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Thermal imaging at plant level to assess the crop-water status in almond trees (*cv*. Guara) under deficit irrigation strategies

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A B S T R A C T

Almond (*Prunnus dulcis* Mill.) has been traditionally associated to marginal land cultivation and rain-fed agriculture in South Spain. However, in the last years, this crop is being progressively introduced in more productive agricultural areas within the Guadalquivir river basin, where the available water resources are not enough to satisfy the adequate crop-water requirements. Considering this limitation, a more precise irrigation scheduling to maximize the yield is required. Infrared thermal imaging emerges as alternative to other traditional methodologies to assess the crop-water status, especially when deficit irrigation (DI) strategies are being applied. The aim of this study was to define the methodology to assess the almond water status by means of thermal information. The trial was conducted during 2014, during the kernel-filling period, in an almond experimental orchard (SW Spain), with 5-year-old trees, subjected to three irrigation regimes: i) a full-irrigation treatment (C-100), which received 100% of ET_C; ii) a regulated deficit irrigation (RDI-50), which received 100% of ET_C except during the kernel filling period, when this treatment was irrigated with 50% of ET_C; iii) and a low-frequency deficit irrigation treatment (LFDI), which received 100% of ET_C except during the kernel filling period, when it was subjected to continuous periods of irrigation-restriction, defined in terms of the threshold values of shaded leaf water potential (Ψ_{leaf}). Three daily curves of canopy temperature (T_C), stomatal conductance to water vapour (g_s) and Ψ_{leaf} with measurements at 8:00, 11:00, 14:00, 17:00 and 20:00 were developed. Additionally, Crop Water Stress Index (*CWSI*), temperature difference between canopy and the surrounding air ($\Delta T_{\text{canopy-air}}$), and the relative index to stomatal conductance (I_G) obtained at different scales (canopy and row) were estimated. Significant correlations of infrared thermal information *vs.* Ψ_{leaf} and g_s were obtained ($p \leq 0.05$ and $p \leq 0.01$), in particular, by using the thermal readings taken at 11:30, 14:30 at 17:30 h, especially robust were the relationships obtained between T_C and *CWSI* with Ψ_{leaf} at 11:30 h; and between T_C and *CWSI* with g_s, and Ψ_{leaf} at 14:30 h. Finally, considering the infrared thermal monitoring procedure (readings at tree and row level), similar values of T_C were obtained, and therefore, the images taken at row level offered a better information with a higher feasibility in terms of image processing.

1. Introduction

Irrigated agriculture in the South of Europe, and more concretely in semi-arid areas such as Andalusia (S Spain), is crucial for their development, especially in those rural regions with a lower economic potential. In this line, for the case of Andalusia, irrigated agriculture generates more than 60% of rural employments, and represents 64% of agricultural production. Currently, 1,176,000 ha are devoted to irrigated agriculture, corresponding to 24% of total Andalusian agricultural surface, and this being 33% of the irrigated agriculture in Spain (ARA, 2011).

Climatic conditions in this area are characterized by the scarcity and irregularity of rainfall, coinciding the dry period with the season of highest evapotranspiration. Moreover, the last forecast predictions argue significant water resources depletions; with an important declining in the soil water reserves, more accused periods of rainfall

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restrictions and increasing in the average temperatures (IPCC, 2014). In this agreement, it is expected that this situation promotes an imbalance between the irrigation demand and the available water resources in the Mediterranean agriculture (Daccache et al., 2012; Olesen et al., 2011). This fact will suppose an important constraint for the competitiveness between agriculture and other more productive sectors such as the industry or tourism. In addition, the introduction of alternative crops in order to maximize the profitability of agroecosystems will be required, together with different strategies to improve the agricultural water management (García-Tejero et al., 2014a).

In this context, almond (*Prunus dulcis* Mill.) is the third crop in terms of surface in Spain, representing globally almost 40%, and 84% within the EU. However, only 5% of the global production is developed in Spain (FAOSTAT, 2016). Concretely, the surface of almond in Andalusia is about 152,000 ha, and within them, 95% are associated to marginal and rain-fed agriculture because of the climate limitations, where annual rainfalls does not exceed of 300 mm with low nut yields (CAPDR, 2016). However, in the last few years, the agricultural surface devoted to almond crop has significant increased, specially, in areas where this crop was not traditionally cultivated, these new orchards being cultivated under intensive and irrigation practices. Thus, almond can be found under very different agricultural systems from the most marginal situations to the most intensive orchards, which promotes a wide range of yields (from 150 to 2600 kg ha^{-1}) (CAPDR, 2016).

According to Goldhamer and Fereres (2016), irrigation is the most limiting factor for this crop, with crop water-requirements oscillating between 900 and 1350 mm (Goldhamer and Girona, 2012). In this agreement, Goldhamer and Fereres (2016) reported values close to 4000 kg ha^{-1} (depending on the cultivar) for irrigation doses around 1250 mm, with yield reductions close to 14% when the irrigation doses were close to 1000 mm. More recently, López-López et al. (2018) in a long-term experience developed in the province of Córdoba (Andalusia, South Spain), reported maximum yield values (> 2500 kg ha^{-1}) in mature almond trees (cv. Guara), when these trees were irrigated receiving the maximum crop water requirements (close to 10,000 m^3 ha^{-1}).

In spite of this, almond is considered a drought-resistant crop because of its xeromorphic properties (Torrecillas et al., 1996), and many authors have reported different results related to the effects of deficit irrigation (DI) strategies (Puerto et al., 2013; Phogat et al., 2017; Spinelli et al., 2016; among others). More recently, López-López et al. (2018) discussed the effects of water deficits in almond trees in terms of water use, evaluating different deficit irrigation (DI) strategies during three consecutive years. These authors found that almond trees under different moderate DI strategies were able of keeping canopy volumes similar to those trees that were fully irrigated, these being directly related with the almond capability to obtain yield values under moderate deficit irrigation similar to those reported by fully irrigated trees; this fact being accompanied with similar soil water depletions and transpiration level.

Taking into account the maximum crop-water demand, the water scarcity in semi-arid areas, and the proper response of this crop to moderate water stress, DI would be a suitable alternative to reach equilibrium between the available water resources and a proper crop development with final yields able to ensure the competitiveness and feasibility of this crop (García-Tejero et al., 2016a). However, the application of DI strategies requires a proper knowledge about the crop physiological status, with the aim of ensuring the correct crop development without significant compromising the yield and fruit-quality, especially when water-stress is applied in different crop stages (Spinelli et al., 2016). In this sense, according to Puerto et al. (2013), when a DI strategy is applied in fruit trees, this is mainly developed supplying a specific water withholding, taken as reference the crop water requirements by means of the crop evapotranspiration (ET_C), without taking into account the effects of canopy architecture, the degree of canopy cover or the soil management (among others); or without considering the crop physiological status when this water stress is applied. In this regard, the most proper irrigation scheduling should consider the whole of soil-plant-atmosphere system; although in terms or representativeness, the live component (plant) would be offering the most valuable information, inasmuch as this reflects the most integrative information, mainly in terms of final yield.

Traditionally, crop water monitoring has been developed by using punctual measurements of stem (Ψ_{stem}) or leaf (Ψ_{leaf}) water potential at midday or pre-dawn (Ψ_{pd}) (Shackel, 2011; Nortes et al., 2005) or monitoring the gas-exchange parameters such as transpiration (E), stomatal conductance (g_s) or net photosynthetic rate (A) (Gomes-Laranjo et al., 2006).

According to Remorini and Massai (2003), Ψ_{Stem} is not only a proper indicator of plant-water status as well as the crop productivity. In the same vein, Mirás-Avalos et al. (2016) reported that water potential is a suitable indicator of almond water status, although its usefulness is reduced, because of a minimum number of replications are required, and the representativeness in the whole plant is reduced.

In the last years, the use of remote sensing in agriculture, and more concretely, infrared thermal imaging to monitor the crop water status has been progressively introduced (Costa et al., 2013). This technique has been properly described as a good methodology for crop-water monitoring in different woody crops such as citrus (García-Tejero et al., 2011; Gonzalez-Dugo et al., 2014); young almonds (García-Tejero et al., 2012), vines (García-Tejero et al., 2016b) or olives (Egea et al., 2017). This technique is based on the leaf energy balance. When a water stress situation is applied, plants responds with a partial stomatal closure, reducing the stomatal conductance, limiting the leaf transpiration and promoting an attenuation of the evaporative cooling process, resulting in higher leaf / canopy temperature values (Jones, 1999, 2004).

This technique can be applied at different monitoring scales, from "leaf or canopy" to "orchard or basin" level (Poblete-Echeverría et al., 2014, 2016). The selection of the most proper methodology will be related with the desired goal and the economic availability (Costa et al., 2013). In this sense, the use of thermography at orchard scale by using satellites images, allows to take decisions related to crop variability or irrigation scheduling, but some constraints must be taken into account. On one hand, thermal images taking by satellites have the difficulty of depending of the moment in which the satellite passes above the orchard; and on the other hand, the spatial and spectral resolution is not proper. These constraints could be solved by using of unmanned aerial vehicles (UAVs), despite its economically restrictions. In this sense, the use of thermal images at orchard scale, taken by means of UAVs, requires having the proper technology; and this fact can increase the cost of this tool, becoming less accessible the use of this technology. By the contrast, these sensors can be used at plant level, with thermal cameras much more profitable, easing the accessibility to this technique by the irrigation communities or technicians.

Likewise, the main constraints of this technique are focused in the image processing (many times requiring high time consuming), and the correct interpretation of the infrared thermal information (García-Tejero et al., 2015a). Because of this, many times different relationships between infrared thermal information and other physiological parameters such as g_s, A, E, or Ψ_{stem} are required (Jones, 2004; Jones et al., 2009), although these relationships are not always enough robust because of the high dependence of the meteorological conditions (Jones, 1999, 2004), the monitoring proceedings (Costa et al., 2013), the cultivar (Costa et al., 2012; García-Tejero et al., 2016b) or even, the crop phenological stage (Cohen et al., 2015).

Up to day, several authors have developed strategies to optimize this technique, developing different protocols and strategies to take thermal readings under field conditions (Jones et al., 2009; Pou et al., 2014; Poblete-Echeverría et al., 2014, 2016, García-Tejero et al., 2012, 2016b) and describing different relationships between infrared thermal information and physiological parameters.

We hypothesize that thermography could be a suitable technique to