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Feasibility of Low-Cost Thermal Imaging for Monitoring Water Stress in Young and Mature Sweet Cherry Trees

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Abstract: Infrared thermography has been introduced as an affordable tool for plant water status monitoring, especially in regions where water availability is the main limiting factor in agricultural production. This paper outlines the potential applications of low-cost thermal imaging devices to evaluate the water status of young and mature sweet cherry trees (*Prunus avium* L.) submitted to water stress. Two treatments per plot were assayed: (i) a control treatment irrigated to ensure non-limiting soil water conditions; and (ii) a water-stress treatment. The seasonal evolution of the temperature of the canopy (Tc) and the difference between Tc and air temperature (ΔT) were compared and three thermal indices were calculated: crop water stress index (CWSI), degrees above control treatment (DAC) and degrees above non-water-stressed baseline (DANS). Midday stem water potential (Ψstem) was used as the reference indicator of water stress and linear relationships of Tc, ΔT, CWSI, DAC and DANS with Ψstem were discussed in order to assess their sensitivity to quantify water stress. CWSI and DANS exhibited strong relationships with Ψstem and two regression lines to young and mature trees were found. The promising results obtained highlight that using low-cost infrared thermal devices can be used to determine the plant water status in sweet cherry trees.

Keywords: water stress; *Prunus avium* L.; stem water potential; low-cost thermography; thermal indexes; canopy temperature; non-water-stressed baselines; non-transpiration baseline

1. Introduction

Irrigated agriculture is the largest consumer of fresh water, accounting for 70% of worldwide water use [1]. In this sense, water availability in arid and semi-arid regions is the main factor limiting agricultural production. These regions are subjected to water constraints and are particularly vulnerable to climate change. As a direct result, it is expected that there will be an increase in the mean air temperature with severe drought events occurring during the high evapotranspiration demand periods, accompanied by an irregular rainfall pattern during the wet periods [2].

In addition, Spain—the largest fresh fruit producer in the European Union—has been experiencing severe water supply issues in recent decades, caused mainly by a structural imbalance between water resources and demand [3]. With regards to sweet cherry (*Prunus avium* L.) production, Spain is the seventh-largest producer of cherries in the world and the second-largest producer in Europe [4]. The application of water-saving strategies to this crop, such as deficit irrigation (DI) procedures, should be a priority for their production in areas with water supply issues. Sweet cherry has been

described as sensitive to water deficit during the pre-harvest period, when water stress could affect fruit development [5]. However, the application of deficit irrigation in the post-harvest period does not negatively affect yield or fruit size [6,7]. To achieve this, tree water status indicators play the main role and lead to better decisions in DI application strategies, leading to favorable water management at the farm level. These indicators are measured and calculated by sensors which are critical for the correct application of DI. Midday stem water potential (Ψstem) is considered the reference indicator for monitoring plant water status in many woody crops such as sweet cherry trees [8–10]. Even though its measurement is laborious, destructive and cannot be automated, it has been described as the most accurate, reliable and stable water status indicator in fruit trees [11]. In recent years, other water status indicators have increased in popularity due to their consistent, accurate and non-destructive measurements, that enable the implementation of automatic irrigation systems. Moreover, some of them are associated with lower costs and simple management devices.

Infrared thermal sensing has emerged as a powerful technology for monitoring crop water status due to its non-destructive and continuous measurement at an affordable cost and at different scales (from individual plants to complete fields) [12,13]. The principle of infrared thermography is based on leaf energy balance [14]. The transpiration process involves water evaporation through stomata and has a cooling effect, which decreases the crop canopy temperature (Tc) [13]. The degree of canopy cooling can be used as an indicator of stomatal conductance and transpiration rate, and hence, as a measure of plant response to water status, as severe water stress will produce a stomatal closure and the Tc will increase [15]. However, Tc does not only depend on stomatal aperture but is also determined by weather variables such as solar incident angle, solar radiation, air temperature and wind speed [13,16]. To normalize the variation and minimize the effect of environmental factors, several thermal indexes were developed and implemented to monitor and quantify water stress. Idso et al. [17] suggested the first index—the difference between the canopy and air temperature Ta (Tc – Ta = ΔT). ΔT was able to minimize the weather variables; however, it was highly dependent on vapour pressure deficit (VPD). Subsequently, Idso et al. [18] and Jackson et al. [19] developed the crop water stress index (CWSI) for establishing stress for crops by determining non-water-stress baselines (NWSB) and non-transpiration baselines (NTB). NWSB and NTB are the lower and upper limits of temperature that the plant canopy would reach, respectively, related to different VPD values. NWSB refers to a non-limiting water condition when the crop is transpiring at the highest rate and NTB refers to non-transpiration conditions with extreme water stress. Recently, several authors have reported a new index, degrees above the non-stressed canopy (DANS), defined as the difference between the actual temperature of the canopy and the NWSB [14,15]. It is much simpler than CWSI and has been successfully used as the water status indicator in different crops. It is yet to have been used for woody crops; thus, it is important to evaluate the feasibility of using DANS for sweet cherry trees.

Thermal and multispectral cameras have been used over recent years for water stress monitoring with unmanned aerial vehicles (UAVs). However, the difficulty and high cost of using UAVs regularly has meant that their use is reduced to specific events in the crop phenology. Conesa et al. [20] recommended that care should be taken when using instantaneous remote sensing indicators to evaluate moderate water deficits in deciduous fruit trees, and more severe/longer water stress conditions are probably needed to detect significant differences.

Low-cost thermal cameras could be an alternative and robust means of obtaining satisfactory thermal information instead of high-resolution cameras, due to their price (around 20-fold cheaper), user familiarity and ease of implementation in the farm context as a precision irrigation tool [21,22]. Furthermore, this technology can be integrated into intelligent sensor systems to use appropriate image-segmentation algorithms, which are capable of identifying regions of interest [23]. However, the lower sensor resolution must be an impediment for remote acquisition or establishing plant water status at larger scales, such as row-level, due to the pixel size [24,25].

The objectives of the present study were (i) to test the feasibility of low-cost thermal imaging using several thermal indicators (Tc, ΔT, CWSI and DANS) to detect and quantify the water status of young

and mature sweet cherry trees subjected to water stress; (ii) to define the non-water-stressed baseline (NWSB) and non-transpiration baseline (NTB) for both cultivations; and (iii) to assess the relationship between thermal indicators and midday stem water potential by linear correlation analysis.

2. Materials and Methods

2.1. Study Site

Two experiments were carried out during 2018 in Murcia (SE Spain). Plot 1 (from 29 June to 1 October, 180–274 DOY) located at the "Tomás Ferro" Experimental Agro-food Station of the Technical University of Cartagena ($37°41'$ N, $0°57'$ W, 32 m elevation, La Palma). The plant material consisted of three-year-old sweet cherry trees (*P. avium* L.), 'Lapins' grafted on 'Mirabolano' rootstock. The trees, planted at a spacing of 3.5 m × 2.25 m, were drip-irrigated by three on-line pressure-compensated emitters per tree, each with a discharge of 2.2 L h^{-1} and fitted on a single lateral per tree row. The irrigation water, with an electrical conductivity ($EC_{25°C}$) of 1.1 dS m^{-1} and pH of 8, was from the Tajo-Segura Water Transfer System. The soil was deep and well-drained, had a sandy-clay-loam texture (34.5% clay, 21.3% silt and 44.2% sand), with an available water capacity of about 0.18 mm^{-1} and bulk density of 1.4 ± 0.1 Mg m^{-3} and a low organic matter content (1.5%). Plot 2 (from 27 April to 7 November, 117–311 DOY) is located in a commercial orchard ($38°8'$ N; $1°22'$ W, 680 m elevation, Jumilla) and consisted of sweet cherry trees (*P. avium* L.) 'Prime Giant' that were fifteen years old grafted onto 'SL64' rootstock, and with 'Brooks' and 'Early Lory' as pollinizers. The tree spacing was 5 m between rows and 3 m within rows. The soil was moderately stony and presented a sandy loam texture (67.5% clay, 17.5% silt and 15% sand), with high available phosphorus (108.67 mg kg^{-1}), low potassium (0.32 meq 100 g^{-1}) and a normal active limestone (2.7%) content. The irrigation water was drawn from a well and it had an average electrical conductivity $EC_{25°C}$ of 0.8 dS m^{-1}. Water was applied using a single lateral with three pressure-compensated emitters (4 L h^{-1}) per tree.

2.2. Treatments

Plot 1: the young sweet cherry trees were irrigated to satisfy the full crop water requirements from the beginning of the irrigation season until July 5 2019. From that date, two irrigation treatments were imposed: (i) a control, YCTL, irrigated daily at 115% of the crop water requirements (ETc) to guarantee the trees were under non-limiting soil water conditions; and (ii) severe deficit irrigation, YS, in which the trees were submitted to two drought cycles that reached a midday stem water potential (Ψstem) of −1.6 MPa and −2.2 MPa in the first and second drought cycle, respectively. After each drought period, a recovery period was applied in which YS trees were irrigated until their Ψstem values reached similar values to the YCTL trees.

Plot 2: In the orchard of mature sweet cherry trees, we applied two irrigation treatments: (i) a control, MCTL, irrigated daily at 110% ETc during all irrigation season to maintain the trees under non-limiting soil water conditions; and (ii) a regulated deficit irrigation, MS, irrigated at 100% of ETc during pre-harvest and the first days of flower differentiation (from April until the end of June) and 55% of ETc post-harvest, from the end of June to November (see Blanco et al. [26] for details). The irrigation doses for both Plot 1 and Plot 2 were calculated using the methodology proposed by Allen et al. [27]: ETc = ET_0 × Kc × Kr, where ET_0 is reference evapotranspiration, Kc is a crop-specific coefficient for sweet cherry reported by Marsal [28], and Kr is a factor of localization related to the percentage of ground covered by the crop [29].

Treatments were distributed according to a completely randomized block design in both Plot 1 and Plot 2. In Plot 1, each treatment consisted of three replicates and each replicate had a row of four trees. The two central trees (6 per treatment) were used to measure stem water potential and canopy temperature. In Plot 2, each treatment had three blocks and each replicate consisted of seven adjacent trees. The measurements were taken in the two central trees per replicate, with the other trees serving as guard trees.

2.3. Field Data

Meteorological variables were collected by two weather stations of the Agricultural Information System of Murcia (CA52 for Plot 1 and JU42 for Plot 2; SIAM, http://siam.imida.es/). Daily reference crop evapotranspiration (ET$_0$) was estimated using the Penman–Monteith equation and daily mean air vapour pressure deficit (VPD) using air temperature and relative humidity data [27]. Additionally, in Plot 1, three microclimate sensors (ATMOS-14, METER Group Inc., Pullman, WA, USA) were installed. The ATMOS-14 sensors were connected to a datalogger (CR1000 with AM16/32B multiplexer, Campbell Scientific Ltd., Logan, UT, USA), programmed to take measurements every 30 s and report mean values every 10 min.

In both experiments, every 2–5 days in Plot 1 and 10–15 days in Plot 2, midday stem water potential (Ψstem) was measured at solar noon (12:00 to 13:00 UT) with a Scholander-type pressure bomb (mod. SF-PRES-70, SolFranc Tecnologías, S.L., 43480 Tarragona Spain) following the recommendations of McCutchan and Shackel [30]. Ψstem was measured in 2 mature leaves per replicate (6 leaves per treatment). The mature and healthy leaves, close to the trunk, were enclosed in small black plastic bags and covered with aluminium foil for 2 h before the measurement.

The canopy temperature (Tc) was measured at the same time as Ψstem with a low-cost thermal camera (ThermalCam Flir One, Flir Systems, Wilsonville, OR, USA) connected to a smartphone. Two images per replicate (n = 6) were taken at 1.5 m from the sunny side of the trees in order to identify the highest differences between irrigation treatments, according to Costa et al. [31] and Jones [13]. The camera uses a thermal sensor with a spectral range of 8–14 μm and 80 × 60 pixels, and a visible-light sensor of 1440 × 1080 pixels with ±2% precision. The emissivity, ε, was set at matt (ε = 0.95), as suggested by Stoll and Jones [32] and Costa et al. [31]. The images were analyzed using the Flir Tools application (Flir One, Flir Systems, Wilsonville, OR, USA). The Tc average of four sunny areas was selected within the same image (24 areas per treatment; Figure 1). The distance of the camera from the canopy, the background temperature, relative humidity and air temperature were used as input to discard the effect of reflection by the object's surface and the radiation emitted by the object's surroundings, according to the methodology proposed by Gómez-Bellot [33] and García-Tejero [22].

Three thermal indices were calculated to mitigate the effect of meteorological variables: (i) The difference between the canopy and air temperature (ΔT); (ii) crop water stress index (CWSI), calculated following the recommendation by Jackson et al. [19]; and (iii) the degree above control treatment (DAC) and degree above non-water-stressed baseline (DANS) were calculated according to Taghvaeian et al. [15]:

$$\Delta T = Tc - Tair, \tag{1}$$

$$CWSI = \frac{\Delta Tc - \Delta T_{wet}}{\Delta T_{dry} - \Delta T_{wet}}, \tag{2}$$

$$DAC = T_S - T_{CTL}, \tag{3}$$

$$DANS = T_c - (Tair + \Delta T_{wet}), \tag{4}$$

where Tc is the canopy temperature; Tair is the air temperature at the moment of the measurement; T_S is the canopy temperature of the water-stress treatment; T_{CTL} is the canopy temperature of the control treatment; ΔT_{wet} and ΔT_{dry} are the differences between canopy and air temperature when the crop has the stomata fully transpiring and fully closed, respectively. According to Idso et al. [18] ΔT_{wet} was calculated from non-water-stress baselines (NWSB; ΔT_{wet} = a + b·VPD). As stated by Jones [34], NWSB was obtained by spraying a thin layer of water on leaves 15 to 30 s before images were taken and ΔT_{dry} was estimated by covering two leaves with a layer of petroleum-jelly (Vaseline) on both sides, blocking all transpiration flows. In this regard, several authors do not empirically calculate ΔT_{dry}, and they work with a value set to 5 °C [22,35,36]. Consequently, with the aim of testing whether ΔT_{dry} can always be taken as 5 °C or should be measured every day, CWSI was calculated from the two different methods depending on ΔT_{dry}.
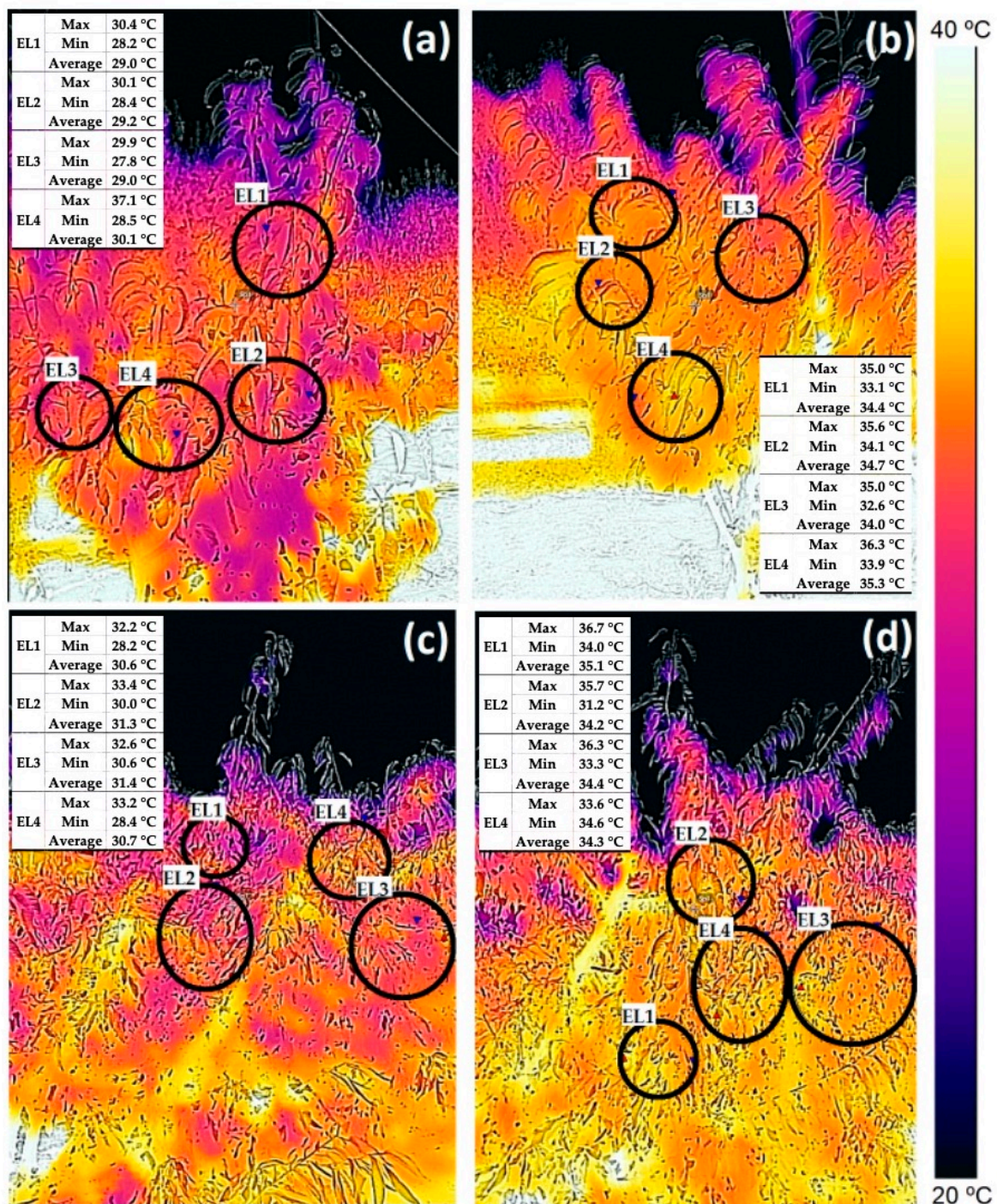
Figure 1. Example of thermal images at plant level taken using Flir One (Flir Systems, Wilsonville, OR, USA) connected to a smartphone for young (**a**,**b**) and mature (**c**,**d**) sweet cherry trees.

2.4. Statistical Analysis

Data were analyzed using statistical software Statgraphics Centurion XVI (StatPoint Technologies Inc., The Plains, VA, USA) and IBM SPSS Statistics (SPSS Inc., 24.0 Statistical package; Chicago, IL, USA). Statistically significant differences among treatments and water stress indicators were determined using analysis of variance (ANOVA) with a significance level of $p < 0.05$. Linear and nonlinear regression analysis among water indicators were determined using Sigmaplot Plus for Windows v.12.5 (Systat Software, San Jose, CA, USA).

3. Results and Discussion

3.1. Environmental Conditions

Environmental conditions at both locations during the experimental period were characteristic of areas with a Mediterranean climate (Table 1). All climatic parameters showed a similar trend with values that increased during spring and early summer and dropped in autumn. Mean temperatures in Plot 1 were generally 3 °C higher than Plot 2. This could be due to the lower daily minimum temperatures recorded in Plot 2 compared to Plot 1. The highest differences in VPD values were recorded during early summer (July) when VPD values in Plot 1 were double those measured in Plot 2.

Table 1. Environmental conditions of Plot 1 (La Palma) and Plot 2 (Jumilla) during the experimental period.

Location	Parameter	May. (121–151) [1]	Jun. (152–181)	Jul. (182–212)	Aug. (213–243)	Sep. (244–273)	Oct. (274–304)	Nov. (305–334)
Plot 1	VPD (kPa)	0.88	1.16	1.10	1.42	0.99	0.71	0.51
	ET_0 (mm d^{-1})	4.99	5.78	6.11	5.34	3.81	2.54	1.60
	P (mm)	3.60	14.00	0.00	0.00	70.20	42.60	106.60
	T (°C)	18.69	22.79	25.62	26.89	24.42	18.91	14.62
Plot 2	VPD (kPa)	0.76	1.27	2.07	1.44	0.83	0.61	0.34
	ET_0 (mm d^{-1})	4.25	5.21	6.07	4.81	3.09	2.09	1.25
	P (mm)	22.95	35.27	0.00	21.17	35.21	22.06	27.95
	T (°C)	15.44	20.44	24.97	23.99	20.61	14.19	9.65

VPD: vapour pressure deficit; ET_0: crop reference evapotranspiration; P: accumulated rainfall; T: mean air temperature. [1]: Day of year.

The highest difference between both experimental sites occurred in late summer. In late August a considerable decline of both air temperature and ET0 occurred in Plot 2, while in Plot 1 the decrease in both parameters was observed in late September.

3.2. Midday Stem Water Potential

Midday stem water potential, Ψstem, accurately reflected the tree water status in both young and mature sweet cherry trees (Figure 2). Ψstem has been reported as a sensitive water stress indicator in mature sweet cherry trees [6,8]; however, there is scarce information about the use of this indicator in young sweet cherry trees, for which pre-dawn stem water potential and midday leaf water potential have been reported as robust water status indicators [37,38].
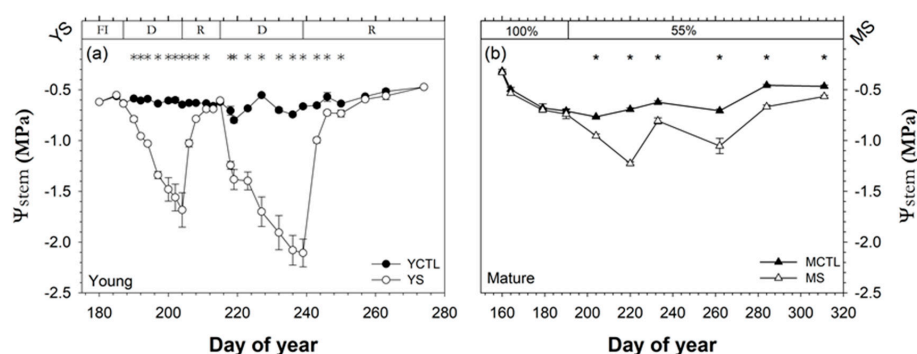

Figure 2. Seasonal evolution of the midday stem water potential (Ψstem) in young (**a**) and mature (**b**) sweet cherry trees during the study period. Each point corresponds to the mean ± standard error of the mean for six measurements per treatment. Asterisks indicate statistically significant differences between treatments by ANOVA ($p < 0.05$). CTL and S correspond to control and deficit irrigation treatment for young (Y) and mature (M) sweet cherry trees, respectively. FI is full irrigation period, D is drought period and R is recovery period in young sweet cherry trees (Plot 1), and 100% and 55% are the percentages of crop water requirements (ETc) applied to mature sweet cherry trees (Plot 2).

The mean Ψstem measured in young and mature CTL trees was between −0.5 and −0.7 MPa, values typical of well-watered trees. These differences in water potential of control trees were due to changes in the climatic demand. Regarding the water stress treatments, the lowest Ψstem values were measured in young trees which were submitted to two drought and recovery cycles, with minimum values that fell below −1.7 and −2.1 MPa for the first and second cycle, respectively. After irrigation was resumed, recovery of Ψstem in young sweet cherry trees was rapid in both cycles. The Ψstem values measured in the young trees showed that they were submitted to severe water stress. During the first drought period, Ψstem in young sweet cherry trees continuously declined from values similar to those of CTL trees down to −1.7 MPa in 16 days, and needed eight days of full irrigation to exhibit similar values to CTL trees. During the second drought cycle, a steeper drop of Ψstem was observed, and the minimum value reached −2.1 MPa (Figure 2a). Ψstem values measured were lower than those reported by Higgs et al. [39] for unirrigated young sweet cherry trees.

In the mature trees (Figure 2b), deficit irrigation trees resulted in Ψstem values that remained above −1.5 MPa, which could be considered a mild–severe water stress that would not compromise the tree's yield the following year [5,40]. Water stress in mature trees resulted in different rates depending on the evaporative demand. Thus, in mid-August (DOY 229, 230), as a result of several rainy episodes in Plot 2, the ET_0 decreased from 6 mm day^{-1} to 3 mm day^{-1} and consequently, mature trees exhibited higher Ψstem values. Similarly, at the end of the season, the evaporative demand decreased and the trees of the deficit treatment resulted in Ψstem values similar to those measured in control trees.

3.3. Canopy Temperature

The pattern of Tc was in accordance with the evolution of Ψstem in young sweet cherry trees (Figure 3); however, in mature trees it was not possible to differentiate between the control and water-stressed trees at the end of the season (September, DOY 270 onwards) using the temperature of the canopy, when the air temperature significantly decreased from 24 to 13 °C (Figure 3a,b).
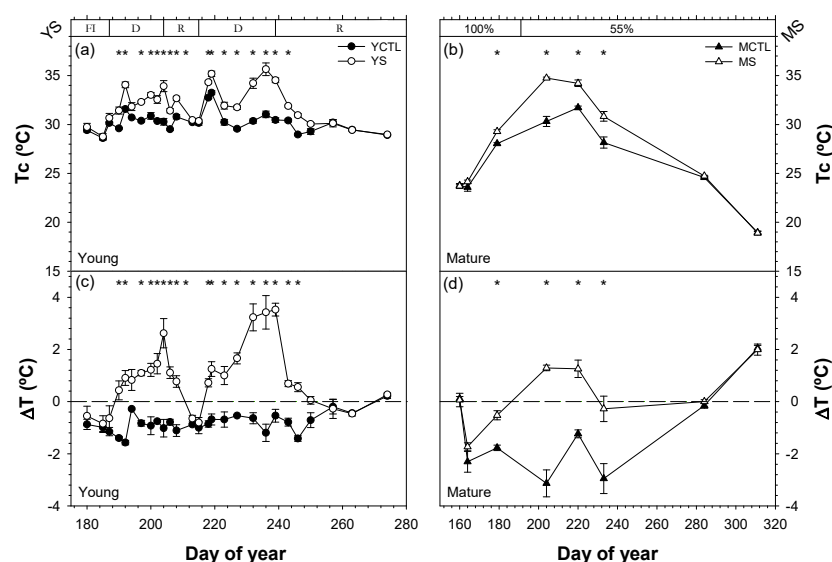

Figure 3. Seasonal evolution of the canopy temperature (Tc) and the difference between canopy and air temperature (ΔT) in young (**a**,**c**) and mature (**b**,**d**) sweet cherry trees during the study period. Each point corresponds to the mean ± standard error of the mean for six images per treatment. CTL and S correspond to control and deficit irrigation treatment for young (Y) and mature (M) sweet cherry trees, respectively. Asterisks indicate statistically significant differences between treatments by ANOVA (*p* < 0.05). FI is full irrigation period, D is drought period and R is recovery period in young sweet cherry trees (Plot 1), and 100% and 55% are the percentages of ETc applied in mature sweet cherry trees (Plot 2).

As expected, young and mature control trees had lower values of canopy temperature minus air temperature than water-stressed trees during the period of water restriction (Figure 3c,d). Regarding the control trees, it was observed that mature control trees had a canopy temperature on average 2.5 °C below the temperature of the air, while in the same period the young trees had a temperature of the canopy only 1 °C below the air temperature. This difference in ∆T of control trees depended on their age, according to Taghvaeian et al. [15], who related the influence of leaf area on the temperature of the plants. Thus, mature trees with greater canopy volume exhibited lower canopy temperatures than young trees with lower canopy volume.

The maximum ∆T was measured on DOY 239 in stressed young trees (3.5 °C), which was the day with the lowest Ψstem (−2.1 MPa, Figure 2a). The difference in canopy temperature between stressed and control young trees was higher than 4 °C on that day. These results indicated a smaller difference than that reported by Ballester et al. [41] and Wang and Gartung [42] in non-irrigated citrus (∆T = 5.0 °C) and peach trees (∆T = 6.5 °C) under similar values of Ψstem (<−2.0 MPa). Similarly, the maximum difference of ∆T observed between water-stressed and control mature trees was 4.4 °C (DOY 204, Figure 3d). The difference of 4.4 °C between treatments was mainly due to the contribution of the control trees (ΔT_{MCTL} = −3.1 °C) rather than the high value of the temperature of the canopy of water-stressed trees above the air temperature (ΔT_{MS} = 1.3 °C). These values of canopy temperatures that were lower than the air temperature in control sweet cherry trees are similar to those reported in almond [43] and peach trees [42], but are contrary to those recorded for orange trees [44]. This difference with citrus trees might be due to the stomatal closure of citrus trees at midday, which increases the leaf temperature even though the tree has no soil water restrictions, while in well-watered *Prunus* trees this does not occur [45,46].

Data from control and water-stressed trees were pooled to determine the upper (non-transpiration) and lower (non-water-stress) baselines for the mature and young sweet trees (Figure 4). All the obtained equations for the non-water-stress baselines showed a strong linear relationship between VPD and canopy temperature of sunny leaves (Table 2). Regardless of the different location and age of trees, the non-water-stress baseline did not differ among them, and fitted in the linear regression: ∆T = 3.87 − 2.62·VPD (R^2 = 0.91). Mature trees overestimated ∆T by 1 °C compared to young trees for the lowest VPD value (1 kPa), and underestimated by 1.3 °C for the highest value (4 kPa). The non-transpiration baseline obtained for both young and mature trees achieved 6 °C, a similar value to that reported in peach trees under semiarid climate conditions by Paltineanu et al. [47] and 1 °C above the stated value of 5 °C reported by Jones et al. [35].
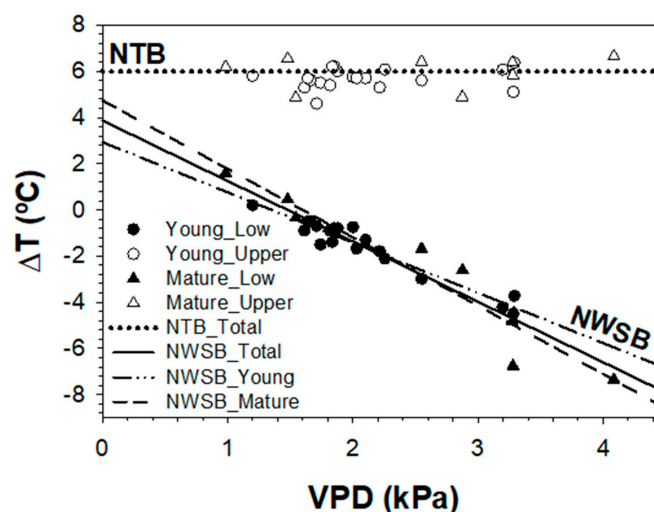

Figure 4. Non-water-stress baselines (NWSB) and non-transpiration baselines (NTB) for young and mature sweet cherry trees. VPD is vapour pressure deficit and ∆T is the difference between canopy and air temperature.

Table 2. Fitted parameters for the non-water-stress baselines ($\Delta T_{wet} = a + b \cdot VPD$) for young and mature sweet cherry trees.

Treatment	Slope (°C kPa^{-1})	Intercept (°C)	R^2
Young sweet cherry trees	−2.174	2.936	0.93
Mature sweet cherry trees	−2.962	4.738	0.92
Global relationship	−2.618	3.868	0.91

3.4. Crop Water Stress Index and Degrees above Non-Stress

CWSI was calculated based on the methodology proposed by Idso et al. [19], which uses a water stress baseline of 5 °C, and with the baselines we obtained from our measures in non-transpiring leaves (Figure 5). In accordance with the results obtained, both methodologies showed similar results; however, the method of Idso et al. [19] led to slightly higher CWSI maximum values.
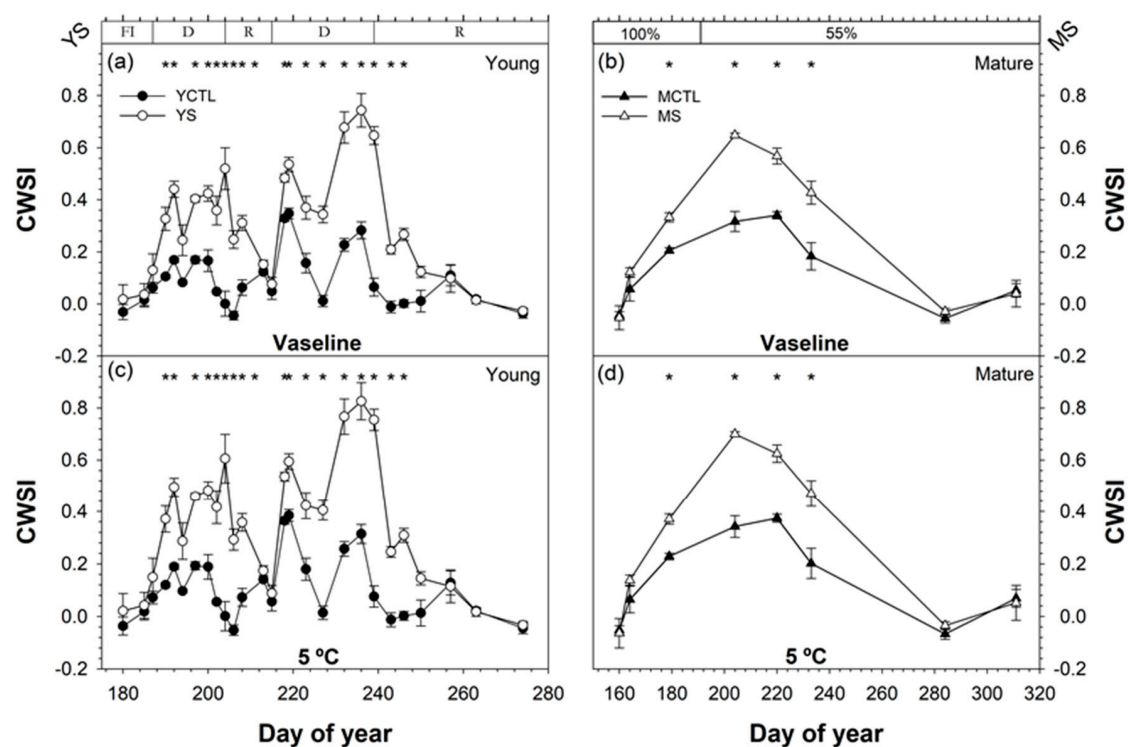
Figure 5. Seasonal evolution of the crop water stress index (CWSI) calculated using a transpiration inhibitor [22] (**a**,**b**) and ΔT_{dry} equal to 5 °C (**c**,**d**) in young (**a**,**c**) and mature (**b**,**d**) sweet cherry trees. Each point corresponds to the mean ± standard error of the mean for six images per treatment. Asterisks indicate statistically significant differences between treatments by ANOVA ($p < 0.05$). CTL and S correspond to control and deficit irrigation treatment for young (Y) and mature (M) sweet cherry trees, respectively. FI is full irrigation period, D is drought period and R is recovery period in young sweet cherry trees (Plot 1), and 100% and 55% are the percentages of ETc applied in mature sweet cherry trees (Plot 2).

In general, the control treatment in both young and mature trees exhibited CWSI values significantly lower than those of water-stressed trees. The CWSI values of control trees ranged from −0.05 to 0.35 (Figure 5). Negative CWSI values were measured on days of low evaporative demand and high Ψstem (−0.5 MPa, Figure 2), and have been related to increased transpiration in almond trees [48]. The water-stressed treatment exhibited CWSI values that achieved 0.75 and 0.65 for young and mature sweet cherry trees, respectively, calculated with the upper baseline of 6 °C (Figure 5a,b). These CWSI values obtained in water-stressed trees were similar to those reported in nectarine trees [49] but are lower than

those described in almond trees [48,50], which reached values close to 1 on dates with similar values of ΔT (4.0 °C). When the evolutions throughout the experiment of CWSI and ΔT were compared, a trend that CWSI values presented sharper peaks and troughs and greater oscillations than the evolution of ΔT values was observed, particularly in young trees. However, CWSI as a water stress indicator showed significant differences between treatments on the same days that ΔT showed differences, and the absolute minimum and maximum values occurred on the same days in both water stress indicators.

The DANS index followed the same pattern of significance as the CWSI, with significant differences between treatments on the same dates. The DANS values of young and mature water-stressed trees ranged from slightly below 0.0 °C when they were irrigated as control trees to over 8 °C at the time with the highest difference (DOY 236 and 207 for young and mature trees, respectively; Figure 6). Contrary to CWSI, the DANS index exhibited higher values in mature trees than young trees (Figure 6c,d), despite the young trees being submitted to greater water stress. Regarding the DAC index, in young trees the seasonal evolution was barely higher than results obtained by ΔT; on the other hand, in mature trees, the DAC index resulted in values which achieved a 4.4 °C difference between control and water-stressed trees, while on the same dates ΔT did not achieve values higher than 2.0 °C (Figure 6a,b).
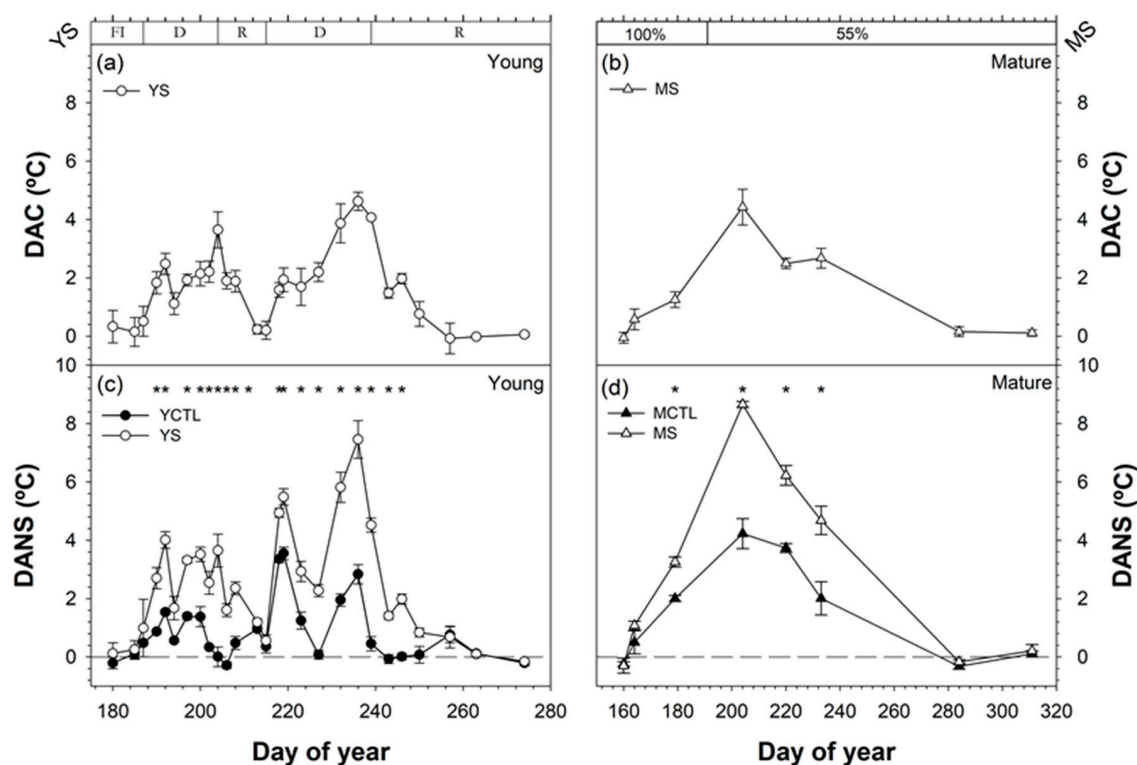

Figure 6. Seasonal evolution of degrees above control (**a**,**b**) and non-stressed (**c**,**d**) in young (**a**,**c**) and mature (**b**,**d**) sweet cherry trees during the study period. Each point corresponds to the mean ± standard error of the mean for six images per treatment. Asterisks indicate statistically significant differences between treatments by ANOVA ($p < 0.05$). CTL and S correspond to control and deficit irrigation treatment for young (Y) and mature (M) sweet cherry trees, respectively. FI is full irrigation period, D is drought period and R is recovery period in young sweet cherry trees (Plot 1), and 100% and 55% are the percentages of ETc applied in mature sweet cherry trees (Plot 2).

A linear relationship between the thermal indicators and Ψstem was calculated. The Tc showed a non-linear relationship with Ψstem (Figure 7a). As expected, higher Tc values were related to trees submitted to water stress (MS and YS). Although the coefficient of correlation obtained between Ψstem and Tc for all the trees exhibited a strong relationship (r = 0.73), Tc as a water stress indicator showed important limitations. Thus, the second-grade polynomial relationship obtained showed

two different relationships. At first, Tc increased linearly as Ψstem fell from −0.5 MPa to a threshold value close to −1.0 MPa, which corresponded to 33 °C. From that value onwards, Ψstem values below −1.0 MPa were not related to higher values of Tc. It was observed that Tc did not exceed values above 36 °C regardless of the intensity of the water deficit applied. Consequently, within the Tc range between 33 and 36 °C, similar values were measured in CTL trees on a hot day of high evaporative demand (Ψstem = −0.8 MPa) and in sweet cherry trees under severe water stress (Ψstem = −2.0 MPa). Therefore, while it is known that in sweet cherry trees water deficit induces stomatal closure and increases leaf temperature [6,8], it is also well known that Tc is highly dependent on tree density, canopy architecture, tree phenological stage and environmental conditions [14,51]. In light of this, the use of absolute values of Tc cannot be recommended as a water stress indicator.
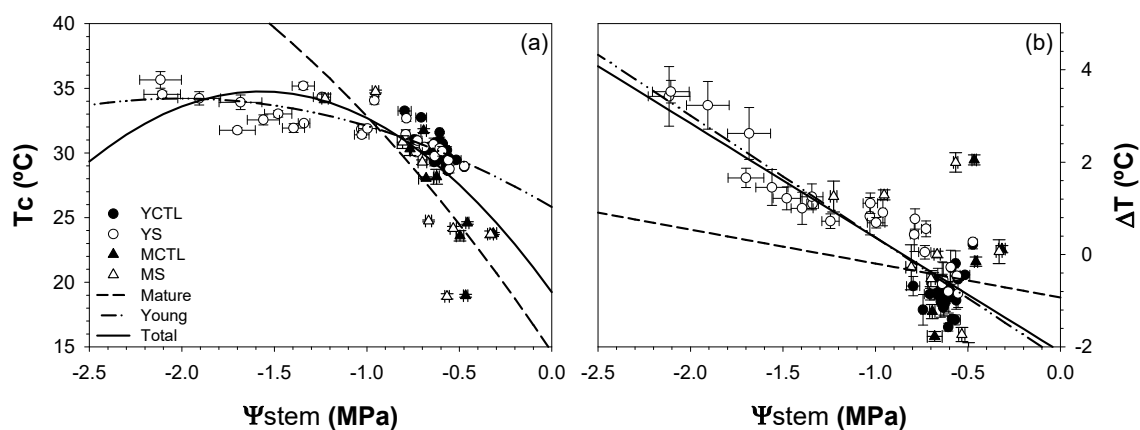
Figure 7. (**a**) Relationship between midday stem water potential (Ψstem) and canopy temperature (Tc). (**b**) Relationship between Ψstem and the difference between canopy and air temperature (ΔT). Each point corresponds to the mean ± standard error of the mean of six measurements per treatment. CTL and S correspond to control and deficit irrigation treatment for young (Y) and mature (M) sweet cherry trees, respectively.

The ΔT exhibited a linear relationship with Ψstem (Figure 7b). The negative ΔT values obtained by CTL trees (young and mature) were related to Ψstem values below −0.8 MPa, which corresponded to trees under non-limiting soil water conditions. In sweet cherry trees under post-harvest deficit irrigation, −1.5 MPa is generally considered a threshold value for irrigation management and higher values have been reported not to negatively affect the yield in the following year and reduce excessive vegetative growth [5]. In this sense, 1.6 °C has been suggested as the ΔT corresponding value to −1.5 MPa. The relationship between Ψsteam and ΔT was significantly different in young and mature trees. The weaker relationship found in mature trees is due to the fact that MS trees did not reach Ψstem values below −1.3 MPa (Figure 2b). The consistent relationship found in the young sweet cherry trees (r = 0.91) was similar to that reported in peach trees by Wang and Gartung [42] and higher than that reported in almond trees by García-Tejero et al. [52] with similar ΔT maximum values at 3.6 °C and Ψstem values below −2.0 MPa. According to the results obtained, ΔT was less dependent than Tc on weather conditions, clearly identified control and stressed trees, and did not show any inflexion point in its relationship with Ψstem. Consequently, these advantages of ΔT over Tc highlight its utility as a water stress indicator.

Similar to ΔT, CWSI showed a strong linear relationship with Ψstem (Figure 8). Young and mature trees resulted in high correlation coefficients (r = 0.89 and 0.88, respectively). These results are similar to those reported in sweet cherry trees by Köksal et al. [53] on the relationship between CWSI and leaf water potential. The correlation between Ψstem and CWSI was identified as CWSI = −0.44 Ψstem = −0.17 in young sweet cherry trees and as CWSI = −0.86 Ψstem = −0.36 in mature sweet cherry trees. Regarding the different regression lines found in young and mature trees, Oberhuber et al. [54] reported that young trees have a greater capacity to extract water from water reserves in their organs

(water storage tissues) than mature trees, and quickly transport it through the plant with the aim of sustaining leaf transpiration. Mature trees require a larger amount of water for their transpiration process because they have a greater leaf area, release more water to the atmosphere and have a proportionally smaller water reserve. Consequently, the mechanism used by mature trees to face water stress does not only consist of recruiting water from the water storage tissues but to promote stomatal closure. Stomatal closure avoids plant water release, decreases tree transpiration, and leads to an increase in leaf temperature [8]. These increments in leaf temperature of mature sweet cherry trees are referred to against the same baselines for young sweet cherry trees (Figure 4). Therefore, for a similar value of Ψstem, mature trees exhibit higher CWSI values. However, despite the difference in results for young and mature trees, it can be stated for both of them that CWSI values lower than 0.2 match with Ψstem values of well-watered trees.
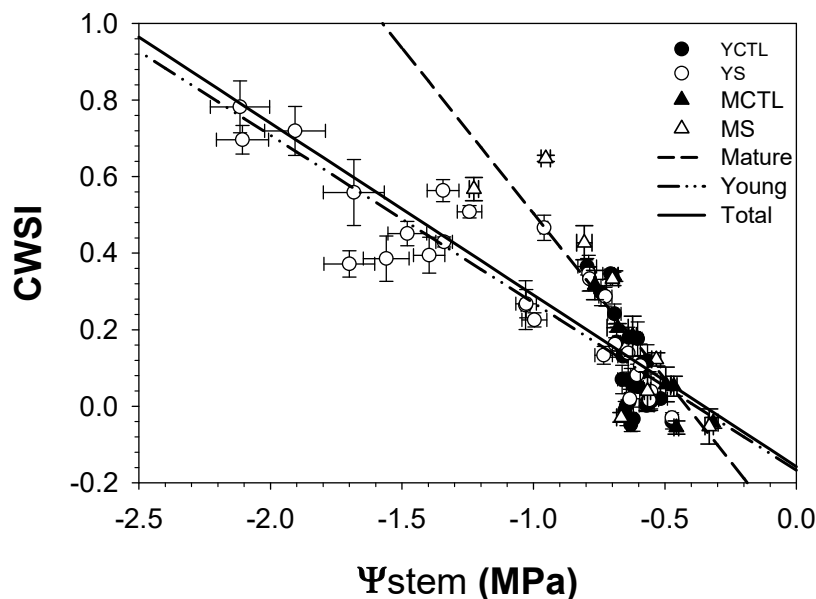
Figure 8. Relationship between midday stem water potential (Ψstem) and crop water stress index (CWSI). Each point corresponds to the mean ± standard error of the mean of six measurements per treatment. CTL and S correspond to control and deficit irrigation treatment for young (Y) and mature (M) sweet cherry trees, respectively.

Similar to CWSI, when DAC and DANS indices were compared to Ψstem, young and mature trees, they showed significantly different linear regressions (Figure 9a,b). In the case of the DAC index, young trees were more closely related to Ψstem than mature trees (r = 0.9 and 0.76, respectively), with maximum values of 4.5 °C. In the case of the DANS index, mature and young trees were closely related (r = 0.84), and the maximum value (8.6 °C) was found in mature trees at −0.95 MPa. As expected according to the results reported by Taghvaeian et al. [15], DAC and DANS were strongly related to CWSI, especially DANS (Figure 9c,d).

In general, water stress indicators derived from thermal imaging evaluated in the present work were not sensitive enough to detect slight plant water stress in sweet cherry trees, due to Tc strongly depending on both stomatal conductance and transpiration rate, which are physiological processes that are less sensitive than other plant water indicators such as micrometric fluctuation of the different plant organs (trunk, branch, fruit, etc.) [8,11,55]. This limitation has been observed in all indices and has been reported in several fruit trees such as apple, citrus and nectarine [56–58]. This is because water status indicators based on leaf temperature when the soil water deficit is not moderate or severe are highly dependent on weather conditions. However, when trees were submitted to moderate water stress, CWSI, ΔT and DANS were robust water indicators able to assess young and mature sweet cherry tree water statuses.
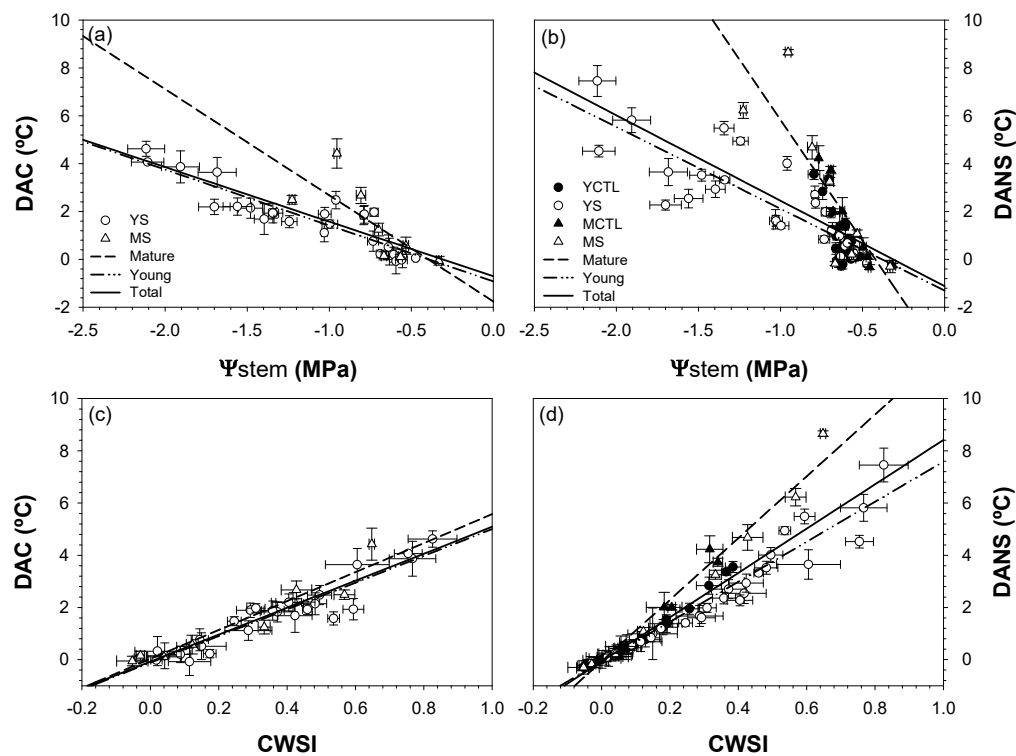
Figure 9. Relationship between midday stem water potential (Ψstem) and (**a**) degree above control treatment (DAC) and (**b**) degree above non-stress baseline (DANS). Relationship between crop water stress index (CWSI) and (**c**) DAC and (**d**) DANS. Each point corresponds to the mean ± standard error of the mean of 6 measurements per treatment. CTL and S correspond to control and deficit irrigation treatment for young (Y) and mature (M) sweet cherry trees, respectively.

4. Conclusions

The use of thermal imaging obtained from low-cost devices provided reliable data which were used to obtain the thermal indicator Tc and to calculate the thermal indices ΔT, CWSI, DAC and DANS to assess the response of young and mature sweet cherry trees submitted to water stress. Our results revealed that Tc was highly dependent on weather conditions, while the thermal indices mitigated this dependency, so the use of Tc in water stress detection is not recommended. ΔT was highly influenced by VPD, and when upper and lower baselines were obtained there were no differences found either between young and mature sweet cherry trees or between plots, which supports the use of the proposed baselines. CWSI and DANS were strongly related to Ψstem and were calculated on the basis of the experimental non-water-stress baseline and water stress baseline, over arange of VPD values between 1 and 4 kPa. The DANS index differentiated between irrigation treatments as well as CWSI, despite being much easier to calculate than CWSI, and exhibited a strong relationship with Ψstem. These results indicate that the DANS index is a promising thermal index which can be used in fruit tree water assessment. It must also be added that CWSI and DANS resulted in different regression lines with Ψstem, depending on the plot studied. These differences might not be solely attributable to the different age of the trees but also to the different soil and weather conditions of each plot. When thermal indices were compared with Ψstem, it was observed that, under non-limiting soil water conditions (values below −0.7 MPa), all indices were highly influenced by climatic conditions. Moreover, despite thermal indices being a non-invasive and fast means with which to assess tree water status, Tc strongly depends on crop transpiration rate. This is a limiting factor in the interpretation of thermography data for the early detection of water stress, so in phenological stages when even slight water stress must be avoided, its use should be coupled with other water status indicators. However, when deficit irrigation was applied, CWSI and DANS could be considered reliable water

stress indicators. The results of this study could help improve sweet cherry cultivation, as well as other *Prunus* fruit trees with similar phenology and water stress behavior such as extra early plum trees, and not only in areas where water is scarce, but in regions where water availability is not currently a problem and sweet cherry trees are mainly rainfed, to assess the tree water status.

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