; the difference decreasing after irrigation. The Non-Water-Stressed Baseline (NWSB), obtained from clear-sky days canopy-air temperature differential and vapour pressure deficit (VPD) in the control treatment, showed a marked diurnal variation in the intercept, mainly explained by the variation in solar radiation. By contrast, the NWSB slope remained practically constant along the day. Diurnal evolution of calculated CWSI was stable and near zero in the control, but showed a clear rising diurnal trend in the RDI treatment, increasing as water stress increased around midday. The seasonal evolution of the CWSI detected large treatment differences throughout the RDI stress period. While the CWSI in the well-irrigated treatment rarely exceeded 0.2 throughout the season, in the RDI it reached values of 0.8-0.9 near the end of the stress period. The CWSI responded to irrigation events along the whole season, and detected clearly mild water stress, suggesting extreme sensitivity to variations in tree water status. It correlated well with mid-day leaf water potential (LWP), but was more sensitive than LWP at mild stress levels. We conclude that the CWSI, obtained from continuous nadir-view measurements with infrared thermometers, is a good and very sensitive indicator of water stress in pistachio. We recommend the use of canopy temperature measurements taken from 1200 to 1500h, together with the following equation for the NWSB: $(T_c - T_a) = -1.33 \cdot VPD + 2.44$. Measurements of canopy temperature with $VPD < 2$ kPa are likely to generate significant errors in the CWSI calculation and should be avoided.

1 **Introduction**

2 The relation between plant canopy temperature and transpiration through the effect of
3 the transpirational cooling is well known (e.g. Eaton and Belden 1929; Ehrler 1973;
4 Gates 1964; Wallace and Clum 1938), but practical application of this concept came
5 only with the availability of the infra-red thermometer, or IRT (Monteith and Szeicz
6 1962; Tanner 1963). The temperature of a canopy (T_c) deviates from air temperature
7 (T_a), in a way that is, *ceteris paribus*, strictly dependent on the rate of transpiration.
8 Whenever water is evaporated from a leaf, the latent heat of evaporation is drawn
9 from the leaf, cooling it down. Plants reduce their transpiration rate as water in the
10 soil becomes less available by closing the stomata. Stomatal conductance is thus the
11 physiological parameter that affects canopy temperature: a water-stressed canopy is
12 hotter than a well watered one under the same environmental conditions. Soon after a
13 portable infrared thermometer was developed, it became clear that water stress could
14 be quantified through canopy temperature reading (Jackson et al. 1977). The problem
15 was how to normalise the canopy temperature in a way that the stomatal
16 (physiological) effect on the canopy heat balance could be separated from the physical
17 ones (radiation, convection, vapour pressure, etc). In 1981 an applicable stress index
18 was formulated - the crop water stress index (CWSI) - based on canopy-air
19 temperature difference ($T_c - T_a$) (Idso et al. 1981). If one can obtain the two limits of T_c
20 for potential and null transpiration of a crop (or, similarly, for maximum and
21 minimum canopy conductance) under given environmental conditions, then the CWSI
22 can be calculated as follows (Idso et al. 1981):

23

$$24 \quad \text{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)_{LL}}{(T_c - T_a)_{UL} - (T_c - T_a)_{LL}} \quad (1)$$

1 where $(T_c - T_a)$ is the measured foliage-air temperature differential, $(T_c - T_a)_{LL}$ is the
2 expected lower limit of $(T_c - T_a)$ in the case of a canopy that is transpiring at the
3 potential rate, and $(T_c - T_a)_{UL}$ is the expected differential in case of a non-transpiring
4 canopy. The lower and upper limits of $T_c - T_a$ used in Eq 1 can be obtained using three
5 conceptually different methods.

6 The first was proposed by Idso *et al.* (1981) who found that, under good soil water
7 conditions (ideally maximum stomatal conductance), $T_c - T_a$ is a linear function of VPD
8 (non-water-stressed baseline, NWSB). Once the NWSB is empirically obtained, $(T_c -$
9 $T_a)_{LL}$ is calculated at any given time solving the baseline equation for the actual VPD.
10 The upper limit $(T_c - T_a)_{UL}$ is a constant. It is found solving the same NWSB equation
11 for a hypothetical slightly negative VPD, that represents the vapour pressure
12 difference generated by the temperature differential $(T_c - T_a)$ when $VPD=0$ (Idso *et al.*
13 1981). The upper limit value is expected to be close to the intercept a of the NWSB
14 (depending on temperature) and is equal to a only in the special case that $a = 0$. This
15 method is simple, but requires a specific experiment, and is site-dependent. Idso
16 (1984) found the baselines for many species to be independent of temperature,
17 radiation, and wind speed, when the measurements were taken from 3 hours after
18 sunrise to 3 hours before sunset. However, others disputed this argument (e.g.
19 Gardner *et al.* 1992; Nielsen 1994).

20 The second approach for obtaining the upper and lower bounds of $(T_c - T_a)$ is
21 theoretical, as formulated by Jackson *et al.* (1981), shortly after Idso's (1981) method.
22 Jackson expressed $(T_c - T_a)$ combining energy balance and diffusion equations: the
23 bounds are found by forcing the stomatal resistance $\rightarrow \infty$ or setting it to zero for $(T_c -$
24 $T_a)_{UL}$ or $(T_c - T_a)_{LL}$ respectively. This method requires knowledge of variables which
25 are difficult to obtain (like net radiation and, in particular, aerodynamic resistance).

1 The last approach proposed to obtain the bounds of $(T_c - T_a)$ makes use of direct
 2 measurements over wet or dry reference surfaces, either natural or artificial.
 3 Experiences were successfully carried on with dry leaves replicas (Qiu et al. 1996;
 4 Wang et al. 2005) or petroleum-jelly-sprayed leaves (Jones 1999b) for obtaining $(T_c -$
 5 $T_a)_{UL}$, while wet panels (Cohen et al. 2005; Jones et al. 2002; Moller et al. 2007) or
 6 wetted leaves or canopy portions (Jones 1999a; b; Jones et al. 2002) were used as
 7 reference for $(T_c - T_a)_{LL}$. The design and placement of reference surfaces is paramount
 8 to mimic precisely the heat balance of the canopy, and they are difficult to maintain.
 9 This method has great scientific potential, but few chances, at present, to be used
 10 directly and continuously for irrigation scheduling.

11 A general problem often encountered in assessing plant water stress by canopy
 12 temperature is the representativeness of the target area. The inclusion of non-
 13 transpiring surfaces (like soil, branches etc.) inside the IRT field of view generate
 14 unwanted shifts in the temperature readings, thus decreasing the precision of T_c
 15 measurements (Hatfield et al. 1985; Wanjura et al. 1984). This problem often arises
 16 under incomplete cover, and was partially overcome by using spectral vegetation
 17 indexes (Moran et al. 1994) or narrow-angle IRT sensors (Jones 1999a). At present,
 18 affordable and portable thermal imaging devices with high resolution are available;
 19 this has solved the problem of discriminating between foliage and non-transpiring
 20 surfaces. The thermal images (alone or with the aid of visible Red-Green-Blue
 21 images) can now be stripped of the unwanted non-leaf components, and the inclusion
 22 of reference surfaces in the camera image can aid this process (Jones et al. 2002;
 23 Moller et al. 2007). Another advantage of thermal imaging over classic IRT
 24 thermometry is that it allows to distinguish among temperatures of specific parts of

1 the plant, like sunny or shaded leaves or vegetative organs, and to obtain canopy
2 temperature variability indices, that are also related to water stress (Fuchs 1990).
3 Nevertheless, at present, thermal imaging poses the same practical problem previously
4 mentioned for the reference surfaces normalisation method: they are not suitable for
5 continuous operation. Thermal cameras are still too costly and delicate to be deployed
6 unattended in the field, and complex image processing is not easy to automate, while
7 satellite thermal imagery still don't have the necessary resolution to discern organs of
8 the size of a leaf.

9 The CWSI concept, mainly normalized with Idso's empirical approach, has been
10 applied mostly to annual crops (Abduljabbar et al. 1985; Idso 1982; Nakayama and
11 Bucks 1983; Wanjura et al. 1990; Yazar et al. 1999). It has been used less with tree
12 crops, presumably because their incomplete cover hinder obtaining accurate
13 temperature readings of the transpiring canopy parts. Idso (1982) included only one
14 tree species (fig) in his group of T_c-T_a baselines. Other works appeared on peach
15 (Glenn et al. 1989), nectarines (Tormann 1986), pecan (Garrot et al. 1993), apple
16 (Andrews et al. 1992), and sweet lime (Sepaskhah and Kashefipour 1994).

17 One of the limitations of the CWSI is that its precision is climate-dependent. At low
18 VPDs, the distance between the upper and lower bound temperatures is smaller, while
19 the measurements errors have the same magnitude. The signal-noise ratio is thus
20 worse (Jones 2004), to the point that it is not advisable to use it in very humid
21 climates or when the variability of VPD and radiation is high. In such climates,
22 obtaining the canopy temperature from specific leaves (with thermal imaging) and
23 normalising the CWSI with the aid of reference surfaces can greatly improve the
24 CWSI precision (Jones 1999a; Jones et al. 1997).

1 The use of regulated deficit irrigation (RDI) in orchards (Boland et al. 1993; Chalmers
2 et al. 1986) calls for a precise tool to monitor water stress (Goldhamer et al. 1999). In
3 addition to the traditional water stress indicators used in trees, for instance soil water
4 content, leaf water potential or leaf conductance, there are newer methods, such as
5 trunk diameter fluctuations and sap flow, that provide continuous automatic records.
6 The traditional soil and plant based monitoring is time consuming and provides point
7 measurements; a single location of soil, a leaf, branch, or tree. They are incapable of
8 representing the water status of an entire orchard without being financially impractical
9 due to the number of monitoring sites required. Today IRTs are relatively cheap,
10 rugged, precise and easily automated. The use of the CWSI from simple IRTs
11 continuous measurements, normalised with the empirical approach, could be a simple,
12 cost-effective method to monitor the water stress and schedule irrigations under RDI
13 strategies in tree crops, provided that:

14 1) The IRTs can be positioned in a way that they see only tree foliage. Furthermore, if
15 the frequency of differently illuminated leaves in the canopy portion viewed by the
16 IRTs at the time of measurement is constant enough, then the effect of shaded leaves
17 on the average canopy temperature can be accounted for in the baseline
18 parameterisation.

19 2) The empirical baselines, especially the NWSB, are stable under the environmental
20 conditions expected during the irrigation season. If instability is found, the variation
21 in the baseline should be predictable, thus the errors in CWSI can be minimised. Also,
22 dry, stable weather conditions are desirable to avoid important errors in defining the
23 CWSI.

24 Pistachio orchards (*Pistacia vera* L.) in central California (one of the world's more
25 important pistachio production areas) are irrigated during dry and stable weather

1 conditions. The orchards are mostly homogeneous - only one cultivar is used - and
2 they are pruned to have a globular, dense and regular canopy.

3 The main goal of this work was to assess the reliability of CWSI (obtained with
4 continuous measurements of average infra-red canopy temperature and with the
5 empirical normalisation) for detecting water stress in pistachio. We addressed this
6 problem by obtaining the NWSB, assessed the quality and stability of the CWSI of
7 trees subjected to a water stress cycle, and described and explained the sources of
8 variation in the stress indicator. Importantly, we established the relationship between
9 CWSI and leaf water potential, the more commonly accepted indicator of tree water
10 status in this crop.

11

Materials and methods

Experimental site

The study was conducted in a commercial pistachio orchard located in Madera County, California, 36° 58' 54" N, 119° 57' 25" W, 75m elevation, during the 2006 season. The soil is classified as sandy loam, of variable depth (maximum about 3m).

Pistachio trees of the cv. Kerman (*P. integerrima* rootstock) were planted in 1994, at a spacing of 5.8m x 5.2m in a triangular grid. At the time of the experiment, the trees were 4.8m high, their canopy volume was 37.5m³ per tree, and they covered 57% of the ground in vertical projection (average values obtained in 100 trees). The irrigation method is microsprinkler at the same spacing as the trees, with the sprinklers located in the trees rows mid-way between trees. The microsprinklers' nominal factory discharge rate is 93.9 L h⁻¹ at 1.38 bars, equivalent to 3.1 mm h⁻¹ in the configuration of this experiment and at the same operation pressure.

Two large plots of 32 ha each were irrigated with two different irrigation schedules. The first one (Control) was irrigated restoring 100% of the potential evapotranspiration (ET_c) for the whole season. The second treatment (RDI) was irrigated following a regulated deficit irrigation schedule, that provided only 40% of the crop ET_c during Stage 2 of fruit growth (Goldhamer and Beede 2004), which takes place during the shell hardening period (19 May to 11 July 2006), and 100% of ET_c during the rest of the irrigation season. The ET_c for scheduling the irrigations was calculated as $ET_c = ET_0 \cdot K_c$, where ET₀ is the reference evapotranspiration, and K_c is the pistachio crop coefficient under unstressed conditions (Goldhamer 2005), given in Table 1. The ET₀ and the other relevant meteorological variables were obtained from the nearest meteorological station (Madera, station #145 of the California Irrigation

1 Management Information System network), located about 10 km away from the
2 experimental site. Irrigation was applied weekly, although management and labour
3 constraints occasionally induced small variations in the watering frequency.

4

5 *Canopy temperature measurements and CWSI*

6 Four infrared thermometers (model IRR-P, Precision Infra-Red Radiometer, Apogee
7 Instruments Inc. Logan, UT) were mounted over four average-size trees in each
8 treatment. The sensors angular field of view is 44°, and the absolute accuracy under
9 the experimental conditions was 0.2 °C (manufacturer's specifications). The mounting
10 consisted of an aluminium mast with an horizontal mounting arm, ending with a white
11 PVC case protecting the sensor, that was directed aiming vertically downward (nadir
12 view) and targeting the center of the canopy from a distance of approximately one
13 meter (Fig. 1). A similar instrumental set-up was used by Sepulcre-Canto' et al (2006).
14 With this setting, the infrared thermometers (henceforth IRTs) were viewing
15 approximately 0.5 m² of foliage in the canopy top. Leaves were estimated by visual
16 inspection to occupy at least the 90-95% of the IRTs field of view.

17 All the IRTs were connected to a datalogger (model CR10X, Campbell Scientific,
18 Logan UT), that recorded canopy temperatures every minute and stored the 5-min
19 averages. The canopy temperature measurements started on 13 June 2006 (DOY 164)
20 and continued without interruption until 21 September (DOY 264).

21 The Crop Water Stress Index was calculated continuously, using Eq. 1. T_a and VPD
22 were obtained from the weather station. The NWSBs were derived by linear
23 regression of the values of $(T_c - T_a)$ measured in the Control plot versus VPD, for a
24 given time of the day; the upper limit $(T_c - T_a)_{UL}$ was obtained solving the NWSB

equation for $VPD=0$ then correcting for the difference in vapor pressure induced by the difference in temperature T_c-T_a (Idso et al. 1981).

Leaf water potential

Measurements of midday shaded leaf water potential (Ψ) were obtained in the experimental trees every 5-6 days. Midday shaded leaf water potential was found to be highly correlated with stem water potential in almonds (Goldhamer and Fereres 2001) and is easier to take since covering the leaves with small bags for a given amount of time is not necessary. Four leaves, taken from inside the canopy as close to the trunk as possible, were cut from each tree around 1200h and put in a pressure chamber (model 3005, Soilmoisture Equipment Co., Santa Barbara, CA) immediately after cutting. The leaves were handled with a damp cloth, and the rate of pressure increase in the chamber was relatively slow to avoid reading errors (Hsiao 1990; Turner and Long 1980).

Results and discussion

The nadir-view radiometric temperature of the canopy (henceforth T_c) showed little variation among trees. About 80% of our T_c measurements (5-min averages of 1-min measurements) showed a coefficient of variation C_v (the ratio of the standard deviation to the mean) of less than 2%; 99.6% of the measurements had $C_v < 5\%$. This suggests that: a) the observed trees were in similar water status; and b) that the canopy surface viewed by the sensor (or the number of leaves falling inside the sensor field of view) was big enough to remove the variability due to the leaves' orientation with

1 respect to the sun angle. Thus, we are reasonably confident in the representativeness
2 of the mean.

3 The two treatments showed clear differences in T_c during the RDI timeframe. This can
4 be appreciated in Fig. 2, showing the time series of T_c (on the left side) and $T_c - T_a$ (on
5 the right) during three days that differed in tree water status. The first comparison is
6 for 18 June (DOY 169), when the Control treatment had been irrigated with the full
7 crop water requirement and the RDI had been subjected to a month of deficit
8 irrigation with the last irrigation event on 9 June (Fig. 2a and Fig. 2d). Immediately
9 after sunrise, the canopy of the RDI warmed up faster than the Control, exceeding the
10 Control T_c by about 6 °C at about 1500h (Fig. 2a). The temperature of the RDI
11 canopies was higher than the air temperature from midday to 1700h (Fig. 2D), and a
12 consistent difference in $T_c - T_a$ between the two treatments was apparent until well after
13 sunset. This behaviour in T_c and $T_c - T_a$ is symptomatic of reduced transpiration due to
14 water stress. The effect of irrigation over the thermal conditions of the canopy is
15 shown in Fig. 2b and Fig. 2e, presenting data from 19 June (DOY 170), when an
16 irrigation was applied to RDI in the early morning. The thermal behaviour is similar
17 to the previous day, but the differences between treatments were greatly attenuated;
18 the maximum difference in T_c between the Control and RDI is now only around 2 °C
19 (Fig. 2b), and the RDI canopy temperature barely exceeds air temperature (Fig. 2e).
20 The RDI trees had better water status than the previous day and an apparent increase
21 in transpiration. Nevertheless, the RDI trees had not fully recovered. By 15 August
22 (DOY 227, Fig. 2c and Fig. 2f) the imposition of stress in the RDI treatment had
23 ended more than a month before (11 July) and subsequently, both the Control and
24 RDI regimes had the same amount of applied water; enough to avoid reducing
25 transpiration below the potential rate. Differences in canopy thermal behaviour

1 between the treatments are very small, suggesting that the RDI trees had mostly
2 recovered from the stress period (Fig. 2c and Fig. 2f). The minimum and maximum
3 1300h averages of $T_c - T_a$ registered during this experiment were, respectively, -5.1 °C
4 (Control on 24 July) and 3.10 °C (RDI on 10 July, 1 day before the end of the RDI
5 stress period). The maximum difference between the canopy temperatures of the two
6 treatments was 7.13 °C, recorded at 1530h on 26 June.

8 ***Crop Water Stress Index***

9 The first attempt to obtain the non-water-stressed baseline (NWSB) using clear-sky
10 days data from 0900 in the morning to 1700 in the afternoon in the well watered trees,
11 yielded such a large scatter that it was impossible to obtain a reasonably sound
12 $(T_c - T_a)_{LL}$. Upon analysing the stability of the NWSB at different times of the day, we
13 found a marked change in the diurnal NWSB parameters, while the scatter in the plots
14 of $(T_c - T_a)$ versus VPD for a given time of the day was small (Fig. 3). This diurnal
15 behaviour of the pistachio NWSB is presented in Fig. 3a (morning) and Fig. 3b
16 (afternoon). In these plots the hourly values of $(T_c - T_a)$ are regressed vs. VPD
17 separately in different hours of the day; each point is obtained from hourly average T_c ,
18 T_a and VPD in a given day at a given hour, using the T_c of the well-watered trees. The
19 slope of the baselines (b) seems rather stable, with the partial exception of the 0900h
20 plot, but its slope is not significantly different from the slope of the other hours. By
21 contrast, the intercept (a) is clearly increasing in the morning and decreasing in the
22 afternoon. The parameters of the baseline equations obtained at different times of the
23 day are given in Table 2. An explanation for the shifting of the NWSB is provided by
24 Jackson's theoretical equation for the NWSB (Jackson et al. 1981):

$$(T_c - T_a) = r_a R_n \frac{\gamma}{\rho C_p (\Delta + \gamma)} - \frac{1}{\Delta + \gamma} VPD \quad (2)$$

where Δ is the slope of the saturated vapour pressure vs. temperature, namely $(e_{sc} - e_{sa})/(T_c - T_a)$, where e_{sc} and e_{sa} are the saturated vapour pressures at T_c and T_a respectively, ρ is the density of air, C_p the heat capacity of air, r_a is the aerodynamic resistance to water vapour transfer, and γ is the psychrometric constant.. Eq. 2 shows that the intercept is a function of both r_a and R_n , thus is expected to increase with solar radiation and decrease with wind speed. Such behaviour was predicted theoretically by Hipps et al. (1985), and supported by some measurements, but has never been confirmed in trees.

Our infrared thermometers were arranged for nadir-view, so they targeted a relatively horizontal foliage surface at the top of the canopy. As the trees were quite uniform in height, there was no shading from the neighboring trees, and the radiation incident over the canopy portion enclosed in the IRT field of view, in a clear-sky day, should be closely related to the solar angle by the cosine law. The shift in the NWSB during the day (Fig. 4) is mainly explained by the zenith solar angle, that probably acts on the IRT targeted canopy area not only by changing the total amount of radiation, but also - depending on canopy roughness - the fraction of shaded leaves on the total seen by the sensor.

In practical terms, there is little need to account for the shifting baseline if one uses measurements of T_c and T_a taken from 1200h to 1500h. The parameters of the equation of the NWSB obtained with the measurements in this period of the day are also given in Table 2; the line for 1200h to 1500h is shown (dashed bold) in Fig. 3b.

Changes in the aerodynamic conductance due to wind speed seem to have a less important effect than solar radiation on the NWSB, in the aerodynamic conditions of

1 the experiment: Fig. 5 shows the values of $(T_c - T_a)$ vs. VPD at 1500h, but
2 disaggregated in three arbitrarily chosen wind speed classes. Wind speed seems to
3 have some effect on the slope of the baseline, but statistically the three regression
4 lines are the same as the 1500h regression obtained including all wind speeds (Fig.
5 3b), which equation is given in Table 2. Although the analysis is limited in range (the
6 experimental area is not particularly windy), we can assume that under similar wind
7 speeds (and with trees of similar size) the variation in the aerodynamic conductance
8 has a negligible effect on the NWSB.

9 The variation of the NWSB poses the question of how the resulting CWSI changes
10 when it is determined at different times of the day. The daily evolution of the CWSI in
11 the two treatments on 3 July is shown in Fig. 6, calculated from air and canopy
12 temperature readings at 10-min intervals and varying the NWSB as presented in Table
13 2. On that day, the RDI trees were near the end of the deficit irrigation period and thus
14 quite stressed, as evidenced by the leaf water potential data also shown in Fig. 6.
15 While the CWSI of the Control trees is stable and near zero throughout the day, the
16 CWSI of the RDI trees increases steadily and near-linearly until around 1330h. This
17 was probably the result of a decrease in the canopy conductance of the RDI trees in
18 response to the increasing evaporative demand and the low soil water content.
19 Regardless, the CWSI of the water-stressed trees is different when calculated at
20 different times of the day, which is not effect of the variation of the NWSB, as this
21 has been already accounted for in Fig. 6. On this specific day, for example, the CWSI
22 could be either 0.6 or 0.8, depending if T_c and T_a are measured at 1100h or 1500h,
23 respectively. This finding is in accordance with Jackson et al. (1981), whose analysis
24 lead them to express the CWSI as $1 - E_p/E_{pmax}$, where E_p is the actual and E_{pmax} the
25 maximum (unstressed) transpiration. A stressed plant that reduces its stomatal

1 conductance reduces the ratio E_p/E_{pmax} , consequently its CWSI increases. This
2 statement seems equally valid at the time scale of a day: in the morning, the trees E_p
3 was closer to E_{pmax} than in the afternoon, and this should happen in plants having
4 enough stomatal control capacity to react significantly to the high evaporative demand
5 of summer afternoons in dry climates.

6 The measurements of midday shaded leaf water potential (Ψ) show the seasonal
7 evolution of the water stress in the two treatments (Fig. 7). While the Control never
8 reached the 1.5 MPa except near harvest, the RDI showed values always between 1.7
9 and 2.5 MPa during the stress timeframe, then approached the Ψ of the Control
10 treatment soon after the full irrigation schedule was restored.

11 The seasonal pattern of the CWSI at 1500h for both treatments can be observed in
12 Fig. 8. The CWSI in the RDI trees clearly detects the stress period: the 7-day moving
13 average of CWSI slowly increased as soil water deficits increased during the deficit
14 irrigation period. Also, the CWSI peaks are sharper before irrigations events until the
15 stress period was broken (Fig. 8). Upon the resumption of full irrigation, the CWSI
16 dropped suddenly and remained relatively steady until harvest. The Control, always
17 well irrigated, shows values of CWSI close to zero for the whole season. Certain
18 aspects of the CWSI behaviour should be highlighted. The first is that the CWSI is not
19 entirely stable day-to-day; it shows marked oscillations that are clearly in phase with
20 the irrigation events. Each time an irrigation is applied, the CWSI drops. The
21 reduction in the CWSI after irrigations is more pronounced when the trees are heavily
22 stressed, but this same behaviour can be observed, albeit attenuated, in the Control,
23 with the CWSI always near zero. The amplitude of the oscillations, the quickness of
24 the response after every irrigation, and the absolute values reached at the time of
25 maximum stress are all elements emphasizing the adequacy and the sensitivity of the

1 CWSI as a stress indicator in pistachio. In fact, comparison of the time-course
2 developments of the CWSI for both treatments suggests that it can be thought of as an
3 "amplified" stress indicator (Fig. 8). Such an extreme sensitivity shown in the RDI
4 trees, with CWSI values reaching 80% of the maximum potential under moderate
5 water deficits, has not been previously reported for other crop plants in the literature.
6 Whether this behaviour is specific for pistachio is unknown. Also enhancing the
7 sensitivity of the CWSI as a stress indicator was the view angle of the IRT. The leaves
8 which were targeted for measurements were at the very top of the canopy, and they
9 were the most exposed to solar radiation. They also presumably had the lowest
10 boundary layer resistance, being the most ventilated, of all the leaves in the canopy.
11 Thus, they should be under more severe stress than any other sample of leaves in the
12 canopy, including those where the LWP measurements are routinely taken. This
13 suggests that the sensitivity of other remote sensing approaches, such as using aircraft
14 as platforms for thermal imaging, will depend on their ability to assess the Tc of only
15 sunlit leaves, requiring the removal of all other surfaces in the thermal image. In turn,
16 this implies that both thermal and visible Red-Green-Blue images must be used in that
17 the latter can better distinguish between sunlit and mixed pixels. Thus, the smaller the
18 pixel size, the better will be the ability to identify only sunlit pixels and eliminate both
19 soil and shaded leaf pixels. This has implications for the optimal combination of
20 flight height and camera resolution.

21 The second relevant aspect to be pointed out from Fig. 8 is that the RDI recovery after
22 the end of the deficit irrigation schedule, although fast, was not complete. This may be
23 due to either some temporary stress-induced damage to the water transport system
24 (xylem cavitation) or to incomplete restoration of the soil water content throughout
25 the profile, as the irrigation system was probably not able to refill the soil profile in

1 the deeper layers after the intensive depletion during the stress period. The partial RDI
2 recovery was reflected in the leaf water potential data (Fig. 7).

3 The last important aspect to be noted in Fig. 8 is that there are some days of
4 unreasonably high CWSI, namely DOY 258, 259 and 260. There is no evidence of
5 extreme stress in these periods, as can be seen in Fig. 7, and from the irrigation
6 applied. These high CWSI days are characterised by air temperatures below average
7 and low VPD. Air temperatures were 21, 23 and 25 °C, VPD was 1.7, 1.8 and 2.0 kPa
8 respectively for days 258, 259 and 260: a different atmospheric environment from the
9 period used to derive the baseline (except for wind, that was close to average). Under
10 these conditions, the difference between $(T_c - T_a)_{LL}$ and $(T_c - T_a)_{UL}$ is very small. Thus,
11 the CWSI is unreliable and the signal-noise ratio of the CWSI is necessarily worse
12 (Jones 2004; Stockle and Dugas 1992). In general, due to the empiricism of the CWSI
13 approach, extreme care must be taken when calculating the CWSI in days when
14 meteorological conditions depart significantly from the average days used to calculate
15 the baselines. For the conditions of this experiment, an unreliable pistachio CWSI
16 may be obtained in days when the VPD was lower than 2 kPa at the time of
17 measurement.

18 There is general agreement that the best current plant-based stress indicator is tree
19 water status since it has been shown to be related to physiological processes (Naor et
20 al. 2006) and crop production (Ferreles et al. 2003; Shackel et al. 1997). The best test
21 of the potential utility of other water stress indicators that overcome the logistical
22 limitations of obtaining tree water status is how well they correlate with tree water
23 status. The relationship between CWSI taken at 1500h and the midday shaded leaf
24 water potential (Ψ) for the RDI trees is shown in Fig. 9. The coefficient of
25 determination ($R^2 = 0.83$) is higher than what is normally found in literature for other

crops (e.g. Benasher et al. 1992; Sepaskhah and Kashefipour 1994; Wang et al. 2005). The relationship between these two variables can be sometimes misleading: although the leaf water potential is the more widely used index of water stress, its sensitivity, when measured during the day, can be attenuated in fruit trees by the feedback of stomatal closure (Ferreira and Goldhamer 1990). In the mild stress range, one may find similar leaf water potentials at midday, with different stomatal conductances and different transpiration rates. On the contrary, the CWSI is theoretically a function of the relative transpiration (Jackson et al. 1981). This may be the reason for the appearance in Fig. 9 of the vertically stretched group of points close to 1.5 MPa. In this range of relatively mild stress, the variability in CWSI (the response to the irrigation events even at low CWSI that can be appreciated in Fig. 8) is not reflected in the leaf water potential measurements.

Conclusions

The temperature of pistachio trees showed great responsiveness to variations in plant water status. The canopy temperature in the stressed trees was considerably higher than in the well-watered ones during most of the day, and irrigation applications reduced the difference.

The intercept of the NWSB of pistachio trees changed along the day, while the slope remained constant. The changes in the baseline are mostly explained by the diurnal variations in solar radiation, as evidenced by the relationship found with the zenith solar angle (closely correlated with irradiance in clear sky days).

Even when using specific baselines for each time of measurement, the CWSI of pistachio canopies increases significantly during the day if the canopy is

1 water-stressed, while it is stable in the absence of stress. More stable and sounder
2 values of CWSI, for evaluating the water status for irrigation purposes, are obtained in
3 our experience from 1200h to 1500h, when the CWSI of stressed pistachio canopies
4 reaches its maximum diurnal value.

5 The CWSI measured in the first afternoon hours resulted to be a good descriptor of
6 the seasonal changes in the water status of a pistachio orchard submitted to variable
7 water stress by regulated deficit irrigation. Moreover, it exhibited an extreme
8 sensibility, by responding to irrigations events even when the canopies were under
9 very weak stress conditions. Such responsiveness may be the consequence of
10 targeting the more exposed leaves of the canopy with the infrared thermometers. The
11 viewing angle and the sample of foliage targeted by the IRT devices in our set-up is
12 the same as any remote sensing apparatus (satellite or air-borne), thus we consider the
13 results obtained in this work of great importance for remote sensing studies or
14 applications focused on thermal detection of water stress. This, of course, is only true
15 if the thermal image acquired remotely provides enough resolution to spot only the
16 top of the tree canopies.

19 ***Acknowledgements***

21 This work would not have been possible without the assistance of AgriWorld, Inc.,
22 our cooperating grower. They graciously let us use a large block of trees, including
23 installation of equipment and sensors that complicated their farming activities, and
24 never complained. We expressly thank Chris Wylie, ranch supervisor, and Richard
25 Pasley, ranch President. We dedicate this paper to the late Bertrand Gaillard, general

1 manager, who encouraged and supported our research. We also are grateful for the
2 work of our many field technicians, including Jesus Salinas, Rene Resendez, George
3 Salinas, and Juan Salinas. We appreciate the help of Dr. Elias Fereres in the
4 experimental planning, execution, and data analysis. This work was funded by the
5 California Department of Water Resources, Office of Water Use Efficiency and we
6 thank Peter Brostrom, project manager, for his support and guidance.

References

- Abduljabbar AS, Lugg DG, Sammis TW, Gay LW (1985) Relationships between Crop Water-Stress Index and Alfalfa Yield and Evapotranspiration. *Trans. ASAE* 28: 454-461
- Andrews PK, Chalmers DJ, Moremong M (1992) Canopy Air-Temperature Differences and Soil-Water as Predictors of Water-Stress of Apple-Trees Grown in a Humid, Temperate Climate. *J Am Soc Hortic Sci* 117: 453-458
- Benasher J, Phene CJ, Kinarti A (1992) Canopy Temperature to Assess Daily Evapotranspiration and Management of High-Frequency Drip Irrigation Systems. *Agric Water Manag* 22: 379-390
- Boland AM, Mitchell PD, Jerie PH, Goodwin I (1993) The Effect of Regulated Deficit Irrigation on Tree Water-Use and Growth of Peach. *Journal of Horticultural Science* 68: 261-274
- Chalmers DJ, Burge G, Jerie PH, Mitchell PD (1986) The Mechanism of Regulation of Bartlett Pear Fruit and Vegetative Growth by Irrigation Withholding and Regulated Deficit Irrigation. *Journal of the American Society for Horticultural Science* 111: 904-907
- Cohen Y, Alchanatis V, Meron M, Saranga Y, Tsipris J (2005) Estimation of leaf water potential by thermal imagery and spatial analysis. *Journal of Experimental Botany* 56: 1843-1852
- Eaton FM, Belden GO (1929) Leaf temperatures of cotton and their relation to transpiration, varietal differences, and yields. *U.S.D.A Technical Bulletin* n. 91: 1-39
- Ehrler WL (1973) Cotton Leaf Temperatures as Related to Soil-Water Depletion and Meteorological Factors. *Agronomy Journal* 65: 404-409
- Fereres E, Goldhamer DA (1990) Deciduous fruit and nut trees. In: Stewart BA, Nielsen DR (eds) *Irrigation of Agricultural Crops*, Madison, Wisconsin, pp 987-1017
- Fereres E, Goldhamer DA, Parsons LR (2003) Irrigation water management of horticultural crops. *Hortscience* 38: 1036-1042
- Fuchs M (1990) Infrared Measurement of Canopy Temperature and Detection of Plant Water-Stress. *Theoretical and Applied Climatology* 42: 253-261
- Gardner BR, Nielsen DC, Shock CC (1992) Infrared Thermometry and the Crop Water-Stress Index .2. Sampling Procedures and Interpretation. *Journal of Production Agriculture* 5: 466-475
- Garrot DJ, Kilby MW, Fangmeier DD, Husman SH, Ralowicz AE (1993) Production, Growth, and Nut Quality in Pecans under Water-Stress Based on the Crop Water-Stress Index. *J Am Soc Hortic Sci* 118: 694-698
- Gates D (1964) Leaf temperature and transpiration. *Agronomy Journal* 56: 273-277
- Glenn D, Worthington J, Welker W, McFarland M (1989) Estimation of peach tree water use using infrared thermometry. *J. Amer. Soc. Hort. Sci* 114: 737-741
- Goldhamer DA (2005) Tree Water Requirements and Regulated Deficit Irrigation. In: Ferguson L (ed) *Pistachio production manual* (4th ed.). University of California, Fruit and Nut Research and Information Center, Davis, Ca, USA, pp 103-116

- Goldhamer DA, Beede RH (2004) Regulated deficit irrigation effects on yield, nut quality and water-use efficiency of mature pistachio trees quality and. *Journal of Horticultural Science & Biotechnology* 79: 538-545
- Goldhamer DA, Fereres E (2001) Simplified tree water status measurements can aid almond irrigation. *California Agriculture* 55: 32-37
- Goldhamer DA, Fereres E, Mata M, Girona J, Cohen M (1999) Sensitivity of continuous and discrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. *J Am Soc Hortic Sci* 124: 437-444
- Hatfield JL, Wanjura DF, Barker GL (1985) Canopy Temperature Response to Water-Stress under Partial Canopy. *Trans. ASAE* 28: 1607-1611
- Hipps LE, Asrar G, Kanemasu ET (1985) A Theoretically-Based Normalization of Environmental-Effects on Foliage Temperature. *Agric For Meteorol* 35: 113-122
- Hsiao T (1990) Measurements of plant water status. In: Stewart BA, Nielsen DR (eds) *Irrigation of agricultural crops*. American Society of Agronomy, New York, pp 244-280
- Idso SB (1982) Non-Water-Stressed Baselines - a Key to Measuring and Interpreting Plant Water-Stress. *Agricultural Meteorology* 27: 59-70
- Idso SB, Jackson RD, Pinter PJ, Reginato RJ, Hatfield JL (1981) Normalizing the Stress-Degree-Day Parameter for Environmental Variability. *Agricultural Meteorology* 24: 45-55
- Idso SB, Reginato RJ, Clawson KL, Anderson MG (1984) On the Stability of Non-Water-Stressed Baselines. *Agric For Meteorol* 32: 177-182
- Jackson RD, Idso SB, Reginato RJ, Pinter PJ (1981) Canopy Temperature as a Crop Water-Stress Indicator. *Water Resour. Res.* 17: 1133-1138
- Jackson RD, Reginato RJ, Idso SB (1977) Wheat Canopy Temperature - Practical Tool for Evaluating Water Requirements. *Water Resources Research* 13: 651-656
- Jones HG (1999a) Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. *Agricultural and Forest Meteorology* 95: 139-149
- Jones HG (1999b) Use of thermography for quantitative studies of spatial and temporal variation of stomatal conductance over leaf surfaces. *Plant Cell and Environment* 22: 1043-1055
- Jones HG (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. *J Exp Bot* 55: 2427-2436
- Jones HG, Aikman D, McBurney TA (1997) Improvements to infra-red thermometry for irrigation scheduling in humid climates. *Second International Symposium on Irrigation of Horticultural Crops*, Vols 1 and 2, pp 259-265
- Jones HG, Stoll M, Santos T, de Sousa C, Chaves MM, Grant OM (2002) Use of infrared thermography for monitoring stomatal closure in the field: application to grapevine. *Journal of Experimental Botany* 53: 2249-2260
- Moller M, Alchanatis V, Cohen Y, Meron M, Tsipris J, Naor A, Ostrovsky V, Sprintsin M, Cohen S (2007) Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. *Journal of Experimental Botany* 58: 827-838
- Monteith J, Szeicz G (1962) Radiative temperature in the heat balance of natural surfaces. *QJR Meteorol. Soc* 88: 496-507

- Moran MS, Clarke TR, Inoue Y, Vidal A (1994) Estimating Crop Water-Deficit Using the Relation between Surface-Air Temperature and Spectral Vegetation Index. *Remote Sensing of Environment* 49: 246-263
- Nakayama FS, Bucks DA (1983) Application of a Foliage Temperature Based Crop Water-Stress Index to Guayule. *J Arid Environ* 6: 269-276
- Naor A, Gal Y, Peres M (2006) The inherent variability of water stress indicators in apple, nectarine and pear orchards, and the validity of a leaf-selection procedure for water potential measurements. *Irrigation Science* 24: 129-135
- Nielsen DC (1994) Non-Water-Stressed Base-Lines for Sunflowers. *Agric Water Manag* 26: 265-276
- Qiu G, Momii K, Yano T (1996) Estimation of plant transpiration by imitation leaf temperature. I. Theoretical consideration and field verification. *Trans. Jpn. Soc. Irrig., Drain. Reclam. Eng* 64: 401-410
- Sepaskhah AR, Kashefipour SM (1994) Relationships between Leaf Water Potential, C_{ws}, Yield and Fruit-Quality of Sweet Lime under Drip Irrigation. *Agric Water Manag* 25: 13-22
- Sepulcre-Canto G, Zarco-Tejada PJ, Jimenez-Munoz JC, Sobrino JA, de Miguel E, Villalobos FJ (2006) Detection of water stress in an olive orchard with thermal remote sensing imagery. *Agric For Meteorol* 136: 31-44
- Shackel K, Ahmadi H, Biasi W, Buchner R, Goldhamer D, Gurusinghe S, Hasey J, Kester D, Krueger B, Lampinen B (1997) Plant water status as an index of irrigation need in deciduous fruit trees. *HortTechnology* 7: 23-29
- Stockle CO, Dugas WA (1992) Evaluating Canopy Temperature-Based Indexes for Irrigation Scheduling. *Irrig Sci* 13: 31-37
- Tanner CB (1963) Plant Temperatures. *Agron J* 55: 210-&
- Tormann, H (1986) Canopy temperature as a plant water stress indicator for nectarines. *South African journal of plant and soil* 3: 110-114
- Turner NC, Long MJ (1980) Errors Arising from Rapid Water-Loss in the Measurement of Leaf Water Potential by the Pressure Chamber Technique. *Aust J Plant Physiol* 7: 527-537
- Wallace R, Clum H (1938) Leaf Temperatures. *American Journal of Botany* 25: 83-97
- Wang LM, Qiu GY, Zhang XY, Chen SY (2005) Application of a new method to evaluate crop water stress index. *Irrig Sci* 24: 49-54
- Wanjura DF, Hatfield JL, Upchurch DR (1990) Crop Water-Stress Index Relationships with Crop Productivity. *Irrigation Science* 11: 93-99
- Wanjura DF, Kelly CA, Wendt CW, Hatfield JL (1984) Canopy Temperature and Water-Stress of Cotton Crops with Complete and Partial Ground Cover. *Irrig Sci* 5: 37-46
- Yazar A, Howell TA, Dusek DA, Copeland KS (1999) Evaluation of crop water stress index for LEPA irrigated corn. *Irrig Sci* 18: 171-180

Tables

Table 1

Kc values adopted for scheduling the irrigations in this experiment (from Goldhamer 2005).

Period	K_c
1-15 Apr	0.07
16-30 Apr	0.43
1-15 May	0.68
16-31 May	0.93
1-15 Jun	1.09
16-30 Jun	1.17
1-15 Jul	1.19
16-31 Jul	1.19
1-15 Aug	1.19
16-31 Aug	1.12
1-15 Sep	0.99
16-30 Sep	0.87
1-15 Oct	0.67
16-31 Oct	0.50
1-15 Nov	0.35

Table 2

Parameters of the non-water-stressed baseline ($a + b \cdot \text{VPD}$) at different time of the day presented in Fig. 3. Also given are the parameters for the baseline obtained from all the measurements taken from 1200 to 1500 h. Data obtained from all available days in the well-irrigated Control plot.

hour	Intercept (a)	Slope (b)	R^2
0800	0.28	-1.55	0.77
0900	1.27	-1.68	0.88
1000	1.74	-1.50	0.88
1100	2.35	-1.46	0.89
1200	2.50	-1.36	0.89
1300	2.49	-1.29	0.86
1400	2.46	-1.30	0.87
1500	2.00	-1.30	0.88
1600	0.97	-1.25	0.85
1700	0.48	-1.19	0.75
1200 to 1500	2.44	-1.33	0.87

List of figures

Fig. 1

Mounting position of the infra-red thermometers over the trees.

Fig. 2

Examples of diurnal courses of the canopy temperature (T_c , left side, plots a-b-c) and canopy-air differential ($T_c - T_a$, right side, plots d-e-f). Plots a and d: DOY 169 (18 June), during the deficit irrigation timeframe for the RDI treatment, after 10 days from the last RDI irrigation. Plots b and e: DOY 170 (19 June), during and after an irrigation, but RDI still deficit irrigated. Plots c and f: DOY 227 (15 August), 34 days after the RDI irrigation scheduling was switched to optimum water requirements.

Fig. 3

Changes in the non-water-stressed baseline of a mature pistachio orchard along the day. The slope of the baselines (obtained by regressing $T_c - T_a$ of the well watered crop versus VPD) is almost always the same, while the intercept noticeably moves upward in the morning (a) and downward in the afternoon (b). The bold dashed line in b is the non-water-stressed baseline obtained using data from 1200h to 1500h. Data obtained from all available days in the well-irrigated Control plot.

Fig. 4

Relation between the intercept of the non-water-stressed baseline and the zenith solar angle in clear-sky days.

Fig. 5

Non-water stressed baselines at 1500h in different classes of wind speed. The average wind speeds for the three classes are: 2.1, 3.0 and 4.1 ms⁻¹. Data obtained from all available days in the well-irrigated Control plot.

Fig. 6

Diurnal evolution of CWSI in the Control (black dots) and RDI (black squares) on 3 July 2006 (DOY 184). The values are calculated with 10min average canopy and air temperatures measurements and by varying the NWSB as described in Fig. 3 and Table 2. The bold lines are 5-periods moving averages. Also shown is the midday shaded leaf water potential (Ψ , white circles = Control, white squares = RDI).

Fig. 7

Seasonal evolution of midday shaded leaf water potential (Ψ) in the Control (black dots) and RDI (white squares) treatments. The length of the error bars is the standard deviation. The vertical dotted line marks the end of the RDI stress timeframe.

Fig. 8

Seasonal evolution of CWSI in Control (black dots, dashed thin line) and RDI (white squares, solid thin line), obtained by air and canopy temperatures measurements at 1500h. The bold lines (dashed for the Control and solid for the RDI) are the 7-day moving averages. The arrows indicate the days of irrigation in the two treatments: upward arrows in the Control and downward arrows in the RDI.

Fig. 9

Relation between the mid-day shaded leaf water potential (Ψ) and the CWSI at 1500h measured during the season in the RDI treatment. The error bars are twice the standard deviation.

Figures

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9