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Estimating Almond Crop Coefficients and Physiological Response to Water Stress in Semiarid Environments (SW Spain)

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ABSTRACT

Water is the most limiting factor in irrigated agriculture, mainly in Mediterranean environments, as in the case of southwest Spain. In this area, almond is one of the most valuable crops due to its high drought tolerance. This work examines the crop coefficients (K_C) based on four drainage lysimeters installed in an experimental young almond orchard. Complementary, two deficit-irrigation treatments were tested: (1) moderate deficit-irrigation (M_{DI}), which received 100% of the crop evapotranspiration (ET_C) during the irrigation period, except during the kernel-filling stage and pre-harvest, when irrigation was 50% of ET_C; and (2) severe deficit irrigation (S_{DI}), in which water was applied according to the values of leaf-water potential at midday (Ψ_{leaf}), this being maintained at between -1.6 and -2.0 MPa. The crop's physiological response to water stress was monitored throughout the study period by assessing the leaf-water potential (Ψ_{leaf}) and canopy temperature (T_C) dynamics. The K_C values changed from 0.4 at the beginning of irrigation period to a maximum of 1.1 during the maximum evaporative demand period. From this stage on, the *Kc* gradually decreased to 0.4 at the end of the season. In physiological terms, both Ψ_{leaf} and T_C showed a temporal evolution according to defined irrigation strategies. Moreover, significant relationship (r2 = 0.63, P<0.05) was obtained between Yleaf and the difference between leaf and air temperature values (AT). the difference between leaf and air temperature values; evidencing the feasibility of using T_C for water-stress management. Thus, the findings highlight the importance of local K_C to optimize water use and irrigation scheduling in almond orchards.

Keywords: Almond, Deficit-irrigation, Drainage lysimeters, Leaf temperature, Water stress.

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INTRODUCTION

Almond (*Prunus dulcis* Mill) is the third crop, after olive and grape, in terms of cultivated area in Spain, with 536,000 ha and annual production of 211,000 t (FAOstat, 2013), this being the most important tree-nut crop in the Mediterranean area (Egea *et al.,* 2009). However, this crop has traditionally been associated with marginal areas, being cultivated under rainfed conditions, and therefore the profit margin is relatively low (García-Tejero *et al.,* 2011a).

Knowledge of the accurate water loss through crop evapotranspiration (ETc) is necessary in order to avoid mistakes in estimating crop water needs, especially in areas characterized by water scarcity and drought. Many irrigation deficiencies are related to inadequate irrigation estimations, which promote higher costs, wastes of irrigation water, and negative environmental repercussions (Katerji and Rana, 2011). This issue was largely solved through the water-

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balance method proposed by Allen *et al.* (1998, 2005). This method consists of estimating the ET_C by calculating the reference evapotranspiration (ET_0) and the specific crop coefficient (K_C). The latter is highly dependent on local conditions, crop architecture, canopy resistance, albedo, and soil-surface evaporation (Abrisqueta *et al.,* 2013).

Today, it can be assumed that this is the most widely used and popular method to estimate the crop-water requirements, although there are some questions that are not totally clear, such as the possible effects of local variations on K_C values. In this sense, K_C values are affected by many factors, such as irrigation system (Doorenbos and Pruitt, 1977; Wright, 1982), weather conditions, soil characteristics, crop management, canopy development, and practices that could determine the irradiance fraction by the plant and soil (Stanghellini *et al.,* 1990; Annandale and Stockle, 1994). Consequently, most of the K_C values reported in the literature can vary significantly from the actual ones if growing conditions differ from those where the K_C values were experimentally estimated (Tarantino and Onofrii, 1991).

In arid and semi-arid areas such as the south-western Spain, irrigation can be considered the main limiting factor in almond trees, despite its ability to adapt to unfavourable conditions (Hutmacher *et al.,* 1994). In this context, the implementation of irrigation systems in rainfed areas constitutes an alternative and an opportunity to improve the productivity of this tree crop. Some authors have demonstrated that the adoption of regulated deficit irrigation (DI) strategies have improved almond productivity (Goldhamer *et al.,* 2006; Romero *et al.,* 2006; Egea *et al.,* 2010). Considering the optimal response of almond under non-limiting water conditions, and its strong drought resistance, strategies such as DI could be considered a promising alternative to improve the crop productivity when the water resources are scarce.

When a DI practice is applied, an effective monitoring of crop-water status is essential in order to optimize the crop response to water stress both in physiological terms as well as in yield. The use of plant-based water-stress indicators for monitoring the effects of DI has been widely studied in several crops. In this sense, leaf-water potential (Ψ_{leaf}) and stomatal conductance (g_s) are the most commonly used parameters to monitor the plant water status, when the crop is subjected to water stress. However, these measurements are time consuming and cannot be automated (Fulton *et al.,* 2001; Romero and Botía, 2006). By contrast, canopy temperature (T_C) measured with infrared thermometry or other remote infrared sensors can be used as an alternative technique for monitoring the crop-water status, especially when this is subjected to DI strategies (García-Tejero *et al.,* 2011b). This parameter is a particularly relevant biophysical traits in many crops, because it is a robust indicator specially of drought (Costa *et al.,* 2012), and can be used for a more precise management of deficit irrigation strategies (Jones *et al.,* 2002; García-Tejero *et al.,* 2011b). T_C is the result of an energy balance between the power gains (incident radiation and temperature of the surrounding air) and losses (due to transpiration and evaporation of water from the surface of the leaves), which entails a loss of heat from the surface studied and energy-transfer processes (Sepulcre *et al.,* 2006). From an energy balance point of view, as a consequence of stomatal regualtion (partial clousure) under a mild or moderate water stress, leaf temperature trends to increase, because of a descend in the heat dissipation associated with the transpiration process (Jones *et al.,* 2002; Costa *et al.,* 2013), which is known as the evaporative cooling process, in which there is a heat loss associated with transpiration process from the canopy so that a transpiration decline is traduced in an increase of leaf temperature (Jones, 1992). However, direct relationhips between leaf temperature values and other physiological

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parameters are not really significant because temperature readings are very dependent on other meteorological variables such as air temperature, solar radiation, wind speed, air humidity or air pressure deficit vapour (Pou *et al.,* 2014). For this reason, some reference temperature values are used to obtain some stress indices which allow normalizing the obtained values of absolue leaf temperature (Jones *et al.,* 1997, 2009; Costa *et al.*, 2013). Within these indices, ΔT (this being the difference between leaf and air temperature) allows to normalize the leaf temperature values and obtain more representative relationships between the temperature readings and other physiological variables (Costa *et al.*, 2013; García-Tejero *et al.*, 2011b).

The aim of the present work was to estimate the local crop coefficients (K_C), and the relationships in the soil-plant-atmosphere system in a young almond orchard in SW Spain subjected to water stress, analyzing its physiological response to drought, and the effects of some climatic parameters in the K_C evolution during the irrigation period.

MATERIALS AND METHODS

Experimental Site

The trial was conducted during 2013 in an experimental plot of four-year-old almonds (*Prunus dulcis* Mill. D. A. Webb. *cv*. Guara, grafted onto GF677), located in the Guadalquivir river basin (37° 30’ 47’’ N; 5° 58’ 2’’ W) (Seville, SW Spain). Planted in 2009, the trees were spaced 6×7 m, and drip irrigated using two pipe lines with emitters of 2.3 L h^{-1}, spaced at 1 m (14 emitters per tree). The soil is a silty loam, typical Fluvisol (Soil Survey Staff, 2006), 2.5 m deep, fertile, and low organic matter content (< 15.0 g kg^{-1}). The roots were located predominately in the first 0.5 m of soil, corresponding to the intended wetting depth, although they exceeded more than 1 m in depth. Soil-water content values at field capacity (–0.3 MPa) and wilting point (–1.5 MPa) in 1 m of soil depth were 255 and 90 mm, respectively.

The climatology in the study area is attenuated meso-Mediterranean, with an annual ET_0 rate of 1,400 mm and accumulated rainfall of 540 mm, distributed from October to April, for an accumulated water deficit up to 800 mm yr^{-1}.

Drainage Lysimeters and K_C Calculation

The soil-water balance was analyzed in fully irrigated trees, through four drainage lysimeters, with one tree in each (3×3×1 m) located inside an almond orchard, which were used to determine the ET_c and the soil-water-content time course for the entire profile.

Each lysimeter had eight Time Domain Reflectometry (TDR) probes (CS616, Campbell Sci.) placed twice at 15, 35, 50, and 75 cm of soil depth, at 35 cm from the vertical line of the trunk. These probes were connected to a data logger (CR1000 Campbell Sci.), and readings were taken every 15 minutes (Figure 1). An automatic collector (micro rain gauge; Campbell Sci.) controlled the water that drained after irrigation or rain episode in each lysimeter.

This system determined the crop-water demands, quantifying the entries and losses of water, according to the following equation:

$$ET_C = P + I - D - \Delta\theta - R \quad (1)$$

$$\Delta\theta = \Sigma(\theta_i - \theta_{i-1})\, Z \quad (2)$$

Where, *P* is the precipitation (mm), *I* is the irrigation water amount (mm), ET_C the crop evapotranspiration (mm); *D*, the drainage (mm); $\Delta\theta$, the soil-water content variation (L m^{-3}); θ_i and θ_{i-1} are the initial and final soil-water content, respectively; *Z* is the thickness of each horizon (m), and R the runoff, this being assumed as null.

The seasonal values of ET_0 were determined by the Penman-Monteith equation (Allen *et al.,* 1998), using the climatic data recorded at an automated

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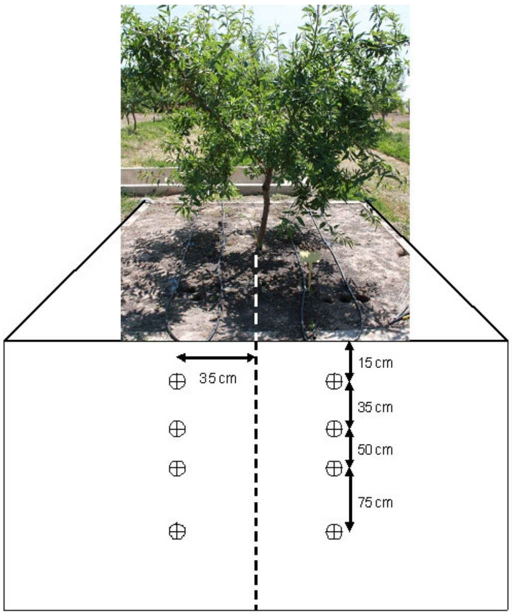

Figure 1. Drainage lysimeter used for the experiment with TDR probe distribution across the soil profile.

weather station located at 100 m from the experimental orchard.

To ensure that the almonds located in the lysimeters received enough water, these were irrigated at 130% of a theoretical ET_C, this being calculated using the ET_0 values and the K_C values reported by Girona (2006).

Considering ET_0 and ET_C values, K_C was estimated by the following equation (Allen *et al.,* 1998):

$$K_C = ET_0 / ET_C \qquad (3)$$

Irrigation Treatments in Almond Orchards

Two deficit-irrigation treatments were applied: (1) a moderate deficit-irrigation treatment (M_{DI}), which received 100% of crop evapotranspiration (ET_C) during the irrigation period (120–304 day of the year, DOY), except during the kernel-filling stage and pre-harvest; that is, from 182 DOY to harvest 235 DOY, when this treatment was irrigated at 50% of ET_C; and (2) a severe deficit irrigation (S_{DI}), with water applied according to the Ψ_{leaf} values at midday. As in the previous treatment (M_{DI}), this was watered at 100% ET_C throughout the irrigation period, except from 182 to 235 DOY. In this treatment, Ψ_{leaf} values were maintained between -1.6 and -2.0 MPa, i.e., when Ψ_{leaf} values approached -1.8 MPa, these trees were irrigated at 100% of ET_C. When Ψ_{leaf} was around -1.6 MPa, this treatment was subjected to a new restriction period until the threshold of Ψ_{leaf} (≈ -1.8 MPa) was again surpassed. Additionally, as a control, a fully irrigated treatment (F_{IT}) receiving the 100% of ET_C was used, according to the crop-water balance developed using the information from the drainage lysimeters. At the end of irrigation period, F_{IT}, M_{DI}, and S_{DI} had received 397, 307, and 175 mm, respectively.

The irrigation treatments were laid out in a randomized-block design with three replications per treatment. Each plot had three rows and 4 trees per row, with the four central trees being used for physiological measurements while the other trees served as border trees.

Plant and Soil Measurements

During the experimental period, the Ψ_{leaf} was measured in two sunlit leaves per sampling tree, between 12:00 and 13:00 hours solar time, with a periodicity of 3 to 5 days, using a pressure chamber (Soil Moisture Equipment, Mod. 3000, Santa Barbara, CA, USA).

Canopy-temperature (T_C) readings were made in three sunlit leaves per tested tree, using a portable thermal infrared thermometer (Raytek, MX), between 12:00 and 13:00 hours solar time, and with the same periodicity as the Ψ_{leaf} measurements.

Finally, besides the TDR probes installed inside the lysimeters (exclusively used to monitor the soil water balance in fully irrigated trees), volumetric soil-water content (θ_V) was measured at different soil depths (10, 20, 30, 60, and 100 cm) using a Frequency Domain Reflectometry (FDR)

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probe (Mod. PR2, Delta-T), with eight access tubes per treatment, four of them installed near the dripper closest to the trunk, and the remaining between the two farthest emitters from the tested tree. These access tubes allowed us to monitor the soil-water time course in each treatment, focusing on the effects of drought in soil water content.

Statistical Analysis

An exploratory and descriptive analysis was made in each physiological variable, followed by an analysis of variance (ANOVA) with mean separation analysis. In order to find the hypothetical effects of local climatic conditions on the K_C values, these were correlated with the daily values of radiation, wind speed, air temperature, and vapor pressure deficit.

Moreover, the difference between leaf and air temperature (ΔT) were obtained and correlated with the Ψ_{leaf} measurements to evaluate the viability of canopy temperature for monitoring the crop water status when a deficit irrigation strategy is being applied.

RESULTS AND DISCUSSION

K_C from Drainage Lysimeters

Figure 2 shows the daily time course of the maximum, minimum, and average air temperature (a), air-vapour-pressure deficit (VPD) (b), and ET_0 and rainfall (c) during the experimental period in the study area, all following the typical Mediterranean trend. The maximum values of ET_0, average temperature, and VPD were registered during the kernel-filling period, from 182 DOY to harvest (235 DOY), with an accumulated ET_0 and rainfall of 335 and 0.2 mm, respectively.

Figure 3 displays the dynamics of the average K_C for young almonds over the monitoring period, comparing these results with those reported by Girona (2006) and

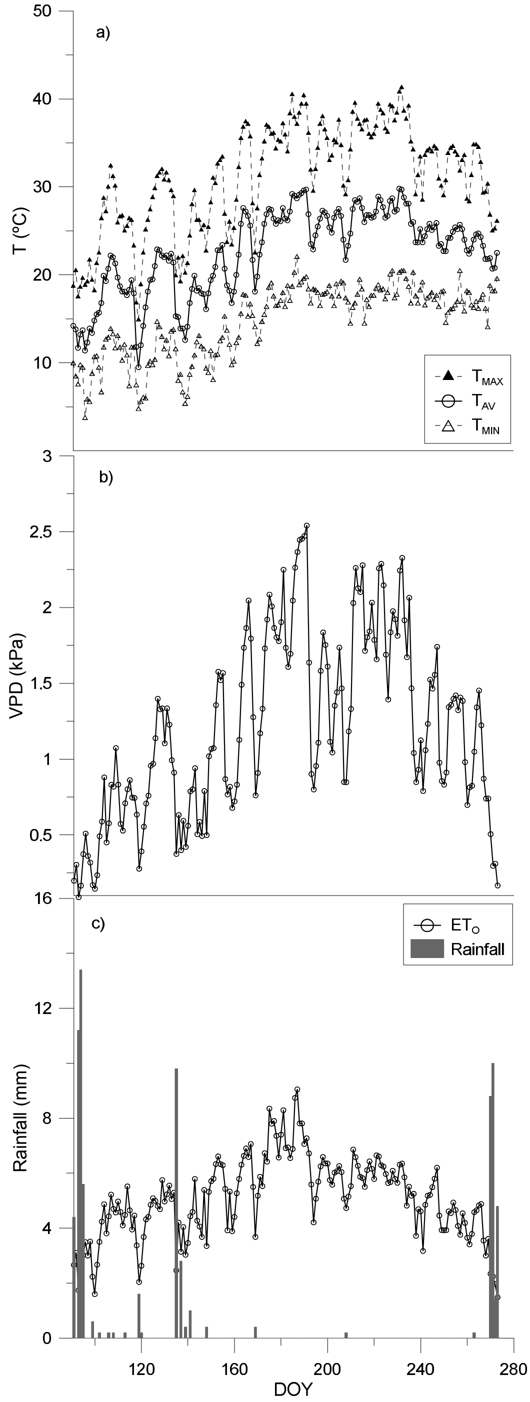

Figure 2. Daily values of maximum, minimum, and mean air temperature (a); daily mean of air-vapour-pressure deficit (VPD) (b); and daily mean of reference evapotranspiration and rainfall (c), during the monitoring period.

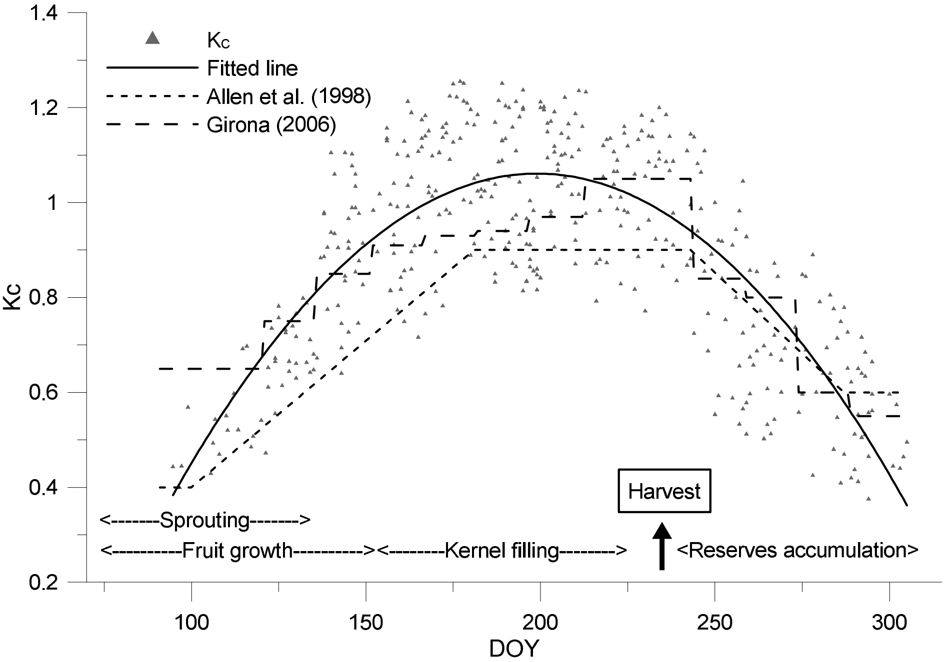

Figure 3. Time course of calculated crop coefficient K_C for almond trees in a semi-arid

Allen *et al.* (1998). According to this, different patterns were observed during each phenological stage.

The K_C values during the sprouting and fruit-growth period were significantly higher than those reported by Allen *et al.* (1998), although at the beginning of irrigation period the values were slightly lower than those described by Girona (2006). The main differences between them appeared during the maximum evapotranspiration demand, with K_C values close to 1.2. Generally, the K_C values found were higher than those described by Allen *et al.,* (1998) throughout almost the entire season. Finally, fewer differences were found during post-harvest, these values being more similar to our adjusted K_C than those reported by earlier authors.

According to Annandale and Stockle (1994), the K_C of woody crops, or those with lower resistance to drought, are especially sensitive to weather fluctuations, such as the changes in air temperature, air-vapour density, wind speed, and also solar radiation. For this reason, the K_C under different environmental conditions must be applied with some caution, taking into account the weather conditions of the area where the values were recorded.

Although the K_C has been estimated for many crops, the accuracy of these estimations can vary sharply for the same crop, especially in young trees, and even more so in arid and semiarid environments. Consequently, for miscalculations to be avoided, the K_C should be calculated and adjusted to real water needs.

In this sense, different relationships between adjusted K_C and some climatic variables were estimated, in order to define the influence on this parameter. Figure 4 shows the main relationship between radiation (a), wind speed (b), air temperature (c), and vapor pressure deficit (d) *vs.* the average of adjusted K_C. Considering the results, vapor pressure deficit (r^2= 0.85), temperature (r^2= 0.78), and radiation (r^2= 0.31) would have a significant effect (P< 0.05) in the local crop coefficient, whereas wind speed would have no significant effect on K_C. Several authors have noted a significant K_C variability between years because of the different weather conditions registered in a given area, this being especially remarkable in the case of tree

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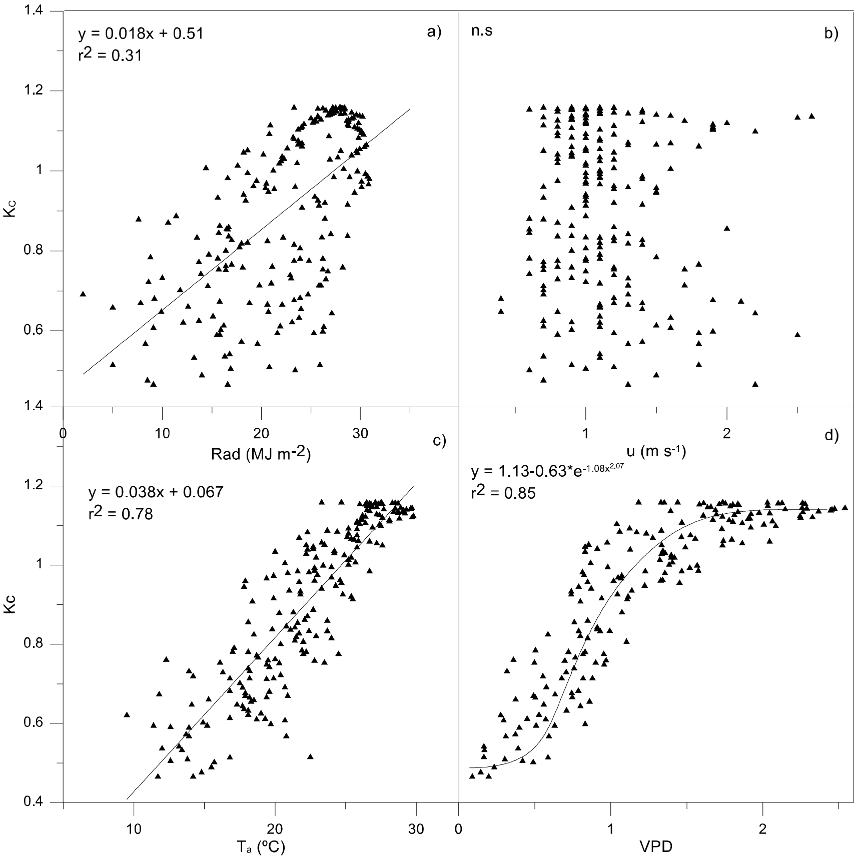

Figure 4. Relationship among radiation (a), wind speed (WS) (b), air temperature (c), and vapour pressure deficit (VPD)(d) with the calculated crop coefficient K_C in the study area ($P< 0.05$).

crops. Therefore, one alternative would be to estimate K_C as a function of some vegetation indices, which could reflect the effects of climatic conditions in crop development, as stated by many authors (Williams *et al.,* 2003; Testi *et al.,* 2004; Lovelli *et al.,* 2005).

Thus, according to the findings of the present experiment, the K_C applications which have been determined in regions with different conditions or under different management could promote over-irrigation or reduced profits because of a partial drought. For this reason, the estimation of the local K_C could improve the irrigation management especially in arid and semiarid environments, where water scarcity is the most limiting factor and higher water-use efficiency is sought.

Soil-Water Content Evolution and Crop Physiological Response to Water Stress

The dynamics of the water content in the soil profile reflected the influence of the irrigation regime applied. In this sense, F_{IT} registered values between the limits of field capacity and the allowable depletion level. By contrast, M_{DI} as S_{DI} reflected a significant fall in soil-water contents, consistent with the water demands and deficits incurred in each case (Figure 5). Therefore, both M_{DI} and S_{DI} were below the allowable depletion level throughout the kernel-filling period, with only a partial recovery after harvesting. Soil-water depletion in S_{DI} was very significant with

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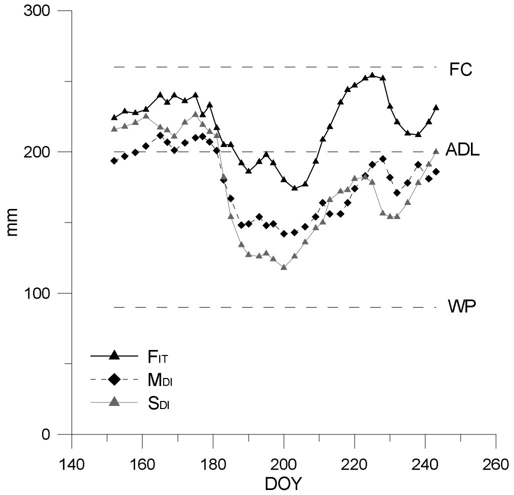

Figure 5. Time course of soil-water content in the upper 0.7 m of soil profile for each treatment. (FC: Field Capacity; ADL: Allowable Depletion Level, WP: Wilting Point).

short recovery periods, corresponding to times in which this treatment was irrigated according to F_{IT}.

The Ψ_{leaf} values recorded in each treatment were in line with the periodicity and amounts of irrigation water applied (Figure 6-a). The Ψ_{leaf} in F_{IT} ranged between -1.1 and -1.5 MPa, these values being in line with those reported by other authors under non-limiting water availability (Goldhamer and Fereres, 2004, García-Tejero *et al.,* 2012). In this sense, the water restriction from 182 DOY caused a significant decrease in the values of Ψ_{leaf} in deficit irrigation treatments. These values were particularly low in S_{DI}, during the kernel filling, reaching values of Ψ_{leaf} below -1.7 MPa, with slight recoveries corresponding to times when this treatment was irrigated at100% ET_C. Figure 6-b shows the time course of sunlit canopy temperature in each treatment. These values were in line with those results obtained for Yleaf. In this sense, Tc in Fit was from 27.5 to 29 ºC, and Mdi and Sdi from 28.5 to 31ºC, with some values that were close to 33ºC. Overall, S_{DI} was the treatment that registered the highest values of T_C, which was in line with the soil-water contents and the leaf-water potential values found in this treatment. Significant relationships ($P< 0.05$) were detected between ΔT and Ψ_{leaf} values (Figure 7, $r^2= 0.63$), showing the direct relationship between the effects of leaf-water potential conservation and the diminishing of crop transpiration. This finding was related to a less evaporative cooling effect on sunny leaves, as reported for young almond trees (García-Tejero *et al.,* 2011a, 2012) and orange trees (García-Tejero *et al.,* 2011b).

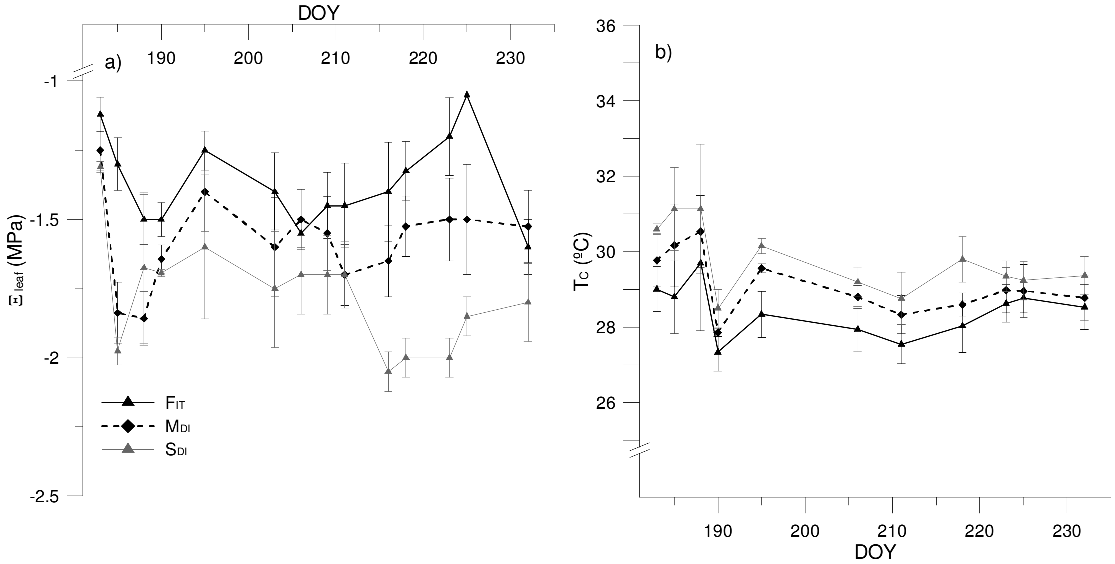

Figure 6. Time course of leaf-water potential (a) and sunlit canopy temperature (b) in each treatment. Vertical bars indicate the standard error.

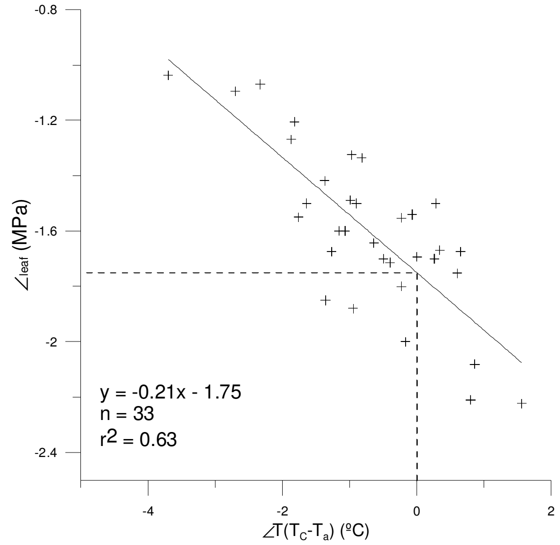

Figure 7. Relationships between the difference in temperature (ΔT) of sunlit canopy temperature (T_C) and air temperature (T_a) with the leaf-water potential (Ψ) ($P< 0.05$)

CONCLUSIONS

The calculated K_C values from lysimeters provide a useful tool for improving almond irrigation management, reconciling irrigation volume and frequency with water demand in a semiarid Mediterranean climate. In this sense, the results evidence significant effects of some climatic variables on this parameter, suggesting the necessity of delving more deeply in this technique to recalculate the local crop coefficients, especially when treating young trees.

Based on the results of this experimental work, significant correlations were found between leaf-water potential and canopy temperature, suggesting that the latter could be an advantageous and less time-consuming technique to monitor water stress in comparison to the former. Thus, this study highlights the urgency to establish the optimal water use with respect to crop requirements by estimating local K_C, in order to properly manage water stress by using physiological parameters, thereby achieving more sustainable agriculture in almond-orchard cultivation in semiarid environments.

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برآورد ضریب گیاهی و واکنش فیزیولوژیکی بادام به تنش آبی در منطقه نیمه خشک جنوب غربی اسپانیا

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چکیده

آب محدود کننده ترین عامل در کشاورزی آبی (فاریاب) است، به ویژه در آب وهوای مدیترانه ای مانند جنوب غربی اسپانیا. در این منطقه، بادام به خاطر داشتن تحمل زیاد به خشکی، یکی از با ارزش ترین محصولات است. در این پژوهش، ضریب گیاهی (Kc) با استفاده از چهار لایسیمتر که در یک باغ جوان و پژوهشی بادام کارگذاری شده بودند بررسی شد. تیمارهای آزمون شده عبارت بودند از تیمارهای تکمیلی و دو تیمار کم-آبیاری شامل: ۱) کم آبیاری متوسط (M_{DI}) که در آن ۱۰۰٪ تبخیر و تعرق گیاه (ETc) در طی دوره آبیاری تامین شد به جز در طی مرحله پرشدن دانه و قبل از برداشت که در این دوره، آبیاری ۵۰٪ از ETc را در اختیار گیاه قرار می داد، و ۲) کم آبیاری شدید (S_{DI}) که در آن بر پایه پتانسیل آب برگ (Ψ_{leaf}) در وسط روز که مقدارش بین ۱/۱۶- و ۲/۰- مگا پاسکال متغییر

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بود آبیاری انجام می شد. در طول آزمایش، واکنش فیزیولوژیکی گیاه به تنش آبی با استفاده از پتانسیل آب برگ و درجه حرارت آسمانه (Tc) پایش می شد. بر اساس داده های آزمایش، ضریب گیاهی Kc بین ۰/۴ در اوایل دوره آبیاری تا مقدار بیشینه ۱/۱ درطی دوره حد اکثر تبخیر تغییر می کرد. از این مرحله حد اکثر به بعد، Kc به تدریج تا آخر فصل کم شد و به ۰/۴ رسید. از نظر فیزیولوژیکی، Ψ_{leaf} و Tc مطابق با استراتژی های آبیاری مشخص، تکامل زمانی نشان دادند. نیز، رابطه معنی داری($r^2 = 0.63, p< 0.05$) بین Ψ_{leaf} و ΔT که تفاوت بین درجه حرارت برگ و هوا است به دست آمد که گواهی بود بر این که در مدیریت تنش آبی می توان از Tc استفاده کرد. به این قرار، نتایج این پژوهش اهمیت ضریب گیاهی محلی را برای بهینه کردن مصرف آب و برنامه ریزی آبیاری در باغ های بادام روشن می سازد.

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