

# Improving Almond Productivity under Deficit Irrigation in Semiarid Zones

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**Abstract:** Sustainable water use is one of the greatest challenges of irrigated agricultural systems. This study presents the results related to the agronomic and physiological response to the deficit irrigation of almond trees (*Prunus dulcis* DA Webb Mill cv. Guara) under semiarid Mediterranean conditions in the Guadalquivir river basin (SW Spain). Two deficit-irrigation strategies were tested: i) regulated deficit irrigation (RDI), which was irrigated at 100% of crop evapotranspiration ( $ET_C$ ) throughout the irrigation period, except during the kernel-filling stage, when these trees were irrigated at 30%  $ET_C$ , and ii) low-frequency deficit irrigation (LFDI), in which trees were subjected to different irrigation-restriction periods, defined in terms of stem water potential at midday ( $\Psi_{Stem}$ ). As control, a fully irrigated treatment (C-100) was used, which received irrigation covering the 100% of  $ET_C$ . The stem water potential ( $\Psi_{Stem}$ ), the stomatal conductance ( $g_s$ ), the photosynthesis rate ( $P_n$ ) and canopy temperature ( $T_C$ ) were monitored, revealing significant differences mainly in LFDI in comparison with C-100. Also, highly significant relationships were found among plant physiological parameters, showing that the water status is strongly related to the crop water availability. On other hand, in terms of nut yield, there was a notable improvement under LFDI compared with RDI, with increases of 16% in relation to C-100, and with water savings of close to 170 mm. Thus, these findings demonstrate that the LFDI is a sustainable strategy to improve almond productivity as well as water-use efficiency under limited water resources.

**Keywords:** Almond orchards, deficit irrigation, water stress, water-use efficiency.

## INTRODUCTION

Almond (*Prunus dulcis*), covering more than 650,000 ha in Spain, is the country's third largest crop in growing area, after olive and grape [1]. However, profits are relatively low, this being a representative woody crop to which few resources are dedicated.

The implementation of new irrigation systems in rainfed farming areas is an alternative and opportunity to improve the productivity and viability of this tree crop. For this, under semiarid conditions, the most limiting factor is water to cover crop demands.

Although almond, being highly drought tolerant, has traditionally been associated with marginal rainfed areas, this crop under non-limiting conditions would offer significantly improved yield with a high economic return. In this context, in the San Joaquin Valley (California, USA), with irrigation rates of close to  $12,000 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , almond trees reach yields of up to 10 times higher than under rainfed conditions [2].

This crop has been repeatedly linked to extreme water-stress situations, being grown in many areas under rainfed conditions, and excellent adaptability to different situations of water availability has been reported [3, 4], non-limiting water conditions significantly boosting yield and kernel quality [5-7].

However, in areas where water is limited, a viable compromise between full irrigation and rainfed conditions is deficit irrigation (DI), providing acceptable crop-yield levels similar to those achieved under non-limiting water conditions and thus improving those reached under rainfed situations [8, 9].

Many mathematical expressions have been proposed in relation to water-use efficiency (WUE) and crop-water productivity, generally from an agricultural perspective. This parameter is related to the output:input ratio in an agroecosystem, more specifically, relating the amount of biomass production to water consumption by the crop [10, 11]. It is well known that WUE can be altered by water regimes. Although WUE frequently decreases under water deficit [12], it is possible in arid and semi-arid areas, with significant water scarcity, to increase these values under different strategies of DI [13]. Clearly, WUE depends not only on the total water applied but also when and how it is applied.

The knowledge of plant response to environmental conditions is a key factor for proper irrigation scheduling and optimization. Traditionally, we have used measures based on the soil or atmospheric variables for proper irrigation management and scheduling. The use of plant-based water-stress indicators for monitoring the effects of DI has been widely studied in several crops to reduce risks of crop failure or tree damage by water stress. In this sense, stem-water potential ( $\Psi_{stem}$ ) 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, although these measurements are time consuming and cannot be

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automated, hampering continuous monitoring [14-16]. The canopy temperature ( $T_c$ ) measured with infrared thermometry or other remote infrared sensors can be used as a technique for monitoring plant-water status under DI. In this sense, canopy-surface temperatures provide a reliable indicator for detecting plant-water stress, and are closely related to daily transpiration [17-19].

The aim of this study was to assess the nut yield and physiological responses of almond trees subjected to two deficit-irrigation strategies in a semiarid region, analyzing the relationships of physiological parameters for monitoring the plant-water status.

## MATERIAL AND METHODS

### Location and Experimental Design

The trial was made in an experimental plot of mature almonds (*Prunus dulcis* Mill. D.A. Webb cv. Guara), located in the Guadalquivir river basin (37° 30' 47'' N; 5° 58' 2'' O) (Seville, SW Spain). The trees had been planted in 2000, and spacing 6 x 7 m, under drip irrigation with two pipe lines with emitters of 4 L h<sup>-1</sup>, and 14 emitters per tree.

The soil of the experimental plot was deep (> 2.5 m), with a silty-loam texture. The organic-matter content was low (< 15.0 g kg<sup>-1</sup>), for a water-holding capacity of 0.17 m<sup>3</sup> m<sup>-3</sup>. The roots were located predominately in the first 50 cm of soil, although these exceed one m in depth.

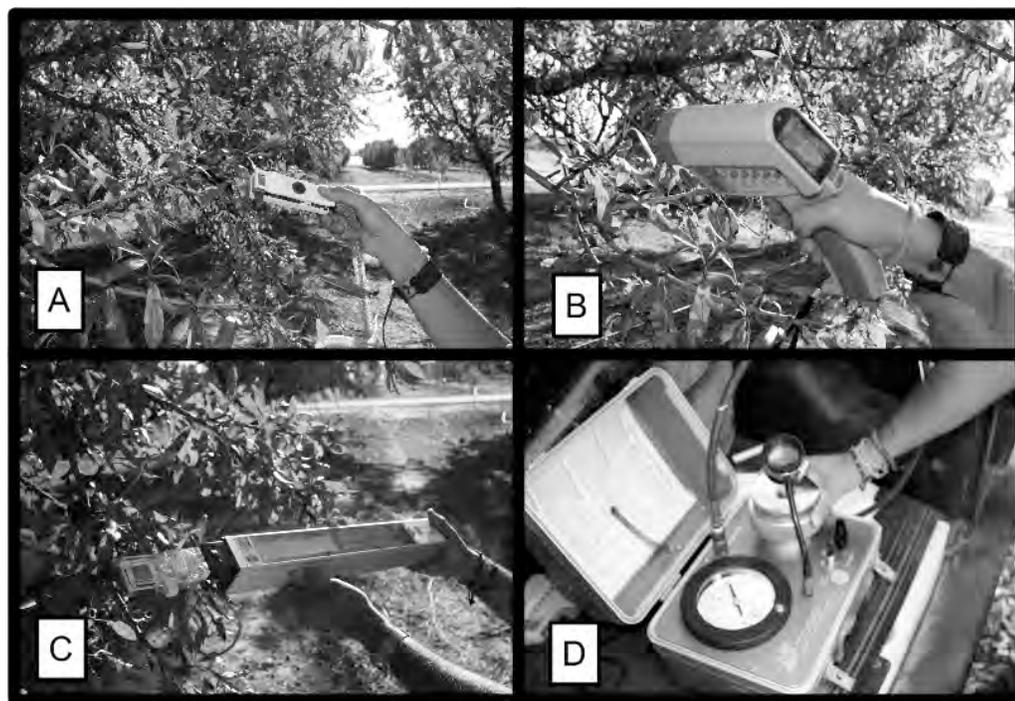
The climatology in the study area is typically semi-arid Mediterranean, with an annual evapotranspiration rate ( $ET_0$ ) of 1,200 mm and an accumulated rainfall of 550 mm, these being distributed from October to April, for an accumulated water deficit of nearly 700 mm yr<sup>-1</sup>.

Two deficit irrigation treatments were applied: i) a regulated deficit-irrigation treatment (RDI), which received the 100% of crop evapotranspiration ( $ET_C$ ) during the irrigation period, except during the kernel-filling stage, when this treatment was irrigated at 50% of  $ET_C$ , and ii) a low frequency-deficit irrigation (LFDI), in which trees were subjected to different irrigation-restriction periods, defined in terms of stem-water potential at midday ( $\Psi_{Stem}$ ). As in the previous treatment, this was irrigated at 100%  $ET_C$  throughout the irrigation period, except during kernel filling. In this case, when  $\Psi_{Stem}$  values approached a threshold value of -2.0 MPa, these trees were irrigated at 100% of  $ET_C$ . On the other hand, when these values were similar to those detected in well-watered almond trees, these were subjected to restriction periods until the  $\Psi_{Stem}$  threshold value was again reached. Additionally, a fully irrigated treatment (C-100, i.e. irrigated at 100% of  $ET_C$ ) was used as a control. The DI treatments and control were displayed in a randomized-block design with three replicates. Each plot had 10 trees per row, the five central trees of the rows being used for nut-yield and physiological measurements while the other five trees served as border trees.

### Field Measurements

During the experimental period the  $\Psi_{Stem}$  was measured in two leaves per sampling tree, between 11:00 and 12:00 h solar time, and every 5-7 days.  $\Psi_{Stem}$  was monitored in shaded mature leaves close to the north quadrant and near the trunk, using a pressure chamber [20], following Turner [21] protocol (Fig. 1).

With the same periodicity, stomatal conductance ( $g_s$ ) and photosynthesis rate ( $P_n$ ) were measured in two sunny leaves per tree, using a diffusion porometer AP-4 (Delta-T Devices,



**Fig. (1).** Devices used for field measurement: the stomatal conductance (A), canopy temperature (B), photosynthesis rate (C) and stem-water potential (D).

Cambridge, UK) and a Photosynthesis system (CI-340, CID, Inc.), respectively. Finally, canopy-temperature readings were made with a thermal infrared thermometer (Raytek, MX) with the same periodicity as the previous readings.

Additionally, the volumetric soil-water content ( $\theta_v$ ) was measured at different soil depths (10, 20, 30, 60, and 100 cm) using a Frequency Domain Reflectometry (FDR) probe (Mod. PR2, Delta-T).

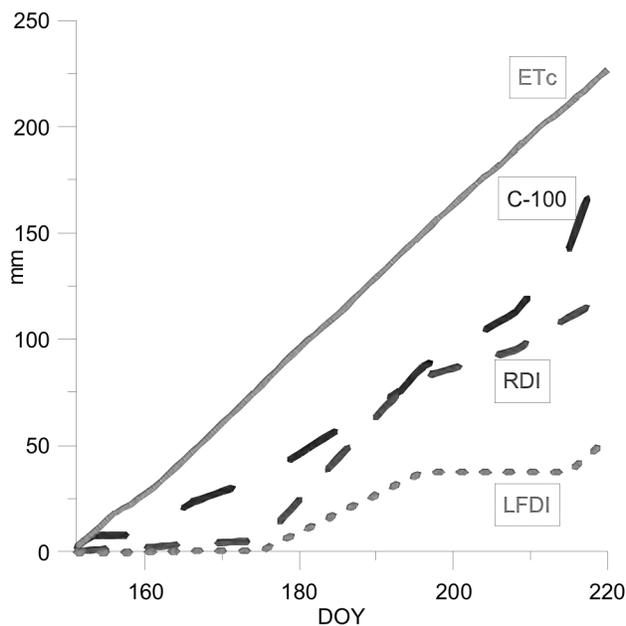
Finally, nut yield was measured by harvesting four trees per treatment, whereupon the fruit and kernel weight were recorded.

### Data Analysis

An exploratory and descriptive analysis was made for  $\Psi_{\text{Stem}}$ ,  $g_s$ ,  $T_c$ , and  $P_n$ , followed by analysis of variance (ANOVA) with a mean separation analysis, ( $p < 0.05$ ). Additionally, these variables were correlated, evaluating the viability of these readings as plant-based water-stress indicators for monitoring the effects of DI, establishing the physiological threshold values during the application of water stress.

## RESULTS AND DISCUSSION

During the monitoring period (151-220 DOY), treatments received irrigation water amounts according to the experimental design. Control trees received water amounts similar to 100%  $ET_c$ , whereas RDI received approximately, a 50%  $ET_c$ . In the case of LFDI, this was subjected to three restriction periods, one from 151 to 159 DOY; the second from 166 to 175 DOY; and the third from 196 to 215 DOY (Fig. 2).



**Fig. (2).** Crop water evapotranspiration ( $ET_c$ ) and irrigation water amounts applied in each treatment. C-100, control treatment; RDI, regulated deficit-irrigation treatment; LFDI, low-frequency deficit-irrigation treatment.

The  $\Psi_{\text{Stem}}$  as the  $g_s$  under DI treatments registered significant differences with C-100, these being especially

remarkable in LFDI during the restriction periods. In this context, partial recoveries were observed during the irrigation periods in both physiological variables (Fig. 3). Regarding to RDI, these differences were not noticeable as in LFDI. This situation could be explained through the crop capability for adapting to water-stress situations or considering the situation of the experimental plot, near to the Guadalquivir riverbed. The  $\Psi_{\text{Stem}}$  values in C-100 ranged between  $-0.8$  and  $-1.3$  MPa, these values being in line with those reported by other authors under non-limiting water availability [14, 22]. On the other hand,  $\Psi_{\text{Stem}}$  in RDI were similar to those measured in C-100, except on certain days with temperatures of up to  $40^\circ\text{C}$ . Finally, LFDI showed the highest fluctuations with similar values to those of control trees during the recovery periods, and  $\Psi_{\text{Stem}}$  values fell below to  $-2.5$  MPa.

The  $g_s$  readings showed a similar pattern to  $\Psi_{\text{Stem}}$ , with values of between  $210$  and  $520$   $\text{mmol m}^{-2} \text{s}^{-1}$  in control trees, and significant differences for LFDI and RDI, as was determined for  $\Psi_{\text{Stem}}$ . Major declines in  $g_s$  values for RDI and LFDI were detected from 183 DOY, when these values dropped below to  $100$   $\text{mmol m}^{-2} \text{s}^{-1}$ . These results imply that high water-stress levels are necessary to prompt a clear response in terms of  $g_s$  and  $\Psi_{\text{Stem}}$ , as observed by Romero *et al.*, [23].

Regarding both the temporal variation of  $P_n$  and the  $T_c$ , these values followed similar trends as those of  $\Psi_{\text{Stem}}$  and  $g_s$  (Fig. 4).

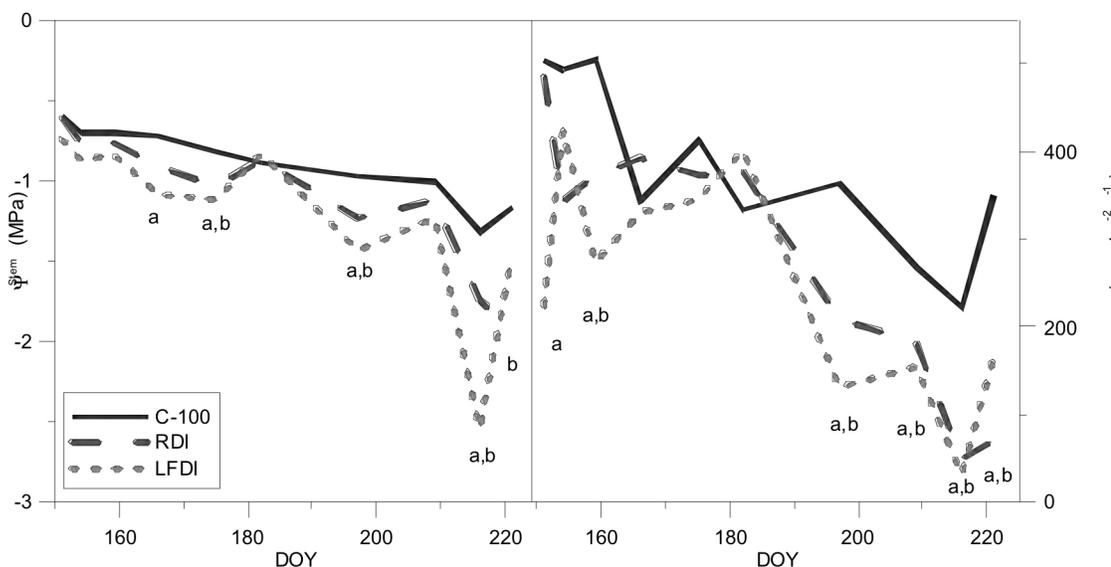
Significant differences in  $T_c$  were substantially greater than those previously found for  $\Psi_{\text{Stem}}$  and  $g_s$ . In this sense, García-Tejero *et al.*, [24] reported higher sensitivity variations in the  $T_c$  in response to water deficit, in contrast to  $\Psi_{\text{Stem}}$  or  $g_s$ .

In terms of  $\Psi_{\text{Stem}}$  and  $g_s$ , the RDI treatment showed significant differences with respect to control trees, and with some delay with respect to LFDI. However, the higher sensitivity of these parameters for reflecting water-stress situations, promoted significant differences that were noted before those of  $\Psi_{\text{Stem}}$  and  $g_s$ . In relation to LFDI treatment,  $P_n$  significantly increased while  $T_c$  decreased during the irrigation periods.

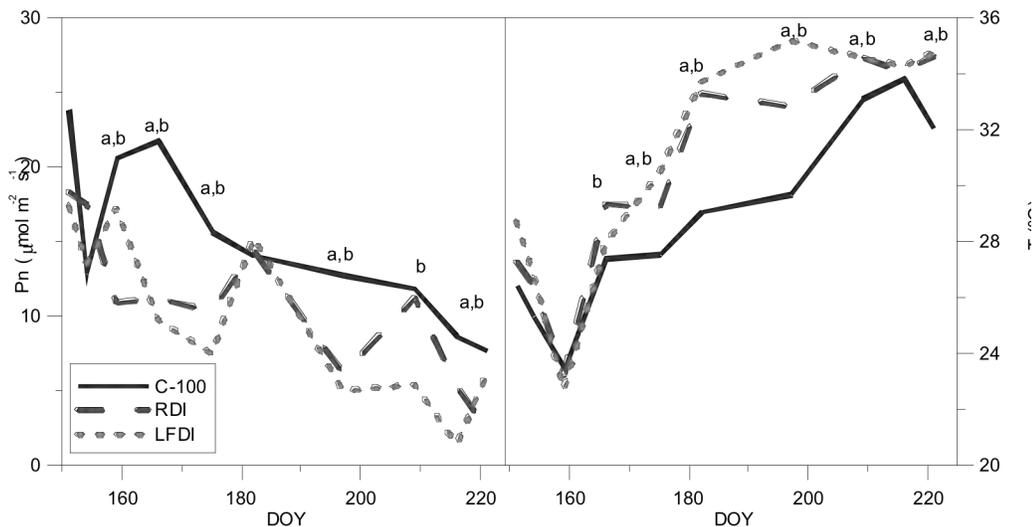
The pattern of the physiological variables resulted in different relationships among them. In this sense, especially remarkable were the exponential relations of  $\Psi_{\text{Stem}}$  vs.  $g_s$  and  $\Psi_{\text{Stem}}$  vs.  $P_n$  (Fig. 5). On the other hand, the photosynthesis rate showed highly significant correlations with  $T_c$  and  $g_s$ , evidencing its relationship. Finally,  $T_c$  was highly correlated with  $g_s$  and  $\Psi_{\text{Stem}}$ , indicating linear relationships. Many authors have shown highly significant correlations among  $\Psi_{\text{Stem}}$ ,  $g_s$ , and  $P_n$  such as Naor *et al.*, [25] in apple, Marsal *et al.*, [26] in pear, or Naor [27] in plum.

In addition, Ferreira *et al.*, [28] and Valancogne *et al.*, [29] reported strong correlations between crop transpiration and  $\Psi_{\text{Stem}}$  in peach, plum, apple, and walnut; although these relationships changed over the seasons, implying that thresholds values for irrigation scheduling may change over the season as well.

On the other hand, the sensitivity of different water stress indicators appears to be related to the degree of change in



**Fig. (3).** Time course of stem-water potential ( $\Psi_{\text{stem}}$ ) and stomatal conductance ( $g_s$ ) during the study period. C-100, control treatment; RDI, regulated deficit-irrigation treatment; LFDI, low-frequency deficit-irrigation treatment. 'a' and 'b' show significant differences for C-100 with RDI and LFDI, respectively.



**Fig. (4).** Time course of photosynthesis rate ( $P_n$ ) and canopy temperature ( $T_c$ ) during the study period. C-100, control treatment; RDI, regulated deficit-irrigation treatment; LFDI, low-frequency deficit-irrigation treatment. 'a' and 'b' show significant differences for C-100 with RDI and LFDI, respectively.

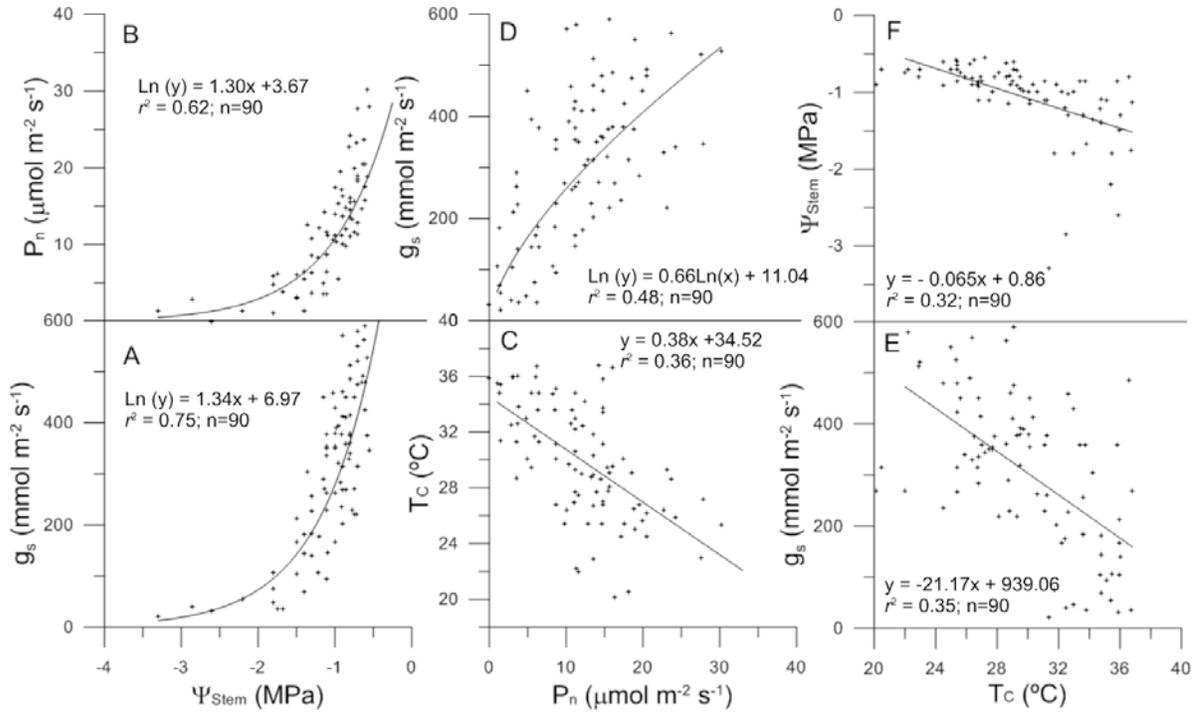
water status that can be detected statistically, i.e. the least significant difference for a given number of measurements. In this sense, the sensitivity of a water-stress indicator is expected to increase with the level of response of the sensor to changes in water status, and to decrease with increasing variability between sensors/readings [30]. In contrast to our findings, Remorini and Massai [31] argued that  $T_c$  was less sensitive to a water-stress situation than was  $\Psi_{\text{stem}}$ . However, in line with these results, water stress was detected earlier with  $\Psi_{\text{stem}}$  than with transpiration rate, although these findings are not definitive.

Given the experimental location (very close to the riverbed), and the high crop capacity to adapt to water-stress conditions, the soil-water content was monitored at different depths (Fig. 6). The main differences between treatments were found to occur at 30 cm of soil depth, especially during

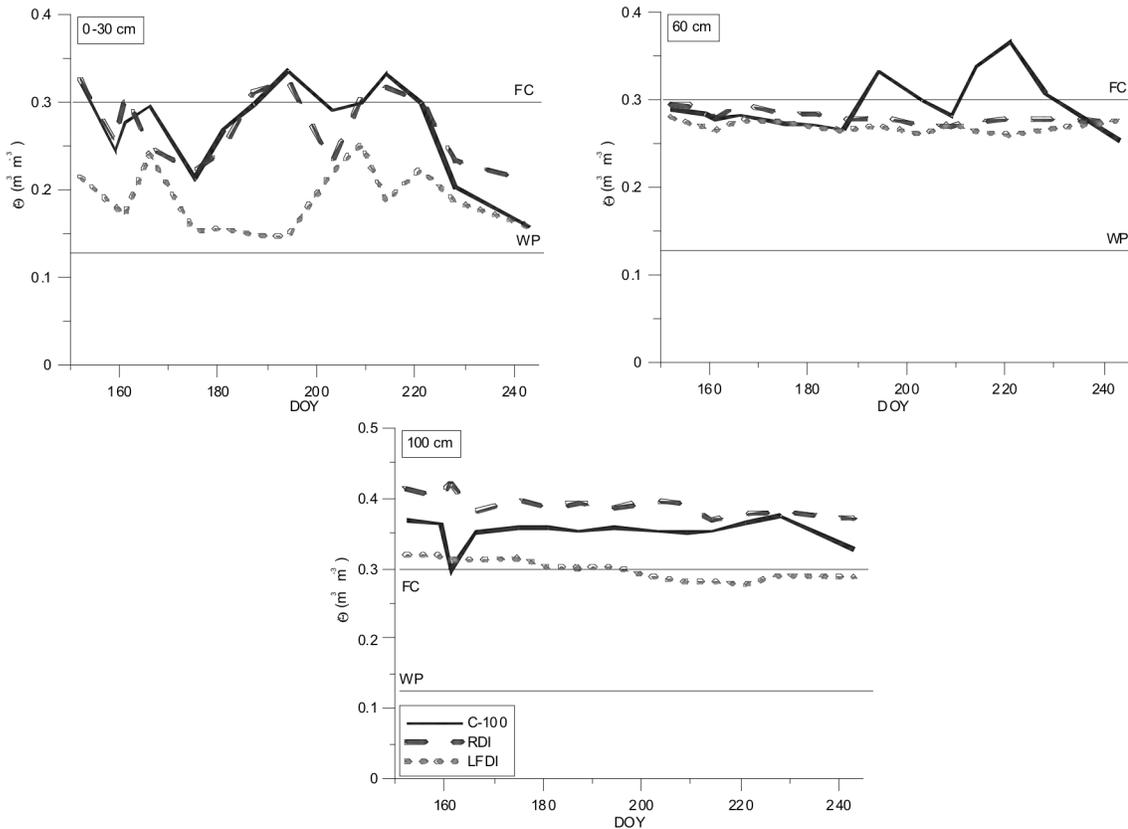
the restriction periods in LFDI. Also, there was a noticeable absence of differences between RDI and control trees, which would explain the scarcity of significant differences between these treatments in relation to the plant physiological parameters.

The soil-water contents registered in the deepest zones showed an absence of differences between treatments, and with values close to field capacity. This situation could explain the moderate crop physiological response, which, despite the detection of significant differences, was not patent throughout the kernel-filling stage.

In relation to the impact of DI on nut yield, the results showed that LFDI was the most effective treatment, improving the results of RDI and control trees. In this context, RDI showed a final yield of 1,100 kg ha<sup>-1</sup> whereas C-100 and LFDI reflected final nut yield of 1,600 and 1,800



**Fig. (5).** Relationships among plant physiological parameters.  $\Psi_{Stem}$ , stem-water potential;  $g_s$ , stomatal conductance;  $P_n$ , photosynthesis rate;  $T_c$ , canopy temperature.

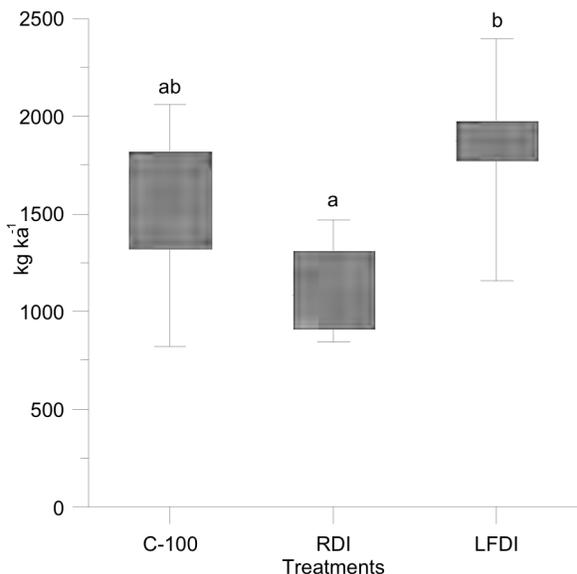


**Fig. (6).** Soil-water-content dynamics at different depths. C-100, control treatment; LFDI, low-frequency deficit irrigation; RDI, regulated deficit irrigation; FC, field capacity; WP, wilting point.

kg ha<sup>-1</sup>, respectively (Fig. 7). Regarding the weight ratio of kernel vs. almond shell, better results were found in LFDI with a 40 and 38% for RDI and C-100, respectively.

In line with this finding, several authors have shown the advantages of RDI in almond trees when water stress is applied during kernel filling, without significant yield

reduction [6, 16]. Also, Goldhamer *et al.*, [7] argued that kernel growth was reduced when a severe pre-harvest water stress was applied, this lowering kernel weight and thus the final yield.



**Fig. (7).** Nut yield in each treatment. C-100, control treatment, RDI, regulated deficit irrigation; LFDI, low-frequency deficit irrigation. Different letters indicate significant differences at  $p < 0.05$ . Vertical bars represent the standard deviation.

In addition, there were remarkable the effects of DI in terms of water-use efficiency (WUE). In this line, C-100 registered a WUE of  $203.64 \text{ g m}^{-3}$ , whereas RDI registered lower closely to  $175.89 \text{ g m}^{-3}$ . Especially remarkable were the WUE for LFDI, being significantly better than those determined in C-100 and RDI, with about  $476 \text{ g m}^{-3}$ . In this context, García-Tejero *et al.*, [13] showed substantial improvements in WUE under the LFDI strategy applied to citrus trees, in comparison to regulated or sustained deficit irrigation.

Thus, our findings support the agronomic and environmental benefits of low-frequency deficit irrigation *vs.* other strategies such as sustained or regulated deficit irrigation.

According to the results of the present study, we concluded that the low-frequency deficit irrigation is a viable and sustainable management strategy for limited water resources in the almond crop in semiarid regions.

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None declared.

## CONFLICT OF INTEREST

None declared.

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