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Usefulness of thermography for plant water stress detection in citrus and persimmon trees

C. Ballester*, M.A. Jiménez-Bello, J.R. Castel, D.S. Intrigliolo

Instituto Valenciano Investigaciones Agrarias (IVIA), Centro Desarrollo Agricultura Sostenible, Apartado Oficial 46113, Moncada, Valencia, Spain

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ABSTRACT

The feasibility of using canopy temperature (T_c) measured with a hand-operated infrared thermographic camera as a water stress indicator was evaluated in the field during two seasons on citrus and persimmon trees subjected to different levels of deficit irrigation. In both species, which differ in leaf anatomy and stomatal response to environmental conditions, T_c was compared with midday stem water potential (Ψ_s) measurements. In persimmon trees, leaf stomatal conductance (g_s) was also measured. In 2009, images were taken from the sunlit and shady sides of the canopies. Based on the results obtained, during the second experimental season images were taken from the sunlit side of the trees and also from above the canopy. In persimmon, trees under deficit irrigation had lower Ψ_s and g_s what resulted in a clear increase in T_c regardless of the position from where the pictures were taken. The maximum T_c difference between deficit-irrigated and control trees observed was of 4.4 °C, which occurred when the stressed trees had Ψ_s values 1.1 MPa lower than the control ones. In persimmon trees, T_c was the most sensitive indicator of plant water status particularly due to the lower tree-to-tree variability as compared to Ψ_s and g_s. On the other hand, in citrus trees T_c was not always affected by plant water stress. Only in the second experimental season, when air vapour pressure deficit values were below 2.7 kPa and images were also taken from above the canopies, deficit-irrigated trees had higher T_c than the control ones, this difference being at most 1.7 °C. Overall, the results show that hand-operated thermographic cameras can be used to detect plant water stress in both fruit tree species. Nevertheless, the use of T_c measurements to detect plant water stress appears to be more precise in persimmon than in orange citrus. This might be because persimmon trees have larger leaf size which determines higher canopy resistance allowing for higher increases in canopy temperature in response to water stress via stomatal closure.

1. Introduction

The perspectives for the foreseeable future point out that irrigation water demand will continue to increase leading to a shortage of water resources in many world regions (Fereres and Gonzalez-Dugo, 2009). Thus, irrigation strategies that allow farmers to increase water use efficiency are becoming essential in irrigated agriculture. Among the irrigation strategies applied to fruit crops, regulated deficit irrigation (RDI) may allow substantial water savings without negatively affecting yield. The success of this strategy, however, is dependent on the timing and severity of the plant water stress. Surpassing a threshold value of plant water stress usually leads to a reduction in the final fruit size and in the economic return. Therefore, when RDI strategies are applied, it is important to frequently check the plant water status to avoid exceeding the threshold values.

Currently the plant indicators most commonly used to determine crop water status are the stem water potential (Ψ_s) and the stomatal conductance (g_s), but their measurements are labor-intensive and unsuitable for automation, characteristics that make the regular use of these methods difficult for farmers or even technicians in the field. Thus, methods for monitoring crop water status that could be automated are needed. In this sense, the possibility of using plant temperature as an indicator of soil water availability for plants is known since decades ago (Gates, 1964). Plants under soil water deficit often decrease stomatal conductance, thereby reducing transpiration and increasing leaf temperature. The measurement of the infrared radiation emitted by the canopy can therefore be used as an indicator of plant water stress (Jackson, 1982; Jones, 1999; Merlot et al., 2002; Jones et al., 2002). However, it is important to keep in mind that stomatal aperture can be affected not only by soil water deficit, but also by other environmental and endogenous tree factors as well as biotic stresses such as pests and diseases (Jones et al., 2009). Besides, environmental conditions such as incoming radiative energy, air temperature and wind, plant morphology's aspects like canopy shape and leaf size,

* Corresponding author. Tel.: +34 963424000; fax: +34 963424001.
E-mail address: ballester_carlur@ivia.gva.es (C. Ballester).

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as well as plant-controlling transpiration mechanisms have a direct influence on canopy temperature (Scherrer et al., 2011).

Thermal sensing can be used remotely allowing a large crop area to be measured, especially when thermal imaging is employed (Jones, 2004). Images can be taken by thermographic cameras installed on airborne platforms (Berni et al., 2009) or by hand-operated cameras assisted with auxiliary devices as tripods, platforms or cranes (Möller et al., 2007). In the case of hand-operated cameras, these can take images of individual plants or even portions of them (shady or sunlit zones) with a higher spatial resolution than aerial images (Jiménez-Bello et al., 2011). With the involvement of a single operator a large number of images can be obtained. The subsequent analysis of the images to determine mean canopy temperature of each single tree can be automated and speeded with methodologies as the one developed by Jiménez-Bello et al. (2011), which allows the analysis of images taken on individual trees without the participation of an operator, saving almost 16 min per image with respect to the manual process. Besides mean canopy temperature, the measurement of the intra-crown standard deviation has also been suggested by some authors as an indicator of water stress (Fuchs, 1990; González-Dugo et al., 2012). González-Dugo et al. (2012) observed in almond that the variability of T_c increased during the early stages of water stress while diminished when the stress became more severe. However in other woody plants such as grapevines intra-canopy variations in T_c were not impacted by vine water status (Grant et al., 2007; Möller et al., 2007). Thus, studies in other perennial crops are needed to evaluate the feasibility of using intra-canopy T_c variability as an indicator of plant water status.

The general goal of this study was to explore the feasibility of canopy temperature measured with a hand-operated thermographic camera as a water stress indicator compared with common water status indicators as Ψ_s and g_s in persimmon and citrus tree crops. The specific aims were (i) to assess the use of mean canopy temperature and temperature variability within the crowns as water stress indexes; (ii) to test this water stress indexes in persimmon and citrus tree crops which were selected because of their differences in leaf anatomy (larger and thicker leaves in persimmon than in citrus) and differential stomatal response to air vapor pressure deficit (VPD) under favorable soil water conditions. It is well known that citrus trees tend to reduce stomatal conductance in response to high VPD (Oguntunde et al., 2007; Villalobos et al., 2009); while in Persimmon trees there is some evidence that stomatal conductance might be more insensitive to air VPD (Badal et al., 2010).

2. Materials and methods

2.1. Plot characteristics and irrigation treatments

2.1.1. Persimmon experiment

The experiment was carried out in a 0.52-ha orchard located in Manises (Valencia, Spain) planted with eight-year-old Persimmon (*Diospyros Kaki*) trees, cv. "Rojo Brillante". Trees were planted at a spacing of 5.5 m × 4 m and grafted on *Diospyrus Lotus*. The soil was calcareous; of sandy loam to sandy clay loam texture with an effective depth of 0.8 m. Trees were drip irrigated with two laterals per row and 8 emitters of 4 L h^{-1} per tree. At the beginning of the experiment, trees had a canopy ground cover of 39% of the soil surface area allotted per tree. Other orchard characteristics are described in Badal et al. (2010).

The experimental orchard was designed to test four irrigation regimes but only two of them were used for the purpose of this manuscript: (i) control, irrigated at 100% of the estimated crop evapotranspiration (ET_c) during the whole season and, (ii) water stressed (WS), irrigated at 50% ET_c from May 22nd, day of the year (DOY) 142, to August 18th (DOY 230) in 2009 and from May 21st (DOY 141) to August 27th (DOY 239) in 2010.

The experimental layout was a randomized complete block design with three replicates per treatment and 6–7 sampled trees per replicate. Perimeter trees were used as guard.

2.1.2. Citrus experiment

A field trial was performed in a 1.7-ha grove located in Chulilla (Valencia, Spain), planted at 6 m × 4 m with Navel Lane Late (*Citrus sinensis* (L.) Osbeck) trees, grafted onto Carrizo citrange (*Citrus sinensis*, Osb. × *Poncirus Trifoliata*, Raf). The soil was of clay to clay loam texture, rich in calcium carbonate and with 11% by weight stones. Trees were drip irrigated with two laterals per row and 8 emitters of 4 L h^{-1} per tree. At the beginning of the experiment, trees had a canopy ground cover of 32% of the soil surface area allotted per tree. Grove characteristics are more detailed in Ballester et al. (2012a).

Three irrigation treatments were studied in this case: (i) control, irrigated at 100% ET_c during the whole season; (ii) mild water stressed (MWS), irrigated at 50% ET_c from last July to mid September and at full dose during the rest of the season; and (iii) severe water stressed (SWS), irrigated at 35% ET_c during the same period as MWS.

The experimental layout was a randomized complete block design with four replicates per treatment and at least 10 sampled trees per replicate. Perimeter trees were used as guard.

2.2. Plant water status measurements

During the period of water restrictions plant water status was periodically measured in both orchards by means of stem water potential, and canopy temperature. In addition, in persimmon trees stomatal conductance was also measured.

Stem water potential (Ψ_s) was measured at solar midday with a pressure chamber (Model 600 Pressure Chamber, PMS Instrument Company, Albany, USA) following the recommendations of Turner (1981). Leaves were enclosed in plastic bags covered with silver foil at least two hours prior to the measurements. Measurements were performed in two mature leaves per tree, in three trees per replicate in the persimmon experiment and two trees per replicate in the citrus one. Thus, Ψ_s was measured in a total of 24 and 18 trees in the citrus and persimmon orchards, respectively.

Stomatal conductance (g_s) was measured at noon only in the persimmon orchard with a leaf porometer (SC-1 Porometer, Decagon, WA, USA). Measurements were carried out in five fully exposed leaves per tree and three trees per replicate.

2.3. Image acquisition and processing

Canopy temperature (T_c) was measured at noon with an infrared thermal camera TH9100 WR (NEC Avio Infrared Technologies Co., Ltd., Tokio, Japan). The camera had a precision of ±2% of reading and was equipped with an angular field of view of 42.0 × 32.1°. It had a visible of 752 × 480 pixels and a 320 × 240 pixel microbolometer sensor, sensitive in the spectral range of 8 and 14 μm. The emissivity was set at 0.98, value indicated for healthy vegetation by Monteith and Unsworth (2008).

In 2009, T_c was measured in both sunlit ($T_c$sunlit) and shaded ($T_c$shady) sides of the crowns by taking frontal thermal images from a distance of 3 m in persimmon trees and 1–2 m in the citrus ones. Pictures were taken in four representative days for persimmon (DOY 170, 205, 226 and 240) and in seven days for citrus (DOY 204, 218, 225, 232, 239, 246 and 253).

Based on the results obtained in 2009, images were only taken from the sunlit side of the trees in 2010. During this season pictures were taken in nine days for the persimmon orchard (DOY 138, 155,