Assessing the Water-Stress Baselines by Thermal Imaging for Irrigation Management in Almond Plantations under Water Scarcity Conditions

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Abstract: This work examines the use of thermal imaging to determine the crop water status in young almond trees under sustained deficit irrigation strategies (SDIs). The research was carried out during two seasons (2018–2019) in three cultivars (Prunus dulcis Mill., cvs. Guara, Lauranne, and Marta) subjected to three irrigation treatments: a full irrigation treatment (FI) at 100% of irrigation requirements (IR), and two SDIs that received 75% and 65% of the IR, respectively. Crop water monitoring was done by measurements of canopy temperature, leaf water potential ($\Psi_{\text{leaf}}$), and stomatal conductance. Thermal readings were used to define the non-water-stress baselines (NWSB) and water-stress baselines (WSB) for each treatment and cultivar. According to our findings, $\Psi_{\text{leaf}}$ was the most responsive parameter to reflect differences in almond water status. In addition, NWSB and WSB allowed the determination of the crop water-stress index (CWSI) and the increment of canopy temperature ($\Delta T_C$) for each SDI treatment, obtaining threshold values of CWSI (0.12–0.15) and $\Delta T_C$ (~1 °C) that would ensure maximum water savings by minimizing the effects on yield. The findings highlight the importance of determining the different NWSB and WSB for different almond cultivars and its potential use for proper irrigation scheduling.

Keywords: thermography; irrigation scheduling; thermal indexes; crop water status

1. Introduction

Irrigation performs an essential role in agriculture. As such, the increase in total irrigated area, coupled with scarce water resources, has encouraged the implementation of irrigation strategies that optimize the water-use efficiency. Specifically, in areas such as southern Spain, this supply is crucial for the proper development of woody crops, when the maximum evapotranspiration rates coincide with the rainfall absence. Considering the current scenarios of climatic change and water scarcity, the adaptation and sustainable strategies to boost the proper water management in irrigated crops is vital [1]. Among them, deficit irrigation (DI) has been implemented to enhance the yield, reducing the irrigation supplies and maximizing the crop productivity [2]. According to this, the implementation
of DI in many arid and semi-arid irrigated areas has been addressed, especially in representative Mediterranean woody species, namely olive [3], mango [4], walnut [5], citrus [6], or pistachio [7], among others.

Almond (Prunus dulcis Mill.) is considered as drought-tolerant crop, and for the case of Spain it has been traditionally cultivated in rainfed and marginal areas; although, recently, its presence in irrigated areas has progressively increased [8]. Because of the representativeness of this crop in arid and semi-arid regions, many authors have already studied its yield response to DI strategies, obtaining significant improvements in terms of water savings without substantial losses in almond yield [9–11]. In addition, different experiments have corroborated that the optimum period to apply moderate-to-severe water restrictions coincides with stage IV (kernel-filling period) [12,13], and hence, most of them have been developed introducing different water withholdings during this period.

Moreover, the success of applying a proper irrigation schedule based on DI strategies requires crop water monitoring by means of plant-based measurements, defining thresholds to maintain water restrictions during phenological development without compromising the final production [14]. Traditionally, this assessment has been done by punctual measurements of stem or leaf water potential (Ψ_leaf) or stomatal conductance (gs), with high representation of the crop water status but a low convenience and practical usage [15], hampering the taking of decisions for irrigation scheduling [16]. Alternatively, canopy temperature (TC) and the related thermal indexes have been recognized as proper indicators of crop water status [17,18], because of their relationship with crop transpiration rates [19]; hence, techniques that are less time-consuming, such as thermography, have been widely accepted [20–23]. Thus, when water restrictions are applied, the plant responds by closing the stomata (reducing gs and transpiration), minimizing the water losses by the leaf and, therefore, increasing the leaf temperature.

Additionally, thermal imaging provides information of the whole canopy, and hence this technique offers the possibility of developing fast spatio-temporal measurements and water status monitoring on a whole-plant basis [24]. However, in accordance with Jones [25] and Jones and Vaughan [26], there are many climatic variables, such as radiation, atmospheric temperature, vapor pressure deficit (VPD), relative humidity, wind, or air convection, that may influence the leaf temperature; thus, not only the water status effects. Therefore, to avoid the effects of these environmental variables, thermal indexes to monitor crop water stress have been defined to normalize the absolute canopy temperature (Tc) readings, such as the crop water-stress index (CWSI), the thermal index to relative stomatal conductance (Ig), or the difference between the canopy and air temperature (∆T_canopy-air) [25,27]. In the case of CWSI or Ig, reference values for well-watered and non-transpiring Tc are required, which provide theoretical lower and upper Tc values for the current environmental conditions. This fact substantially hampers the applicability of these indexes, which normally are obtained by means of artificial measurements of reference materials or leaves that have been previously exposed to modified conditions, which is rather complex and time-consuming [22,23]. To prevent these constraints, the difference between the air and canopy temperature (∆T_canopy-air) is widely used as a simpler thermal index, offering interesting results for crop-water monitoring and irrigation scheduling [28]. Even so, ∆T_canopy-air can substantially change because of other environmental conditions. In order to solve this situation, non-water-stress baselines (NWSB) and water-stress baselines (WSB) are defined. These linear functions relates the values of ∆T_canopy-air with the VPD registered during the Tc readings [22] for fully irrigated and DI strategies, respectively. Moreover, these WSBs can be defined for different levels of water restrictions, establishing a correspondence between a hypothetical WSB and the potential yield losses induced by the water stress imposed.

In addition, when these baselines are obtained under fully irrigated conditions, these can be used to determine the lower and upper limits for the CWSI estimation, as was suggested by Idso et al. [29], enabling the irrigation scheduling and taking decisions.

Furthermore, the NWSB permits to compute the increment of Tc (ITc), which is the difference between the ∆T_canopy-air obtained for a hypothetical irrigation strategy and its corresponding NWSB.
value, using the VPD of that particular day [14]. In this line, one step further towards to DI programming would be to obtain the most appropriate WSB, which would correspond to that obtained for the treatment, and ensure the maximum water saving and minimum yield loss. Moreover, this WSB would allow defining the threshold IT_C, providing the advisable value for the maximum deviation from the NWSB.

Taking these points into consideration, the objectives of this study were (i) to determine the NWSB for three studied almond cultivars during the kernel-filling period; (ii) to define the WSB for two different water-stress levels; and (iii) to establish a protocol to manage the irrigation scheduling by means of these functions and its relation with the yield.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted during the kernel-filling and postharvest period (June to September) in two consecutive years (2018 and 2019), in a commercial almond (P. dulcis Mill. cvs. Guara, Marta, and Lauranne) orchard, grafted onto GN15 rootstock, and located in the Guadalquivir river basin (SW Spain, 37°30′27.4″ N, 5°55′48.7″ W). Trees were planted in 2013, spaced 8 m × 6 m, and drip irrigated using two pipelines with emitters of 2.3 L h⁻¹, spaced at 0.75 m intervals. Canopy volumes were very similar within each cultivar, without differences between irrigation treatments. Thus, for Marta, canopy volumes ranged between 64 and 65 m³; Guara trees, between 65 and 66 m³; and Lauranne, trees between 72 and 74 m³.

The soil was a silty loam, a typical Fluvisol, more than 2 m deep, with organic matter <1.5%. Roots were located predominately in the first 50 cm of the soil, corresponding to the intended wetting depth. Soil water content values at field capacity (−0.33 MPa) and permanent wilting point (−1.5 MPa) were close to 0.40 and 0.15 m³ m⁻³, respectively.

The climatic classification of the study area was attenuated meso-Mediterranean with a hot-summer Mediterranean climate (csa) in the Köppen climate classification [30], with an annual ET₀ rate of 1400 mm, an average temperature of 18 °C, and accumulated rainfall of 540 mm (average data corresponding to the last 15 years (2004–2019); obtained from the Andalusian Weather information Network).

2.2. Irrigation Treatments

Three irrigation treatments were designed as follows: (i) a fully irrigated treatment (FI), which received 100% of the irrigation requirements (IR) during the whole irrigation period; (ii) a sustained deficit irrigation (SDI₇₅) treatment, which received 75% of the IR; and (iii) a sustained deficit irrigation (SDI₆₅), which received 65% of the IR.

In both seasons, irrigation was applied from the middle of March to the end of October, and these doses were calculated according to the methodology proposed by Allen et al. [31] (Equations (1) and (2)); obtaining the values of reference evapotranspiration (ET₀) by using a weather station installed in the same experimental orchard (Davis Advance Pro2, Davis Instruments, Valencia, Spain).

\[
ET_C = K_C \times K_r \times ET_0 \quad (1)
\]

\[
IR \ (\text{mm}) = (ET_C - \text{Rainfall}) \quad (2)
\]

where ET_C is the crop evapotranspiration; K_C is the single-crop coefficient; K_r is the crop reduction coefficient, which depends on the percentage of shaded area cast by the tree canopy; ET₀ is the reference evapotranspiration; and IR is the irrigation requirements.

The local monthly K_C and K_r used during the experimental period are shown in Table 1, as was determined by García-Tejero [32]. Additionally, the IR was reduced for SDI₇₅ and SDI₆₅ by multiplying it by 0.75 and 0.65, respectively.
**Table 1.** Local crop reduction and crop coefficient values used in the experiment.

| Coefficients | March | April | May | June | July | August | September | October |
|--------------|-------|-------|-----|------|------|--------|-----------|--------|
| Kc           | 0.4   | 0.6   | 0.9 | 1.1  | 1.2  | 1.1    | 0.8       | 0.7    |
| Kt           | 0.4   | 0.7   | 0.8 | 0.9  | 0.9  | 0.8    | 0.8       | 0.7    |

2.3. Plant Measurements

During the kernel-filling period (162–225 days of the year (DOY) in 2018; and 162–217 DOY in 2019), crop water monitoring was done throughout the measurements of the leaf water potential (Ψ<sub>leaf</sub>), stomatal conductance, water vapor (g<sub>s</sub>), and canopy temperature (T<sub>C</sub>); all these readings were taken between 12:00 and 13:30 GTM, and with a periodicity of 7–10 days.

The g<sub>s</sub> was measured using a porometer SC-1 (Decagon Devices, INC, WA, USA) in two leaves per tree (monitoring 8 trees per irrigation treatment) fully developed, and completely exposed to the sun, with the aim of monitoring the maximum values of g<sub>s</sub> and detecting the most detectable differences among the irrigation treatments. The selected leaves were at 1.5 m of height, approximately, and were SE facing. On the other hand, the Ψ<sub>leaf</sub> was measured using a pressure chamber (Soil Moisture Equipment Corp., Sta. Barbara, CA, USA), monitoring two leaves per tree, located on the north side of the tree and being totally mature, fresh and shaded, with the aim of minimizing the measurements variability. Selected leaves were at 1.5 m of height, approximately, and NW facing.

Considering the results obtained by García-Tejero et al. [33], who reported that the best moment for assessing the T<sub>C</sub> was between 11:30 and 14:30, and in the sunny side of canopy, thermal images were taken following this procedure: using a ThermaCam (Flir SC660, Flir System, USA, 7–13 µm, 640 × 480 pixels) and an emissivity (ε) of 0.96 (Figure 1). Readings were developed at the sunny side of the canopy, placing the camera at a 4 m distance from the monitored tree, approximately. Afterwards, images were analyzed using the Flir Research Pro Software (Flir System, USA), which allows to select different zones of the images (in our case; 4 different sunny areas per image were selected); each pixel corresponding to an effective temperature value [19].

Once the images were obtained, T<sub>C</sub> was calculated for each treatment, cultivar, and monitoring day, and after this, the thermal index ΔT<sub>canopy-air</sub> was calculated. Taking into consideration the ΔT<sub>canopy-air</sub> values and the VPD registered during the data acquisition, the NWSB and WSB were defined according to Equation (3); these functions corresponding to trees that were subjected to different irrigation doses, and allow to estimate the optimum values of ΔT<sub>canopy-air</sub> for each treatment depending on the VPD values [29].

\[
ΔT_{canopy-air} = b + a \times VPD
\]

where \(b\) and \(a\) are the intercept point and slope of the linear function.

Additionally, taking as reference the NWSB obtained for each cultivar, the CWSI along the monitoring period for each DI treatment was estimated, according to Equations (4) and (5):

\[
CWSI = \frac{ΔT_{canopy-air} - ΔT_{wet}}{ΔT_{dry} - ΔT_{wet}}
\]

where ΔT<sub>canopy-air</sub> corresponds to the canopy readings obtained in each treatment and cultivar; ΔT<sub>wet</sub> is the lower limit calculated from the NWSB equation in each cultivar; and ΔT<sub>dry</sub> is the upper limit obtained according to the methodology proposed by Idso et al. (1981).

\[
ΔT_{dry} = b + a[e_s(T_{air}) - e_s(T_{air} + b)]
\]

where \(a\) and \(b\) are the slope and the interception point for the NWSB; \(e_s(T_{air})\) is the saturated vapor pressure at air temperature; and \(e_s(T_{air} + b)\) is the saturated vapor pressure at the sum of the air temperature and interception point.
2.4. Experimental Design and Statistical Analysis

The experimental design was of randomized blocks, with four replications per irrigation treatment and cultivar. Each replication had 12 trees (3 rows and 4 trees per row); the two central trees for each replication were monitored. Thus, eight trees per irrigation strategy treatment were used. Statistical analysis was done by using the Sigma Plot statistical software (version 12.5, Systat Software, Inc., San Jose, CA, USA). For each measurement day, an exploratory and descriptive analysis of the data (\(T_C\), \(\Psi_{leaf}\), and \(g_s\)) was developed, applying a Levene’s test to check the variance homogeneity of the variables studied. Significant differences among irrigation treatments \((p \leq 0.05)\) were identified by applying a one-way ANOVA, and a Tukey’s test to identify the significant differences. Additionally, there were defined the NWSB and WSB for each irrigation treatment and cultivar, analysing the differences by applying an ANCOVA to evaluate the differences in the interception points and slopes, and obtaining the threshold values of the CWSI and IT \(C\) for each cultivar that ensure minimum yield loss and the highest water saving. For this, at the end of each season, the effects on kernel yield in relation to irrigation treatments were analyzed by applying a one-way ANOVA, and a Tukey’s test to identify the significant differences.
3. Results

3.1. Climate Condition and Irrigation Water Amount Applied

Table 2 shows the climatic conditions during the two studied seasons. During the irrigation period (from April to October), the cumulative rainfall was 326 and 85 mm for 2018 and 2019, respectively. In relation to ET<sub>C</sub>, similar values for 2018 and 2019 (~880 and 840 mm respectively) were registered. This fact, together with the high differences in terms of rainfall, promoted that the irrigation doses applied in the studied treatments were much greater in the second experimental season. In this sense, FI, SDI<sub>75</sub>, and SDI<sub>65</sub> received 4974, 3713, and 3342 m<sup>3</sup>·ha<sup>-1</sup>, respectively, in 2018; and 7700, 5744 and 5159 m<sup>3</sup>·ha<sup>-1</sup>, respectively, in 2019.

Table 2. Monthly average values of the weather parameters for the irrigation period during the study.

| Parameters | April | May | June | July | August | September | October |
|------------|-------|-----|------|------|--------|-----------|---------|
| 2018       |       |     |      |      |        |           |         |
| T<sub>max</sub> | 22.0  | 25.6| 30.5 | 33.7 | 37.7   | 33.6      | 26.3    |
| T<sub>min</sub> | 9.5   | 12.1| 15.2 | 15.9 | 18.7   | 18.3      | 13.1    |
| T<sub>av</sub> | 15.2  | 18.2| 22.5 | 24.4 | 27.6   | 24.9      | 19.0    |
| RH<sub>max</sub> | 967.3 | 936.5| 93.6 | 96.1 | 87.9   | 89.7      | 95.3    |
| RH<sub>min</sub> | 44.1  | 37.3| 33.3 | 27.5 | 20.7   | 30.7      | 41.0    |
| RH<sub>av</sub> | 75.6  | 71.3| 62.4 | 60.9 | 51.9   | 61.9      | 71.8    |
| Rad        | 17.3  | 21.9| 24.9 | 27.0 | 23.5   | 19.6      | 13.9    |
| R          | 97.2  | 103.0| 5.4 | 0.0  | 0.6    | 21.4      | 98.4    |
| ET<sub>0</sub> | 96.6  | 125.5| 150.8| 172.1| 168.8  | 125.4     | 198.1   |
| ET<sub>c</sub>| 57.9  | 113.0| 165.9| 206.5| 185.6  | 100.3     | 49.9    |
| 2019       |       |     |      |      |        |           |         |
| T<sub>max</sub> | 22.2  | 30.4| 31.3 | 34.5 | 36.5   | 32.4      | 27.6    |
| T<sub>min</sub> | 7.2   | 12.2| 17.5 | 17.9 | 17.9   | 16.3      | 11.7    |
| T<sub>av</sub> | 19.8  | 21.5| 22.7 | 25.8 | 26.9   | 23.8      | 18.9    |
| RH<sub>max</sub> | 97.8  | 85.2| 83.2 | 84.0 | 77.2   | 81.9      | 90.7    |
| RH<sub>min</sub> | 39.8  | 23.3| 23.4 | 25.3 | 18.7   | 27.6      | 32.9    |
| RH<sub>av</sub> | 72.2  | 52.3| 51.4 | 55.4 | 45.9   | 54.4      | 63.2    |
| Rad        | 1.9   | 2.1 | 2.1  | 2.9  | 0.8    | 0.9       | 0.7     |
| R          | 71.2  | 0.0 | 0.0  | 0.0  | 0.0    | 3.4       | 10.4    |
| ET<sub>0</sub> | 111.0 | 198.0| 202.9| 238.7| 170.1  | 121.0     | 76.4    |
| ET<sub>c</sub>| 61.6  | 126.2| 151.3| 209.8| 140.1  | 92.8      | 54.8    |

R, rainfall (mm); T<sub>max</sub>, maximum air temperature (°C); T<sub>min</sub>, minimum air temperature (°C); T<sub>av</sub>, average air temperature (°C); RH<sub>max</sub>, maximum relative humidity (%); RH<sub>min</sub>, minimum relative humidity (%); RH<sub>av</sub>, average relative humidity (%); Rad, solar radiation (W·m<sup>-2</sup>); R, rainfall (mm); ET<sub>0</sub>, reference evapotranspiration (mm); ET<sub>c</sub>, crop evapotranspiration (mm).

3.2. Physiological Response to Irrigation Treatments

Table 3 displays the physiological response found for Ψ<sub>leaf</sub>, g<sub>s</sub>, and T<sub>C</sub> during 2018. The main significant differences among the irrigation treatments were detected for Ψ<sub>leaf</sub>. In this sense, cv. Marta showed differences at 190, 197, 211, 218, and 225 DOY. For the case of cv. Guara, these differences were detected at 166 and 225 DOY. Finally, regarding cv. Lauranne, significant differences were observed at 190, 197, and 211 DOY. For the remaining variables, only punctual days showed significant differences.
Table 3. Temporal evolution of the physiological variables measured throughout 2018.

| DOY | Treat | \(\Psi_{\text{leaf}}\) (MPa) | \(g_s\) (mmol m\(^{-2}\) s\(^{-1}\)) | \(T_c\) (°C) | \(\Psi_{\text{leaf}}\) (MPa) | \(g_s\) (mmol m\(^{-2}\) s\(^{-1}\)) | \(T_c\) (°C) | \(\Psi_{\text{leaf}}\) (MPa) | \(g_s\) (mmol m\(^{-2}\) s\(^{-1}\)) | \(T_c\) (°C) |
|-----|-------|----------------|----------------|--------|----------------|----------------|--------|----------------|----------------|--------|
| 162 | FI    | -0.92a        | 154.50a        | 21.80a | -0.92a        | 143.48a        | 22.68a | -0.97a        | 129.08a        | 22.50a |
|     | SDI\(_{75}\) | -0.82a        | 153.17a        | 21.94a | -0.95a        | 117.80a        | 23.04a | -0.98a        | 125.30a        | 23.51a |
|     | SDI\(_{65}\) | -0.88a        | 127.90b        | 22.39a | -1.04a        | 174.48a        | 22.95a | -0.93a        | 130.25a        | 23.21a |
| 166 | FI    | -1.06a        | 144.27a        | 27.02a | -0.93a        | 180.65a        | 28.29a | -1.05a        | 187.85a        | 27.94a |
|     | SDI\(_{75}\) | -1.13a        | 160.50a        | 27.90a | -1.21b        | 175.07a        | 28.30a | -1.08a        | 179.68a        | 28.18a |
|     | SDI\(_{65}\) | -1.11a        | 173.93a        | 27.53a | -1.22b        | 191.10a        | 28.03a | -1.05a        | 180.88a        | 28.00a |
| 190 | FI    | -1.55a        | 76.28a         | 31.09a | -1.58a        | 99.21a         | 31.49a | -1.54a        | 112.00a        | 31.14a |
|     | SDI\(_{75}\) | -1.44b        | 84.09a         | 31.94a | -1.50a        | 99.83a         | 32.26a | -1.70b        | 102.88a        | 31.97a |
|     | SDI\(_{65}\) | -1.40ab       | 79.24a         | 31.91a | -1.67a        | 109.66a        | 32.67a | -1.72b        | 110.64a        | 31.99a |
| 197 | FI    | -1.16a        | 77.14a         | 26.96a | -1.44a        | 79.79a         | 27.81a | -1.40a        | 93.25a         | 28.34a |
|     | SDI\(_{75}\) | -1.27b        | 72.86a         | 27.80a | -1.45a        | 84.64a         | 28.45a | -1.50b        | 89.73a         | 28.58a |
|     | SDI\(_{65}\) | -1.31b        | 78.03a         | 27.44a | -1.42a        | 84.13a         | 28.25a | -1.55b        | 89.35a         | 28.68a |
| 206 | FI    | -1.01a        | 84.41a         | 28.93a | -1.38a        | 107.59a        | 29.63a | -1.38a        | 126.57a        | 27.92b |
|     | SDI\(_{75}\) | -1.09a        | 90.90a         | 29.12a | -1.36a        | 107.90a        | 29.68a | -1.21a        | 128.36a        | 29.00a |
|     | SDI\(_{65}\) | -1.06a        | 89.11a         | 29.73a | -1.40a        | 107.34a        | 29.85a | -1.35a        | 129.50a        | 29.12a |
| 211 | FI    | -1.15a        | 110.80a        | 28.39a | -1.49a        | 120.86a        | 28.91a | -1.36a        | 126.43a        | 28.80a |
|     | SDI\(_{75}\) | -1.31b        | 99.64a         | 28.69a | -1.57a        | 110.65b        | 29.04a | -1.42b        | 133.20a        | 29.43a |
|     | SDI\(_{65}\) | -1.38b        | 96.58a         | 28.99a | -1.53a        | 98.80b         | 29.16a | -1.44b        | 129.07a        | 29.21a |
| 218 | FI    | -1.87a        | 138.02a        | 32.85a | -2.17a        | 154.36a        | 33.15b | -1.84a        | 189.04a        | 33.01a |
|     | SDI\(_{75}\) | -1.82a        | 134.86a        | 33.58a | -2.12a        | 166.15a        | 34.28a | -2.05a        | 181.77a        | 33.62a |
|     | SDI\(_{65}\) | -1.68a        | 140.90a        | 33.7a  | -2.18a        | 150.73a        | 34.40a | -1.71a        | 172.70a        | 33.66a |
| 225 | FI    | -1.74a        | 129.10a        | 31.83a | -1.76a        | 138.99a        | 31.93a | -1.88a        | 166.89a        | 30.95b |
|     | SDI\(_{75}\) | -1.79a        | 116.47a        | 32.02a | -2.29b        | 139.86a        | 32.78a | -2.10a        | 165.27a        | 32.97a |
|     | SDI\(_{65}\) | -2.03b        | 122.47a        | 32.77a | -2.01b        | 129.44a        | 32.87a | -1.92a        | 163.96a        | 32.92a |

Treat: treatment; \(g_s\), stomatal conductance; \(\Psi_{\text{leaf}}\), leaf water potential; \(T_c\), canopy temperature; FI, fully irrigated treatment; SDI\(_{75}\), sustained deficit irrigation at 75% of the crop irrigation requirements; SDI\(_{65}\), sustained deficit irrigation at 65% of the crop irrigation requirements; DOY, day of the year. Different letters represent significant differences (\(p < 0.05\)) among treatments within each cultivar.

A similar pattern was observed during the second experimental season as shown in Table 4, the \(\Psi_{\text{leaf}}\) being the physiological parameter that displayed the most perceptible effects in response to the different irrigation treatments.

In this regard, for the case of cv. Marta, these differences during the monitoring period were at 175, 183, 189, 196, 203, 210, and 217 DOY. In the same vein, cv. Guara registered significant differences for \(\Psi_{\text{leaf}}\) at 162, 175, 183, 189, 196, 203, 210, and 217 DOY. Finally, as was determined for the previous cultivars, cv. Lauranne recorded significant differences throughout the irrigation period for \(\Psi_{\text{leaf}}\) at 175, 183, 189, 196, 203, and 217 DOY.
Figure 2. Meteorological conditions during the data collection in 2018 (A) and 2019 (B). $T_{\text{air}}$, air temperature; RH, relative humidity; VPD, vapor pressure deficit; DOY, day of the year.
Figure 3. Water-stress baselines for cvs. Marta (A), Guara (B), and Lauranne (C). Black continuous, discontinuous and grey lines are the regressions functions that represent the non-water-stress baseline for fully irrigated (FI), and the water-stress baselines for sustained deficit irrigation at 75% of the crop irrigation requirements (SDI\textsubscript{75}) and sustained deficit irrigation at 65% of the crop irrigation requirements (SDI\textsubscript{65}), respectively.

Table 5. Fitted parameters for the non-water-stress baselines and water-stress baselines for the almond cultivars and irrigation treatments.

| Baseline  | cv. Guara | cv. Marta | cv. Lauranne |
|-----------|-----------|-----------|--------------|
|           | Slope     | Intercept | R\textsuperscript{2} | Slope     | Intercept | R\textsuperscript{2} | Slope     | Intercept | R\textsuperscript{2} |
| NWSB      | −2.71\textsuperscript{a} | 5.60a      | 0.82         | −2.33\textsuperscript{a} | 4.14a      | 0.75         | −2.48\textsuperscript{a} | 4.62a      | 0.78         |
| WSB\textsubscript{75} | −2.62\textsuperscript{a} | 5.65a      | 0.76         | −2.45\textsuperscript{a} | 4.73a      | 0.75         | −2.66\textsuperscript{a} | 5.75a      | 0.77         |
| WSB\textsubscript{65} | −2.58\textsuperscript{a} | 5.76a      | 0.74         | −2.49\textsuperscript{a} | 5.01a      | 0.74         | −2.62\textsuperscript{a} | 5.51a      | 0.77         |

NWSB, non-water-stress baseline defined according to the registered values in full irrigated treatment; WSB\textsubscript{75}, water-stress baseline according to the registered values in the sustained deficit irrigation at 75% of the crop irrigation requirements; WSB\textsubscript{65}, water-stress baseline according to the registered values in the sustained deficit irrigation at 65% of the crop irrigation requirements. Equal letters within each column are not significantly different (\(p < 0.05\)).

As shown in Table 5, within each cultivar, the ANCOVA did not manifest differences in terms of the slope and the interception point for any of the studied cultivars. This absence of differences is in accordance with the previous results noted in relation to \(T_C\) and \(g_s\) parameters without differences during the monitoring period. Moreover, this difference could be associated with the inherent variability of the experiment, especially, in \(T_C\) readings. In this agreement, within each treatment it was observed \(T_C\) variations of ±0.5, ±0.9, and ±1.5 °C in the FI, SDI\textsubscript{75}, and SDI\textsubscript{65}, respectively. This variability was also higher the more remarkable the imposed water stress was. Moreover, a higher variability was found in cv. Guara while cvs. Marta and Lauranne showed lower and similar variability trends.

Considering this absence of differences between the irrigation treatments, there was defined a single WSB for each cultivar with the whole dataset (Table 6). These reference water-stress baselines \(r\text{WSB}\) would allow knowing an optimum \(\Delta T_{\text{canopy-air}}\), establishing the lower and upper limits from the NWSB and WSB previously defined for the FI and SDI treatments (Figure 4).

Table 6. Fitted parameters for the reference water-stress baselines \(r\text{WSB}\) for each cultivar.

| Cultivars | Slope | Intercept | R\textsuperscript{2} |
|-----------|-------|-----------|----------------------|
| Marta     | −2.42 | 4.63      | 0.74                 |
| Guara     | −2.63 | 5.67      | 0.77                 |
| Lauranne  | −2.59 | 5.29      | 0.74                 |
According to our findings, the maximum IT\textsubscript{C} reported for each cultivar was \textasciitilde1.0 °C (Figure 4); that is, the highest differences between the FI and SDI\textsubscript{65} strategies would report increases beyond the lower limit around a degree in the sunny side of the almond canopy. Moreover, this deviation would be different depending on the cultivar. For the case of cvs. Marta and Lauranne, the maximum IT\textsubscript{C} were detected in the lower ranges of the VPD that contrasts with cv. Guara.

Finally, taking into consideration the NWSB and WSB for each treatment and cultivar, and with the aim of establishing a useful threshold limit that ensures the maximum water savings, the CWSI on a monthly basis was estimated (Figure 5). It is noticeable the progressive increase along the kernel-filling period, especially in cvs. Marta and Lauranne, displaying a progressive rise because of the water-stress accumulation. Moreover, in cv. Guara and cv. Marta, the SDI\textsubscript{65} reported a CWSI higher than those obtained in cv. Lauranne, where in the latter the SDI\textsubscript{75} registered similar values of the CWSI. For cv. Guara, the maximum CWSI was reached under SDI\textsubscript{65}, with values close to 0.14. Similar results were found for cv. Lauranne (~0.15), whereas in cv. Marta these values were somewhat lower, roughly 0.12.
3.4. Linking the Yield with Water-Stress Baselines Defined for Each Cultivar and Irrigation Treatment

After estimating the different WSBs, the final yield was analyzed for each irrigation treatment and cultivar (Figure 6). This fact is necessary to define the threshold values of $\Delta T_{\text{canopy-air}}$ and CWSI to minimize the yield losses and maximize the water savings (in case of obtaining significant differences between irrigation treatments). On average, for cvs. Marta and Lauranne, no differences were observed, evidencing that water withholding close to 35% of the irrigation requirements would not promote yield losses, at least during two consecutive seasons. Something different was determined for cv. Guara. In this case, in spite of not finding significant differences, there was a trend between the yield loss and water stress imposed; that is, the obtained values for SDI$_{75}$ and SDI$_{65}$ were notably lower than those observed under FI, with yield reductions of 11% and 15%, respectively.

![Figure 6](image_url)  
**Figure 6.** Average kernel yield for the studied almond cultivars during the study. FI, fully irrigated at 100% of irrigation requirements; SDI$_{75}$, irrigated at 75% of the irrigation requirements; SDI$_{65}$, irrigated at 65% of the irrigation requirements. Vertical bars are standard deviation.

4. Discussion

The focus of this paper was to assess the use of thermal data as indicator of crop water status instead of discontinuous measurements, such as $\Psi_{\text{leaf}}$ or $g_s$, which are highly time-consuming with a huge number of measurements that are needed for taking decisions.

Considering the results showed in this work, the $\Psi_{\text{leaf}}$ was the parameter that showed the highest differences between treatments in the two-year experiment, relative to $g_s$ and $T_C$ (Tables 3 and 4). It is remarkable that the decreasing pattern in $\Psi_{\text{leaf}}$ was not followed by $g_s$, likely because of the lower capacity of almond trees to regulate their stomata under mild water-stress situations [3,34]. These findings were in agreement with other works [35,36], showing that under mild stress, almond decreases $\Psi_{\text{leaf}}$ significantly more than $g_s$, which remains fairly constant until severe water stress. As $g_s$ tightly controls plant transpiration, this, in turn, determines to a great extent the leaf temperature. The lack of significant differences in $g_s$ among the irrigation treatments and for none of the cultivars support why there were also no differences between $T_C$ and WSBL. In addition, plant transpiration, in which $g_s$ determines photosynthesis, in conjunction with turgor, is liable for growth and yield. Accordingly, fruit yield did not show relevant differences among the irrigation treatments for cvs. Marta and Lauranne, although these were more evident for cv. Guara. In accordance with our data and to previous works, it seems that to detect a higher response of $g_s$ to water stress it would be necessary to impose more severe water-stress conditions; then the stomatal response would be mainly governed by the crop water status [10,22].

The use of thermal data as indicator of crop water status has been implemented in different works to solve the drawback that $\Psi_{\text{leaf}}$ or $g_s$ carried out with their development [27,36]. In order to define the most proper strategy, many authors have discussed the best time to capture the images, the tree area or the time range to take the images. In this sense, González-Dugo et al. [37] concluded that, for the case of citrus trees, the best moment to capture the thermal images would be between 11:20 and 12:00. They also observed that the maximum differences between the control and stressed trees ranged between 1.5
and 2.5 °C. Their results agree with those obtained in this experiment, in which the maximum difference between the FI and SDI treatments is ±1 °C (Figure 4). In the same line, García-Tejero et al. [33] in an experiment with almond (cv. Guara) concluded that the best moment to capture thermal images was between 11:30 and 14:00 in the sunny exposed side of the tree, when the maximum differences of \( T_C \) between the FI and DI treatments were reached. Therefore, these differences were always from 0.5 to 1.5 °C when a water restriction close to 50% of the irrigation requirements was imposed, similar to findings that was obtained in the present work.

Despite \( T_C \) not always having a direct relationship with \( \Psi_{\text{leaf}} \) or \( g_s \), due to the large environmental variability, the use of different thermal indexes that normalize this parameter to the meteorological conditions make this tool suitable to determine the crop water status [24]. In this study the use of the index \( \Delta T_{\text{canopy-air}} \) allowed to establish the NWSB and WSB for three almond cultivars, adjusting these values with those of the VPD registered. In this context, Bellvert et al. [38] outlined that different WSB can be obtained, and their main differences could be associated with their intercept point; these differences being associated to variation in the crop water status [19,20] or the crop phenological stage. Similarly, García-Tejero et al. [28], for mature almond trees, reported differences in the interception point between different WSBs within a cultivar subjected to different irrigation doses. These results agree with that found in this work (Figure 3, Table 5). In this line, although the ANCOVA did not evidence significant differences in the slope and interception point among the irrigation doses imposed in each cultivar, we observed maximum differences between the NWSB and WSB close to 1.0 °C, comparable to findings by García-Tejero et al. [28] or García-Tejero et al. [33]. The main differences among these results and those reported by the authors would be mainly in the slope of the functions calculated for the studied cultivars. Thus, González-Dugo et al. [37] or García-Tejero et al. [28] reported similar slopes for mature almond trees, cv. Guara, which were growing under similar climatic conditions. In our case, the obtained slopes were substantially different; this being an important fact to be considered in future works. Thus, this fact could be due to the tree age and this work being defined in young trees, whereas the previous works were developed in mature almond trees, in which the transpiration capacity could have substantially changed.

Authors such as Romero-Trigueros et al. [39] largely discussed the advantages of this type of functions when these are applied in isohydric crops, with a higher capacity of stomatal regulation when they are subjected to water withholding. This is not the case for almond, with a downregulation of stomatal conductance, resulting in similar \( T_C \) values for trees subjected to different irrigation doses. Considering that no differences were found among the irrigation treatments, the rWSB defined for each cultivar would be a suitable option for irrigation scheduling under moderate scenarios of water scarcity, knowing that there were no differences in productive terms with water around 2000 m³ × ha⁻¹ (Figure 6).

Finally, in spite of the absence of significant differences in yield for the three studied cultivars, cv. Guara was affected with a progressive depletion in relation to the water stress imposed. Confronting these results with the maximum \( \Pi_T \) registered, cv. Guara was the unique in which \( \Pi_T \) increased for major values of VPD, and it could demonstrate a higher sensitivity to the SDI strategy than the remaining cultivars, especially when atmospheric demand is higher. Likewise, the absence of differences in terms of yield has been widely stated by several authors [10,40–42] and, therefore, this reaction ratifies the advantages of this agronomic practices for almond cultivation in arid and semi-arid environments.

5. Conclusions

From the research that has been performed in this paper, it is possible to conclude that the \( \Delta T_{\text{canopy-air}} \) and its related thermal indexes (CWSI and \( \Pi_T \)) are precise indicators of the crop water status in young almond trees. In detail, the use of \( \Delta T_{\text{canopy-air}} \) to establish the NWSB and WSBs for different cultivars and water-stress levels would offer an optimum tool for irrigation management differentiated by cultivar and water restrictions. On the other hand, considering the three cultivars
studied, cv. Guara offered a higher sensitivity to water stress, as in yield reductions in terms of its physiological response. Following the proposed methodology of this study, using thermal data, it would be possible to materialize other WSB for different cultivars and tree ages for alternative irrigation programming, especially when DI is used. However, taking into consideration that there were no differences found in yield between the water-stressed and non-stressed treatments, future essays imposing more severe water stress should be considered, in order to ensure obtaining the maximum threshold value (in terms of the CWSI or ITc) that would not significantly impact yield, explicitly under long-term irrigation periods.

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