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Thermal imaging to monitor the crop-water status in almonds by using the non-water stress baselines

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ABSTRACT

Thermal imaging has been progressively introduced as a promising technique for irrigation scheduling and the assessment of the crop-water status, especially when deficit irrigation (DI) strategies are being implemented. However, up to day, one of the most important limitations of this technique is related to the data interpretation derived from these sensors; which is in many cases, a severe limitation to its practical usage by farmers and technicians. This work evaluates the potential and usefulness of the non-water stress baselines (NWSB) extracted from thermal information, in order to define a practical protocol for taking decisions related to irrigation scheduling in almond plantations. The present study was developed during the kernel-filling period of three cultivars of mature almond trees (*cvs.* Guara, Lauranne, and Marta), subjected to different irrigation treatments. Thermal information was obtained by using a Thermal Camera (Flir SC660) with a high resolution, and subsequently, confronted with other related plant physiological parameters [leaf water potential (Ψ_{leaf}) and stomatal conductance (g_s)]. Moreover, once defined the NWSB, there were obtained similar functions taking as reference the information from those irrigation treatments under different water stress levels. Finally, and taking into account the yield values, there were defined the most advisable functions in order to maximize the water savings, minimizing the yield losses. Here we demonstrate that the findings allow concluding that thermal information is enough robust to know the crop-water status and define a proper irrigation scheduling for almond plantations, being necessary to consider different thermal functions depending on the cultivar.

1. Introduction

Mediterranean irrigated agriculture is characterized by the scarcity and irregularity of water resources availability, together with a progressive climate change that is promoting scenarios of water-resources depletions, with more severe periods of lower rainfall during the wet periods and more pronounced hot waves during the maximum evapotranspirative demand period (IPCC, 2014). Under this scenario, it is necessary to implement different strategies and methodologies to increase the irrigation water productivity, stablishing the best strategies for an efficient and sustainable water management (García-Tejero and Durán-Zuazo, 2018).

Deficit irrigation (DI) strategies have been traditionally used in many arid and semi-arid irrigated areas, mainly when the available water resources have not been enough to cover the crop water requirements, although these have not been always properly managed. This fact has been associated with the absence of a correct assessing of crop-water status, especially when water depletions are applied in different crop stages (Costa et al., 2007). Traditionally, crop water monitoring has been developed by means of punctual measurements of leaf water potential at midday (Ψ_{leaf}) or pre-dawn (Shackel, 2011; Nortes et al., 2005), or by means of gas-exchange parameters such as transpiration, stomatal conductance (g_s) or net photosynthetic rate (Jones, 2007; Fernández, 2014). By the contrast, these punctual measurements are characterized by the time- and labour-consuming (Jiménez-Bello et al., 2011). By the contrast, thermal imaging has been progressively introduced to monitor the crop water status at different scales (García-Tejero et al., 2016).

Many works have studied the befallen changes in terms of canopy temperature (T_C) of different woody crops when these are subjected to DI strategies; such as citrus (García-Tejero et al., 2011); almonds (García-Tejero et al., 2012), vines (Costa et al., 2012; García-Tejero et al., 2016) or olives (García-Tejero et al., 2017). In this sense, T_C can be considered as a good source of information to assess the plant-water

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status (Jones, 2004; Berni et al., 2009; Jones et al., 2009), although many times the relationships between thermal indicators and other crop physiological parameters are required and these are not always enough robust, especially when these have been obtained under field conditions. This fact is promoted by the large influence of meteorological variables (air temperature (T_{air}), solar radiation, the angle of incident radiation, wind speed, or relative humidity (RH); among others) (Jones, 2004; Grant et al., 2006) or morphological factors (Maes and Steppe, 2012).

With the aim of establish a simple methodology to quantify the crop-water status taking the thermal readings as the main source of information, and minimizing the effects of environmental factors, there were created different thermal 'stress indices'. In this sense, Idso et al. (1981) evidenced high positive differences in temperature values between T_C and T_{air} in plants under water stress, while these differences were much more stable and negative in well-irrigated plants, defining the difference between canopy and air temperature as a simple thermal index ($\Delta T_{canopy\text{-}air}$).

The main constraints of using thermal information to assess the crop-water status are focused in the proper interpretation of thermal information (Maes and Steppe, 2012). Because of this, many times different relationships between infrared thermal information and other physiological parameters such as g_S or Ψ_{leaf} are required. This fact many times difficulties a proper making decision, because these relationships are not always stable, and vary from place to place, for different cultivars, and even for different crop phenological stages (García-Tejero et al., 2016).

A simple way of interpreting the thermal information is by means of the non-water-stressed baselines (NWSBs); a linear function that associates the $\Delta T_{canopy\text{-}air}$ when the crop is transpiring at the potential rate, with the values of vapour pressure deficit (VPD) simultaneously measured with T_C. NWSB allows knowing the optimum value of $\Delta T_{canopy\text{-}air}$, stablishing certain threshold values able to manage properly the irrigation scheduling, especially when DI strategies are being applied (Egea et al., 2017).

Considering these aspects, the aims of this work were i) to determine the NWSB for studied almond cultivars during the kernel-filling and postharvest periods; ii) define the water stressed baselines (WSBs) subjected to different degrees of water stress; iii) and establish a useful protocol to apply these functions for a proper irrigation scheduling, especially when the almond plantations are subjected to DI practices.

2. Material and methods

2.1. Experimental site

The trial was conducted during 2017, from 153 to 224 day of the year (DOY) in a commercial orchard of almonds (*Prunus dulcis* Mill. (D.A. Webb)) *cvs*. Guara, Marta and Lauranne; grafted onto GN15 rootstock), located in the Guadalquivir river basin (37° 29′ 3.19″ N; 5° 59′ 55.1″ O) (Seville, SW Spain). Trees were planted in 2007, spaced 8 × 7 m, and drip irrigated using two pipe lines with emitters of $2.3\,L\,h^{-1}$, spaced 0.75 m.

The soil is silty loam, typical Fluvisol (USDA, 2010), 2.5 m deep, fertile, and organic matter content $< 15.0\,g\,kg^{-1}$. Roots are located predominately in the first 50 cm of soil, corresponding to the intended wetting depth, although these exceed more than one meter in depth. Soil-water content values at field capacity (–0.33 MPa) and permanent wilting point (–1.5 MPa) are 0.42 and 0.17 $m^3\,m^{-3}$ respectively, with an allowable soil-water depletion level of 0.35 $m^3\,m^{-3}$.

The climatology in the study area is attenuated meso-Mediterranean, with an annual ET_0 rate of 1400 mm and accumulated rainfall of 540 mm, mainly distributed from October to April.

The total rainfall and evapotranspiration registered during the monitoring period were 1.2 and 585 mm, respectively. Daily temperatures during the monitoring times ranged between 24.8 and 36.0 °C, whereas the relative humidity ranged between 22.1 and 61.0%.

2.2. Irrigation treatments

Three irrigation treatments were defined in the three cultivars considered: i) a full irrigated treatment (FI), which received 100% of the crop evapotranspiration (ET_C) during the irrigation period, ii) a moderate deficit irrigation (MDI_{65}), which received 100% of ET_C during the whole of irrigation period, except during the kernel-filling stage and pre-harvest, when this treatment was irrigated with 65% of ET_C; iii) and a severe deficit irrigation (SDI_{40}) which received the 100% ET_C during the irrigation period, except during the kernel-filling stage and pre-harvest; when this treatment was irrigated at 40% of ET_C.

Irrigation doses were calculated according to the methodology proposed by Allen et al. (1998), obtaining the values of reference evapotranspiration (ET_0) by using a weather station installed in the same experimental orchard. The local crop coefficients used during the experimental period ranged between 1.0 and 1.2, according to the results obtained by García-Tejero et al. (2015).

2.3. Plant measurements

During the kernel filling period, when water restrictions were applied, crop-water monitoring was done throughout the measurements of leaf water potential (Ψ_{leaf}) in shaded leaves; the stomatal conductance to water vapour (g_s) in well exposed sunny leaves; and canopy temperature (T_C), in the sunny side of monitoring tree. These readings were taken between 12:00 and13:30 GTM, and with a periodicity of 7–10 days.

Measurements of Ψ_{leaf} were developed by using a pressure chamber (Soil Moisture Equipment Corp., Sta. Barbara, CA, USA), monitoring 8 trees per irrigation treatment (one leaf per tree), located in the north side of the tree and being totally mature, fresh and shaded, at 1.5 m of height, approximately. This measurement integrates the effects of soil, plant and atmospheric conditions on the measure of water availability, within the plant itself (Shackel, 2011). Considering the suggestions reported by Nortes et al. (2005), leaf water potential measured on fully exposed leaves is not a suitable indicator under field conditions, because of the effects that leaf microclimate exerts on this measurement. By the contrast, leaf-water potential measured in uncovered shaded leaves is a suitable and proper choice to monitor the crop-water status, minimizing the effects of climatic parameters in this measurement (Goldhamer and Fereres, 2017), reducing the measurements variability, and hence, not being necessary a large number of measurements and reducing the time-consuming (García-Tejero and Durán-Zuazo, 2018).

Additionally, in these same trees, it was measured the g_s, using a porometer SC-1 (Decagon Devices, INC, WA, USA), these measurements being done in one leaf completely exposed to the sun per monitored tree completely exposed, and at 1.5 m of height, following the methodology proposed by the manufacturer (Decagon Devices, 2011). In this sense, the readings should be taken at least in three leaves per plot or treatment (in or case n = 8), in fully exposed leaves to the sun, and considering that, those readings taken for similar conditions (for instance, a same irrigation treatment), should be within 10% or approximately $50\,mmol\,m^2\,s^{-1}$ of each other.

The T_C was measured by thermal imaging at the same time of the remaining readings, with ThermaCam (Flir SC660, Flir Systems, USA, 7–13 µm, 640 × 480 pixels), using an emissivity (ε) set at 0.96. Each pixel corresponds to an effective temperature reading (Jones, 2004). The images were taken in the sunlit side of the trees, with the imager placed at 4 m of the canopy. Images were analysed using the Flir Research Pro Software (Flir Systems, USA), that allows to select different areas of the image (in our case 3–4 sunlit areas within the same image).

Considering the T_C values obtained at tree level, for each variety, irrigation treatment and monitoring day, it was calculated the difference between canopy and the surrounding air ($\Delta T_{canopy\text{-}air}$) as follows: