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Rethinking irrigated almond and pistachio intensification: a shift towards a more sustainable water management paradigm

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ABSTRACT

Global warming is increasing the variability of rainfall and temperature, peculiarly, in arid and semiarid environments, provoking an augmentation in the crop water requirements, and therefore, a collapse in the water resources systems. This review work discusses the potential benefits of deficit irrigation (DI) as a strategy for water management, reducing the vulnerability of woody-fruit crops in the Mediterranean area. In this context, almond (*Prunus dulcis* Mill.) and pistachio (*Pistacia vera* L.) are traditional Mediterranean crops well-adapted to rainfed conditions with highly producer potential under irrigation, and therefore, both fruit crops are convenient alternative due to its congenital response to water-stress. In general, moderate DI enables to save about 30% of irrigation water at yield reductions below 20%. Thus, the application of DI could be recommended especially in those areas where the full water requirements for crops are not available due to environmental constrains. In addition, the success of DI is based on relevant knowledge of crop phenological development and its physiological reaction to water stress. Thus, under climate change, the implementation of properly managed fruit plantations with DI is vital to stabilize yields, increase water-use efficiency, and preserve the production quality.

Keywords: Deficit irrigation, water scarcity, Mediterranean fruit crops, quality production

INTRODUCTION

Water is the most critical resource for sustainable agricultural development, and under scarcity conditions and climate change substantial effort has to be devoted to introduce strategies in improving the water-use efficiency (García-Tejero *et al*., 2011a). Different studies reported the predictably impacts of climate change on the agricultural systems (Bindi & Olesen, 2011; Lobell & Gourdji, 2012; Souissi *et al*., 2013; Lamboll *et al*., 2017). Considering the last prediction models in climate change, the irrigation water demand may increase substantially due to higher temperatures and increased variability of precipitation (Rodríguez *et al*., 2007; Sener, 2011; Cai *et al*., 2015).

The usage of sustainable measures aiming to boost the proper water management in irrigated crops will be essential to hold the long-term progress of the agricultural activity (Garcia-Tejero & Durán, 2018; Lipan *et al*., 2018). In this context, the implentation of drought-tolerant crops in irrigated zones and the application of deficit-irrigation strategies should be contemplated. The adoption of water--saving strategies in the Mediterranean in woody fruit crops involves many considerations relative to environmental constraints and market behavior that may advocate the implementation.

Currently the irrigated almond (*Prunus dulcis* Mill.) and pistachio (*Pistacia vera* L.) are the more attractive crops in the Mediterranean basin. The cultivated area of almonds and pistachios in the Mediterranean area (including Iran) amounted to 1,267 and 385 Mha, respectively, and both represent about the 75% of worldwide surface (Kodad *et al*., 2016). Almond tree requires, for nut production, frost-free springs, a reasonable rainy period during winter and spring (rainfed cultivation), dry and hot summers, and irrigation. Chilling hours is not a problem for almond and in many aspects pistachio tree is quite similar except for this chilling requirement. Therefore, the use of low chill of pistachio cultivars is crucial because of the warm winters.

Most of almond and pistachio orchards in the Mediterranean basin are of two types: i) scattered planting of various local varieties or seedlings with low yield potential, planted on marginal lands under rainfed conditions, and poor fruit quality; and ii) modern orchards with high yielding varieties, regular and intensive planting designs, and appropiate farm management program. This type of orchards correspond to about 20-25% of the total area of Mediterranean countries, in which research and technology advances are attaining higher yield and fruit quality. That is, the difference in orchard management among almond and pistachios producing countries stands on variety performance, planting designs, level of mechanization, and irrigation. In contrast, the high yields in California (USA) almonds and pistachios orchards are mainly explained by planting on fertile soils and intensive use of irrigation, and this could double or triple productions. In addition, almond and pistachio producing countries, most of the improvement of nut yields and fruit quality is mainly due to the use of high yielding cultivars, rational agrochemical inputs, besides irrigation, soil fertility and planting design and spacing.

Rising global demand has promoted farmers to plant irrigated almond and pistachios plantations, creating more water supply demand. Currently, California almond and pistachio plantations are facing important water shortage problems, similarly as the Mediterranean almond and pistachio orchards have faced at all time. Within the global warming and climate change context, water resources shortage for agriculture activities is a major issue, therefore, these facts lead to urgent adoption of sustainable irrigation strategies for both crops in the Mediterranean.

IRRIGATED ALMOND PLANTATION

Almond is not a novelty crop in the south of Europe, thus being widely cultivated in many Mediterranean countries (Italy, Greece, Syria, Tunisia, Argelia, and Morroco), although, Spain is the most important country in terms of surface in the region. However, this contrasts with productivity because USA and Australia are the most relevant producers, providing 80% of the worlwide market (FAOSTAT, 2018). Concretely, the USA with about 400,000 ha is able to reach an annual almond production close to 1.5 Mt with an average productivity between 3,500 and 4,000 kg ha^{-1}. By contrast, Spain with 700,000 ha has a production of 200,000 t with an average productivity of roughly 300 kg ha^{-1} (FAOSTAT, 2018). The main factor for this difference is exclusively related to water availability because this crop is cultivated in marginal areas of south Spain (Arquero, 2013). According to the CAPDR (2016) in the last years a significant increase in the surface devoted to almond was fixed, especially in irrigated areas traditionally occupied by other crops. This fact was linked to an increase in the almond prices during 2014-2016, and after this the almond nut price stabilized around to 6 € kg^{-1} (OPM, 2019).

It is well-known that water availability is the most limiting factor to reach maximum yield in terms of number and size of almond fruits as was stated by Goldhamer & Fereres (2017). Additionally, these authors reported that almond was able to reach yields close to 4,000 kg ha^{-1} with irrigation amounts of 1,300 mm, showing that water withholdings close to 25% provoked yield reductions of 15%. Similarly, Goldhamer & Girona (2012) showed that optimum water requirements for almond ranged between 900 and 1,350 mm, depending on the rootstock, cultivar, canopy size, and tree spacing.

On the other hand, almond has been conventionally considered as a proper crop for drought scenarios, and under irrigated cultivation its particular phenology promotes different responses to water stress (García-Tejero *et al*., 2018a). In this sense, many authors have revealed the advantages and opportunities of deficit irrigation for almond cultivation, obtaining competitive yields under moderate-to-severe water stress situations (Romero *et al*., 2004, 2006; Girona *et al*., 2005; Egea *et al*., 2010; López *et al*., 2018a).

Almond water requirements

Many studies have reported the almond water requirements under different environmental conditions (Girona, 2006; Sanden *et al*., 2012; Espadafor *et al*., 2015; García-Tejero *et al*., 2015). There is an important difference by comparing the almond crop coefficient (K_C) values obtained four decades ago with those recently reported with maximum K_C during the kernel-filling stage. In this sense, Figure 1 shows the maximum K_C reported by Doorenbos & Pruitt (1977) and Allen *et al*. (1998) during the kernel-filling period, and those estimated in recent studies by Sanden *et al*. (2012), García-Tejero *et al*. (2015), and Goldhamer & Fereres (2017). An increasing trend was fixed for K_C from 0.9 to 1.2, which suggests that crop-water requirement was 30% higher for the most recent experiments. These variations could be presumably due to direct response to modifications in the crop management, concretely with practices of minimum pruning (higher canopy volumes) and reductions in the plant spacing (higher plant densities), both changes related to the intensification of the almond plantations (Steduto *et al*., 2012). In this context, as was stated before, the annual water requirements for mature almond plantations in California USA are about 13,000 m^3 ha^{-1} with yield of 4,000 kg ha^{-1} as was pointed out by Goldhamer & Fereres (2017), this means that about 25% higher than those estimated three decades ago with yields that were practically half of current yields (Goldhamer & Viveros, 2000), or 8,000 m^3 ha^{-1} for the case of south of Spain (García-Tejero *et al*., 2018a; López *et al*., 2018b).

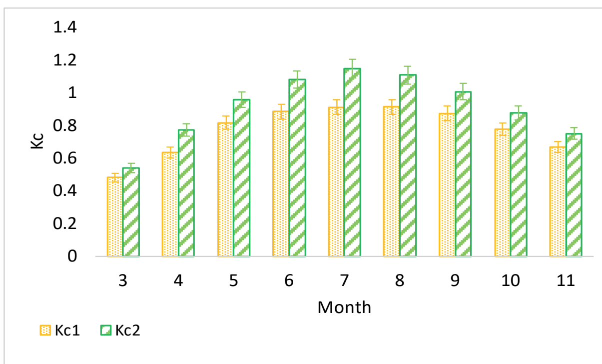

Figure 1 - Crop coefficient (K_C) pattern for two periods in time for almond cultivation. Vertical bars represent standard deviation. Kc1, is the average values reported by Doorenbos & Pruitt (1977), Goldhamer (1989), and Allen *et al*. (1998); Kc2, is the average values by Sanden *et al*. (2012); García-Tejero *et al*. (2015), and Goldhamer & Fereres (2017).

Canopy size directly affects almond transpiration, therefore, canopy volume is vital factor to be appropriately controlled when almond trees are growing under water deficit scenarios. In this sense, Espadafor *et al*. (2015) reported the important relationship among canopy volume, intercepted radiation, and crop transpiration, concluding that there is a relationship between the transpiration coefficient and fraction of intercepted radiation in young almond trees. In this line, López *et al*. (2018b) revealed a transpiration coefficient of 1.02 for mature almond trees with a full canopy developed. These considerations should be considered when almond is going to be cultivated where water allocations are below the total crop water requirements. Furthermore, different authors stated that the radiation interception is the main factor to regulate the ratio ET_C/ET_0 (crop evapotranspiration/reference evapotranspiration) in deciduous orchards such as peaches (Ayars *et al*., 2003), vineyards (Williams & Ayars, 2005), or almonds (Espadafor *et al*., 2015).

WATER STRESS AND PHENOLOGICAL STAGES

Combining the almond cultivation practices with water stress through deficit irrigation (DI) is essential to reach an equilibrium between water allocations and sustainable and competitive nut yields. A yield reduction for crops is the expected response when a DI strategy is applied, although the main objective will be focused to reach maximum water savings by minimizing the yield decrease (García-Tejero *et al*., 2014) and even, if it is possible, improving some fruit quality parameters related to healthy compounds (Lipan *et al*., 2019a). In this context, Gutiérrez *et al*. (2019a) and Lipan *et al*. (2020) reported that the implementation of DI in almond resulted as suitable measure to achieve competitive yield without significant impact on nut quality.

However, to achieve the success of DI strategy different aspects should be contemplated, such as the type of DI, crop phenological development, and threshold values for some physiological indicators. Almond tree phenology throughout the nut production process included different stages [dormant and bloom (stage I), fruit growth and vegetative development (stage II), kernel-filling with dry-matter accumulation and pre-harvest (stage III), and post-harvest with reserves accumulation and buds differentiation before leaf-fall] (Doll, 2009).

Considering the almond phenological development different authors have pointed out relevant findings for regulated-deficit irrigation strategy in which the water stress is applied at different phenological stages. Girona *et al*. (1993) revealed that water stress at stage I could provoke fruit abscission, small fruits, and poor canopy development, which ultimately affects the photosynthetic capacity for the remaining physiological processes. Knowing the weather conditions in the Mediterranean with a low evapotranspiration demand and scarce canopy development during the stage I, together with the rainfall at the end of winter and beginning of spring, it would be challenging to reach severe water stress situations for trees. Similarly, when water-stress situation is applied at stage III, although after nut harvest, the crop water demand progressively decreases, and autumn rainfall events occur typically during this period. In this sense, Goldhamer & Viveros (2000) and Romero *et al*. (2004) reported positive effects on bud differentiation and carbohydrates accumulation, these facts being reflected during the fruit-setting and vegetative development in the next season.

In addition, after flowering, the presence of carbohydrates reserves is crucial to ensure proper shoots development with initial fruit growth, coinciding with a fast cell division process. However, flowering is determined by the crop status during the previous season, insomuch as vegetative development is moving forward, the crop produces photo-assimilates, this being essential for the following fruit-growth stage. The timing coincidence between the fruit growth and canopy expansion provokes a competition for resources as was asserted by Goldhamer & Girona (2012). Therefore, fruit size would be affected by the available resources during the stage I. Thus, flowering and fruit set are directly affected by the reserve's accumulation during the previous season (Esparza *et al*., 2001), and the fruit growth will be more influenced by water and nutrients provided to the crop during the current season.

In this context, a positive response to water stress throughout the kernel-filing period (stage II) was highlighted by Goldhamer *et al*. (2006a) and Romero *et al*. (2004). By contrast, Girona *et al*. (2005) found yield reductions when water withholding was applied during this period, mainly because of depletion in the dry mass accumulation. Recently, García-Tejero *et al*. (2018b) and Gutiérrez *et al*. (2019a) reported no significant differences in terms of kernel weight and yield when regulated-deficit irrigation and low-frequency deficit irrigation were applied during the kernel-filling period, respectively.

Selecting the most suitable DI strategy

In general, water-stress management in almond can be defined in four schemes i) sustained-deficit irrigation (SDI), achieving an equilibrium between canopy and fruit development, ii) regulated-deficit irrigation (RDI), focusing on the sharp differentiation throughout the phenological cycle; iii) low-frequency deficit irrigation (LFDI), which is applied when the crop is subjected to irrigation--restriction cycles, keeping it within a range of stress, and iv) partial-root drying (PRD), aiming to produce chemical signals for control of leaf stomatal conductance (García-Tejero *et al*., 2018b).

Even though many irrigation strategies for almond trees have been revealed, up today, there are no explicit results in terms of yield for SDI and RDI during the kernel-filling stage. Some relevant results provided under Mediterranean conditions by Goldhamer *et al*. (2006a), reporting that under moderate water stress and with similar irrigation amounts, SDI offered lower yield reductions compared with RDI, and even more, being able to obtain similar productions to those registered under full irrigated trees as pointed out by Girona *et al*. (2005). Comparable findings were reported by Gutiérrez *et al*. (2019b) for three juvenile almond cultivars irrigated with SDI strategy at 75% of ET_C under semi-arid Mediterranean conditions (Figure 2).

No differences between SDI and RDI strategies for fruit yield were found by Egea *et al*. (2013) and Alcón *et al*. (2013), although RDI tended to produce lower yield rates than SDI. Additionally, Gutiérrez *et al*. (2019a) highlighted differences in kernel yield with the same almond cultivars (Guara, Marta, and Lauranne) previously shown in Figure 2, when these cultivars were exposed to RDI strategies with respect to full-irrigated trees.

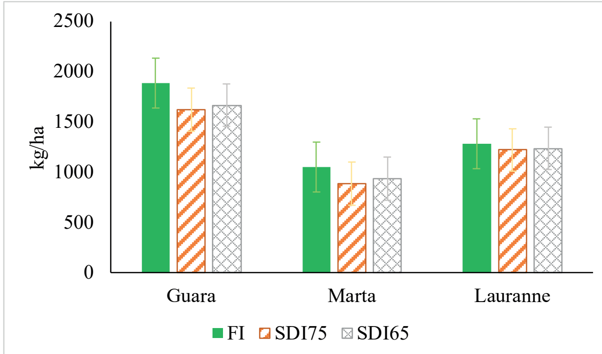

Figure 2 - Yield response of three almond cultivars (Guara, Marta, and Lauranne) to SDI strategies under Mediterranean conditions. Vertical bars represent standard deviation. SDI_{75}, sustained-deficit irrigation at 75% ET_C; SDI_{65}, sustained-deficit irrigation at 65% ET_C; FI, full-irrigated trees at 100% ET_C. (Gutiérrez-Gordillo *et al*., 2019b).

On the other hand, significant findings were reported by García-Tejero *et al*. (2019) for a long--term experiment with almond cv. Guara (Figure 3). These authors studied the almond yield response to two deficit-irrigation treatments: RDI during the kernel-filling period (50% ET_C) and LFDI (consecutive irrigation-restriction cycles during the same period of RDI), both compared with a control trees at 100% ET_C. In the framework of this experiment the LFDI was able to attain similar yields than those recorded from non-stressed control trees throughout the monitoring seasons. Moreover, this strategy was able to improve the yields registered under RDI_{50} with significantly worse results than control trees.

In relation to PRD, Egea *et al*. (2009, 2011) reported that this strategy alternatively irrigated at 50% ET_C recorded comparable nut yield than those with RDI that received 20% more irrigation water. However, more relevant results were obtained with PRD in which water withholdings close to 70% were imposed. This strategy offered similar yields than those registered with an RDI with similar water restrictions, without significant repercussions for water potential and gas exchange parameters. Thus, this fact suggests that PRD strategy did not manifest a relevant chemical signal (abscisic acid synthesis) that able to reduce stomatal conductance (g_s) rates and maintain leaf water potential (Ψ_{leaf}) values.

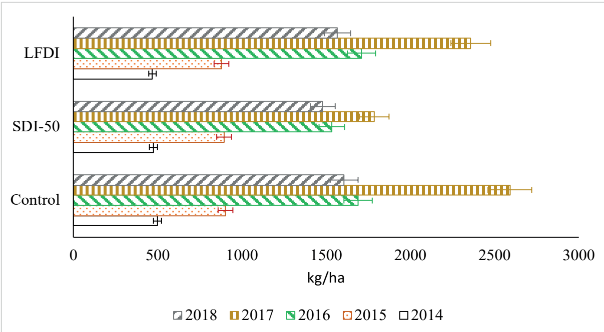

Figure 3 - Kernel yield response in a long-term study for almond cv. Guara to different DI strategies. Vertical bars represent standard deviation. Control, non-stressed trees at 100% ET_C; RDI_{50}, regulated-deficit irrigation at 50% ET_C during the kernel-filling period; LFDI, low-frequency deficit irrigation with restriction cycles during the kernel-filling period, keeping the Ψ_{leaf} similar than those registered in control trees (100% ET_C) during ordinary irrigation period and Ψ_{leaf} of -2 MPa during the restriction period. (García-Tejero *et al.* 2019)

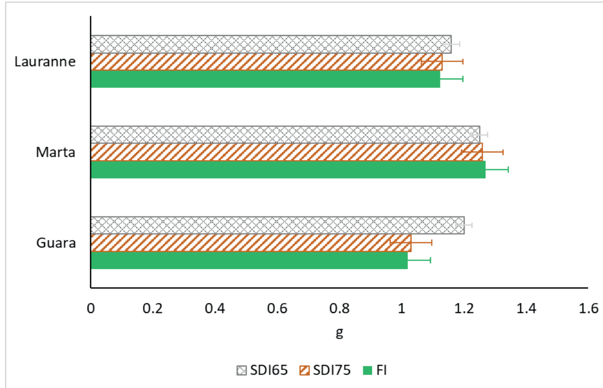

Figura 4 - Average kernel weight for three young almond cultivars (Guara, Marta, and Lauranne) subjected SDI strategies. Vertical bars represent standard deviation. SDI_{75}, sustained-deficit irrigation at 75% ET_C; SDI_{65}, sustained-deficit irrigation at 65% ET_C; FI, full-irrigated trees at 100% ET_C. (Gutiérrez-Gordillo *et al.* 2019b).

Besides the impact of deficit irrigation on almond yield, also some morphological parameters such as kernel size, ratio shell/kernel, and irrigation water productivity could be affected. In this line, Figure 4 displays the unit weight of kernel for three almond cultivars under SDI strategies (Gutiérrez *et al*., 2019b).

No significant differences were found for almond nut size of cvs. Marta and Lauranne. In contrast with cv. Guara that increased in almond nut size under SDI_{65}, these results, together with those obtained in terms of final yield evidenced the impact of water stress on fruit setting (fewer fruits in SDI_{65}), although this effect was adjusted with a larger kernel size. This later aspect could be assumed as a positive quality effect in terms of the final value of almonds. Similar findings were outlined by Gutiérrez *et al.* (2019a) for RDI strategies, this being a positive aspect that has to be taken into account in further research. In short, it could be inferred that the reductions in almond yield does not explicitly depend of the type of deficit-irrigation strategy used but also of the crop physiological response to water stress.

The crop-water status examination under deficit irrigation

Water stress adversely impacts many aspects of the plant physiological mechanisms, particularly its photosynthetic capacity. And plants have evolved complex physiological and biochemical adjustments to adapt to diverse environmental stresses. The symptomatology manifests through plant physiological parameters that help to manage properly the water stress provoked by deficit irrigation. That is, crop productivity response is going to be directly associated by reductions of the photosynthesis rate. The whole mechanism involved in plant carbon assimilation is huge and complex, and therefore, we are going to focus the effort in analysing those usual physiological parameters monitored in the field when water-stress is applied.

In this context, plants under water stress react with reduction rates of g_s (Hsiao, 1990), this being a defensive mechanism to reduce the water losses through stomata. Subsequently, this depletion in carbon assimilation could be accompanied by other biochemical limitations at ribulose biphosphate carboxylase (RuBisCO) level and electron transport chain (Flexas *et al*., 2009; Egea *et al*., 2011). However, the link between water stress and photosynthesis rate reduction does not occur in the same way for the different plant species (Flexas *et al.*, 2014). Almond tree could be considered as an anisohydric crop because of its reduced stomatal regulation under drought conditions (Egea *et al.*, 2011; Xiaoli & Frederick, 2018). In addition, the g_s reduction of roughly 50% from its maximum rate could be associated by decrease of photosynthesis rate about 30% as was pointed out by Romero *et al.* (2004).

By comparing these findings with those reported by García-Tejero *et al.* (2018b), reductions of Ψ_{leaf} (about 50%) induce to decrease the carbon assimilation rate to 15-20%, revealing the high almond capability in maintaining maximum g_s values (~ 0.3 mol H_2O m^{-2} s^{-1}) even when Ψ_{leaf} is close to -2.5 MPa as was stated by Hernández *et al.* (2016). Additionally, before reaching significant exhaustion in g_s, important reductions in Ψ_{leaf} were found without other relevant effect (García-Tejero *et al.*, 2018b). That is, almond tree would be able to hold optimum rates of g_s, carbon assimilation rate, and rise the water-use efficiency (Rouhi *et al.*, 2007). Thus, almond's reaction to water shortage would demand different regulation mechanisms to prevent the adverse impact of water stress. And it is vital to elucidate the most suitable parameter to appraise the almond physiological status under water stress conditions, and the physiological threshold values to avoid significant effects on vegetative growth, yield, and nut quality.

The most relevant studies concerning the effects of deficit irrigation programmes on almond yield and its quality are listed, highlighting the objective and DI strategies and the main findings:

<u>Romero *et al.* (2004)</u>

Objective and DI strategies: The effects of regulated-deficit irrigation (RDI) during the pre-harvest period (kernel-filling stage) on almond yield during 2-year monitoring period: full irrigated trees (100% ET_C) and RDI irrigated at 100% ET_C except from early June to early August (kernel-filling stage) at 20% ET_C.

Main findings: Although kernel yield was correlated with Ψ_{leaf}, RDI provoked no significant 7% reduction in kernel yield without effect on its size. The RDI improved WUE with 30% less irrigation water respect to control trees. Almonds can be successfully grown in semiarid regions with RDI regime, maintaining Ψ above a threshold value of -2.0 MPa.

<u>García *et al.* (2004)</u>

Objective and DI strategies: A cost-benefit analysis was performed for almond plantation to determine its profitability during 4-year monitoring period: full irrigated trees (100% ET_C) coverage throughout the growth cycle, and RDI irrigated at 100% ET_C except during the kernel-filling period irrigated at 20% ET_C.

Main findings: A 28% water saving was achieved with RDI, while yield was reduced by 7%. The cost-benefit analysis for RDI showed a 10% mean annual reduction in operating costs. RDI had a greater short-term than long-term benefit per unit cost. The irrigation costs for full irrigated and RDI trees were 0.76 and 0.58 € kg^{-1}, respectively. The break-even point was lower for RDI with kg cost of 0.05 € less respect to control trees. Thus, RDI was agronomically and economically suitable in semiarid environments.

<u>Girona *et al.* (2005)</u>

Objective and DI strategies: The impact of four irrigation strategies on almond productivity during 4-year monitoring period were studied: 100% ET_C, 130% ET_C, 70% ET_C, and RDI irrigated at 100% ET_C with exception during the kernel-filling period when was reduced at 20% ET_C.

Main findings: The optimum yield was found with 100% ET_C, while 130% ET_C trees never improved kernel production. During the first two seasons, kernel dry matter accumulation did not decrease with RDI, however, yield and kernel growth were reduced during the third and fourth seasons. Although yield reductions for RDI were significant (20% respect to 100% ET_C), water savings (~ 60% of applied respect to 100% ET_C) may recommend RDI. Therefore, RDI seemed to be more appropriate than 70% ET_C.

<u>Egea *et al.* (2010)</u>

Objective and DI strategies: The effects of deficit irrigation strategies during 3-year monitoring period on tree growth, shoot and leaf attributes, yield, and water productivity of almond cv. Marta: three partial root-zone drying (PRD_{30}, PRD_{50}, and PRD_{70}) (reductions of ET_C at 30%, 50%, and 70%) and RDI at 50% ET_C during kernel-filling period were compared with a control of full-irrigated trees at 100% ET_C.

Main findings: The results showed a negative impact on trunk growth parameters by all deficit irrigation treatments. The reduction in trunk growth rate was strongly correlated with the annual volume of water applied (WA) per tree. With exception of PRD_{70}, the kernel weight was significantly reduced in remaining deficit irrigated treatments. Kernel yield, in % of the maximum yield at 100% ET_C, showed a linear decrease with decreasing WA (slope of 0.43), which implies that a 1% decrease in water application lead to a reduction of 0.43% in yield. Water productivity increased with the reduction of WA, reaching 123% in the case of PRD_{30}.

García-Tejero *et al*. (2011b)

Objective and DI strategies: Two deficit irrigation strategies were tested: RDI irrigated at 100% at ET_C throughout the irrigation period, except during the kernel-filling stage irrigated at 30% ET_C, and low-frequency deficit irrigation (LFDI) subjected to different irrigation restriction periods defined by Ψ_{stem}. Both compared with fully irrigated trees at 100% ET_C.

Main findings: Nut yield was a notable improved under LFDI compared with RDI, with increase of 16% in relation to 100% ET_C and water savings roughly to 170 mm. Thus, these findings highlighted the promising possibilities of LFDI as sustainable strategy to enhance almond nut productivity as well as water-use efficiency tool under limited water resources in semiarid Mediterranean environments.

Stewart *et al*. (2011)

Objective and DI strategies: The almond yield under RDI was compared with full irrigated trees (100% ET_C). Irrigation was reduced once the onset of hull split was observed in blank nuts, about a week before the onset of hull split in normal nuts (filled). Before and following the hull-split period, the water amounts applied in RDI and control trees were equivalent. During the hull-split period, Ψ_{stem} was adjusted to achieve a mild-to moderate stress level from −1.4 to −1.8 MPa.

Main findings: No significant yield reductions were found, although average kernel weight was slightly lower. With RDI were only two significant effects on nut quality: decrease in kernel weight and increase in the percentage of severe shrivel. Concretely, average nut weight was 1.18 g in RDI and 1.21 g in control trees, and a severe shrivel in 13.0% for nuts from RDI. Finally, the average water savings throughout the 5-year monitoring seasons amounted to 122 mm of applied water in the RDI regime.

Alcón *et al*. (2013)

Objective and DI strategies: Assessment of a long-term (6-year monitoring seasons) economic viability of deficit irrigation in almond cv. Marta. A discounted cash flow analysis (DCFA) was performed to determine the profitability of irrigation regimes: control full irrigated at 100% ET_C, RDI receiving 40% ET_C during kernel-filling period and irrigated the remaining period as control trees, mild-to moderate sustained-deficit irrigation (SDI_{mm}) (irrigated at 75% ET_C and 60% ET_C), and moderate-to severe SDI_{ms} (irrigated at 60% ET_C and 30% ET_C) over the whole growing season.

Main findings: The DCFA concluded that RDI and SDI_{mm} were the most economically feasible irrigation strategies, whereas 100% ET_C and SDI_{ms} regimes gave similar degree of profitability over the study period. In addition, simulation outputs derived for the whole useful life of the investment indicate that SDI_{mm} would be the most suitable irrigation strategy to be adopted by almond plantations. Thus, in a context of water scarcity scenario, the deficit-irrigation regimes are financially feasible alternative to full irrigated almond plantations.

Egea *et al*. (2013)

Objective and DI strategies: The effect of four irrigation treatments on almond productivity: control with full irrigated at 100% ET_C, RDI irrigated as control trees with exception during kernel-filling period receiving 40% ET_C, mild-to moderate SDI_{mm} irrigated at 75-60% ET_C, and moderate-to severe SDI_{ms} irrigated at 60-30% ET_C over the entire season.

Main findings: The application of water stress from orchard establishment not intensified the negative impact of deficit irrigation on almond productivity. Irrigation water productivity (IWP) increased proportionally to mean relative water shortage. The SDI_{ms} augmented IWP by 92.5%, reduced yield by 29%, and applied 63% less irrigation water. RDI and SDI_{mm} showed similar productive performances, but RDI was more efficient than SDI_{mm} to increase fruiting density and production efficiency. Therefore, the SDI_{ms} appears to be the best option under severe water scarcity conditions, whereas for less water-scarce areas RDI and SDI_{mm} behaved similarly, except for the ability of RDI to more severely limit vegetative development.

Phogat *et al*. (2013)

Objective and DI strategies: The use of HYDRUS-2D model for drip irrigated almond orchard, evaluating the daily fluctuations in water under: full pulsed (FIp) with replace of 100% ET_C, sustained deficit pulsed (SDIp) irrigated to replace 65% ET_C, and full continuous (FIc) irrigation with replace of 100% ET_C.

Main findings: Water uptake efficiency under SDIp (68%) was higher respect to full water application of FIp and FIc (54-55%). The irrigation water productivity increased (37%), yield was reduced by 8%, and 35% of irrigation water was saved with SDIp compared to FIp. Thus, SDIp appears to be a promising strategy, and irrigating almonds above the SDIp level may enhance unproductive water usage in the form of accelerated drainage.

Mañas *et al*. (2014)

Objective and DI strategies: The effects (4-years monitoring seasons) of six irrigation amounts on almond yield: no irrigation (T_1), SDI irrigated at 25% ET_C (T_2) during the whole season, RDI irrigated at 50% ET_C with exception during the kernel-filling period irrigated at 15% ET_C (T_3), SDI irrigated at 50% ET_C (T_4), RDI irrigated at 100% ET_C with exception during the kernel-filling period irrigated at 20% ET_C (T_5), and a control of full irrigated trees at 100% ET_C for the entire irrigation season (T_6).

Main findings: Significant differences in nut yield and WUE among irrigation treatments were found. The optimum yield response (1,260 kg ha^{-1}) was from T_6 throughout the study period. Additionally, there were no significant differences in almond production and WUE between RDI and SDI strategies. The almond yield reductions for T_4 and T_5 respect to control T_6 were 23 and 31%, and the water savings of 50 and 55%, respectively. Therefore, could be recommended the adoption of SDI and RDI strategies in areas where a large portion of irrigation water comes from aquifers that are threatened by over exploitation.

Monks *et al*. (2017)

Objective and DI strategies: The impact of five irrigation levels on almond yield over three seasons: fully irrigated control at 100% ET_C, three RDI levels (55, 70, and 85% ET_C) applied for specific periods during the growing season, or SDI throughout the growing season, and a high irrigation level at 120% ET_C.

Main findings: The findings showed that irrigation at 85% ET_C had no impact on kernel weight and yield, but 70% ET_C or 55 % ET_C decreased kernel yield regardless of strategy, except for SDI 70% ET_C in third season. During the last season, trees with SDI 70% ET_C produced higher kernel yield than those subjected under RDI at 70% ET_C. Water stress tended to accelerate hull split in line with the deficit level. The midday Ψ_{stem} was significantly more negative from 2 to 6 weeks before harvest in the deficit treatments.

López *et al*. (2018b)

Objective and DI strategies: A 3-year experiment to determine the almond cv. Guara yield and water productivity (WP) responses to irrigation deficits: a control received irrigation required to meet the full pre-estimated ET_C, moderate SDI at 75% ET_C, moderate RDI irrigated as control, but only at 40% of control during the kernel-filling stage, and severe RDI irrigated as control trees, and only 15% of control during the kernel-filling stage.

Main findings: Maximum average yield of 2508.4 kg ha^{-1} were obtained from control trees, while the three deficit irrigation strategies yielded 2147.5, 2038.2, and 1496.9 kg ha^{-1}, respectively. Assessment of the consumptive use (ET_C) and its components, soil evaporation (ES) and transpiration (T), amounted seasonal values to 1088, 887, 894, and 699 mm of ET_C, of which T represented 831, 640, 648, and 479 mm, for the four treatments, respectively. Although values varied, the WP_{ET} averaged 0.23 kg m^{-3} and did not differ among treatments. The transpiration efficiency (WPT) had a value of 0.32 kg m^{-3} and was roughly the same for all treatments.

García-Tejero *et al*. (2019)

Objective and DI strategies: Experimental study during 4-year monitoring period subjected to three irrigation regimes: full-irrigation at 100% ET_C (FI), RDI_{50} irrigated at 50% ET_C during the kernel-filling stage, and LFDI subjected to continuous periods of irrigation-restriction defined by threshold value of Ψ_{leaf} during the kernel-filling stage.

Main findings: Significant improvements for WUE were found, and no differences in nut yield between FI and LFDI, leading to important water savings (27 and 40%) can be achieved without compromising the almond productivity. In addition, threshold values of Ψ_{leaf} and thermal indicators could be considered as suitable tools in establishing irrigation scheduling, particularly, when deficit irrigation strategies are being applied.

Gutiérrez *et al*. (2019)

Objective and DI strategies: This work over two seasons examines the response of almond cultivars (Guara, Marta, and Lauranne) to different irrigation regimes: a full-irrigation at 100% ET_C (FI), over irrigated treatment irrigated at 150% ET_C (150-ET_C), and RDI_{65} irrigated at 100% ET_C during the whole irrigation season, except during the kernel-filling period irrigated at 65% ET_C.

Main findings: Significant differences in physiological behaviour and yield responses among cultivars were found. According to the findings, cvs. Guara and Lauranne did not show significant improvements with 150-ET_C in relation to FI and RDI_{65}, whereas cv. Marta recorded significant enhancements with 150-ET_C. Thus, the cultivar is a determinant factor to take into consideration when deficit irrigation programmes are going to be applied in almond plantations.

Lipan *et al*. (2019a)

Objective and DI strategies: Response of almond quality yield to four irrigation treatments: full irrigated control, moderate RDI irrigated during kernel filling stage [when Ψ_{stem} < -1.5 MPa or maximum daily shrinkage (MDS) ≥ 1.75], severe RDI irrigated during kernel filling stage (when Ψ_{stem} < -2.0 MPa or MDS ≥ 2.75), and SDI with a maximum water applied of 100 mm.

Main findings: Almonds yield was not significantly affected by deficit irrigation and its quality can be improved by moderate deficit irrigation strategies, especially, certain fatty acids (e.g. cis-vaccenic) increased with moderate RDI. In addition, almonds from moderated RDI were characterized by a redder colour, a higher fat and K contents. Consequently, moderate RDI could be recommended as a suitable strategy when water availability is below to crop irrigation requirements, without committing the final yield and fruit quality.

Lipan *et al*. (2020)

Objective and DI strategies: This work presents the effects on the quality parameters almond cultivars (Marta, Guara, and Lauranne) subjected to different irrigation doses: full-irrigated at 100% ET_C (FI), over-irrigated at 150% ET_C, and RDI_{65} irrigated as FI, expect during the kernel filling period at 65% ET_C.

Main findings: According to findings, the most sensitive to water stress was cv. Marta, having the most improvements under RDI_{65}. The effects of irrigation doses on almond morphological and physico-chemical parameters were not huge, but some improvements were observed in colour and contents of specific sugars, organic acids and unsaturated fatty acids. Thus, the irrigation regime did not drastically alter the fruit almond quality, even being possible to improve when a moderate RDI strategy is used.

DEFICIT IRRIGATION VS. ALMOND NUT QUALITY

The kernel is the edible part of the almond nut and it is considered a food with a high nutritional value. Almond kernel quality has so far been described exclusively by physical characteristics: size, shape, double kernels, etc. However, the high nutritive value of almond kernels arises mainly from their high lipid content, which constitutes an important caloric source due to their high level of unsaturated fatty acids, and mainly monounsaturated fatty acids. Therefore, little data on chemical examination on the almond kernel has been found and the studies carried out to determine its chemical components and their variability are scarce, explicitly those regarding to the agronomical practices such as irrigation.

Morphological characteristics

The role of water in plants is unlimited, being reactant, essential component for the ionization of the metabolites or stabilization of bio membranes, and keeping the structure rigidity. There are studies reporting the possibility to irrigate below the crop needs, maintaining the almond quality (morphological, mineral content, organic acids and sugars, or the fatty acid profile), even augmenting them without significant impact on nut yield (Goldhamer *et al*., 2006a; Stagnari *et al*., 2016; Lipan *et al*., 2019b).

In this context, Lipan *et al*. (2020) reported the impact of different irrigation amounts on nut quality for three almond cultivars (Guara, Marta, and Lauranne) that were subjected to different irrigation regimes: full-irrigated trees (FI) at 100% of crop evapotranspiration (ET_C), over-irrigated at 150% ET_C, and regulated-deficit irrigation treatment (RDI_{65}) irrigated as was in FI trees with exception during the kernel-filling period, when was irrigated at 65% ET_C. According to their findings the morphological parameters were significantly affected by both factors irrigation and cultivar. Almonds under over-irrigated (150% ET_C) showed the highest values of weight, colour lightness (L^*) and coordinate b^*, while, lowest values of a^* coordinates and texture. That is, softer and lighter almond nuts with less red and more yellow notes were found. Also, smoother texture for almonds from 150% ET_C with 70 N and gradually harder for 100% ET_C with 72 N, and RDI_{65} with 74 N, this was in line with amount of irrigation water applied for each strategy.

In relation to cultivars Guara yielded nuts with higher weight, size, colour, and hardness values. This fact was studied being consumer acceptability depends on the texture parameter as was highlighted by Lipan *et al*. (2019a), and therefore, harder almonds such as Guara (76 N) and Lauranne (74 N) might be more accepted by the consumers. Almonds from RDI_{65} resulted hard and fracturable nuts with darker skin (L^*=49), while a higher hardness characterized cultivars such as Guara and Lauranne, work to shear and average force values. Also, Guara almonds presented the lighter skin and Marta the darkest one, and this latter also exhibited an intense red skin (a^*=18.7).

Fatty acids profile

Lipids are compounds that are present as intracellular oil droplets in the cotyledon tissue of the seed (Young *et al*., 2004). Almond lipid content ranged from 35 to 67%, and the Spanish almonds showed values between 40 and 67% (Yada *et al*., 2011). Almonds, as well as other nuts, are a good source of lipids and a good caloric source without increasing the cholesterol level in humans due to its composition mainly composed by mono (MUFA) and polyunsaturated fatty acids (PUFA). According to Yada *et al*. (2011) the lipid content and profile fraction are not only genotype-dependent but also might be affected by other factors such as edafo-climatic conditions, season, harvest timing or any interaction of them.

Thus, it is extremely important to specify the irrigation strategy for a given almond cultivar in order to ensure optimal productivity with minor impact on nut quality. In this line, Lipan *et al*. (2020) reported the lipid profile for almond cultivars with different irrigation regimes. This study identified and quantified fatty acids with almond lipid fraction of MUFAs mainly oleic acid (C18:1n9), PUFAs mainly linoleic acid (C18:2n6), and saturated fatty acids (SFA), especially palmitic (C16:0) and stearic (C18:0) acids. The content of myristic, palmitoleic, *cis*-heptadecenoic, oleic, linoleic, ◎-linolenic, arachidic, eicosenoic, and erucic acids were significantly affected by the irrigation dose. Also, palmitic and arachidic acids (SFAs) were higher in almonds from control non-stressed trees than from RDI_{65} and 150% ET_C, while palmitoleic (MUFAs), *cis*-heptadecenoic (MUFAs), and linoleic (PUFAs) were higher in RDI_{65}. The effect of cultivar on lipid fraction was evident, with cv. Marta producing significantly more myristic, *cis*--heptadecenoic, oleic, ◎-linolenic, arachidic, eicosenoic, and erucic fatty acid contents. The highest content of palmitoleic and linoleic acids was found for cv. Lauranne, and both Guara and Marta recorded the highest content of arachidic acid.

Almonds from RDI_{65} registered lower oleic: linoleic ratio and MUFAs content, and in contrast with a higher content of PUFAs. This suggests that almonds were more susceptible to oil oxidation because of high oleic: linoleic ratio means fewer MUFAs (oleic acid), and this compound is connected to high oil stability as was stated by Kodad *et al.* (2014). Regarding the health properties, linoleic acid is a PUFA (omega 6) indispensable for the humans with a vital role in the death of cardiac cells (EFSA, 2009). And the human organism is not able to produce this fatty acid, which is necessary for biological and metabolic integrity. The European Food Safety Authority recommends 10 g day^{-1} of linoleic acid (EFSA, 2009). Thus, the consumption of 50 g of almonds from RDI_{65} will help to assure approximately 33% of the linoleic acid daily intake recommended by EFSA. In this sense, high content of MUFAs and PUFAs was recorded for Marta and Lauranne, respectively (Lipan *et al*., 2020). An increase in PUFAs content was also found by other studies with pistachios and olives under deficit irrigation (Cano *et al*., 2015; Carbonell *et al*., 2015).

Mineral, organic acid and sugars contents

Many factors such as environmental and agronomical techniques (cultivar, irrigation system, fertilizers, pest and disease management, etc.) can affect the mineral content of almond kernel (Yada *et al*., 2011). In this context, Spanish almond kernels contain approximately 3.3 g 100 g^{-1} of ash (Lipan *et al*., 2020), Lebanese cultivars of 3.4 g 100 g^{-1}, Italian cultivars of 2.3-3.7 g 100 g^{-1}, and California cultivars of 2.4-4.6 g 100 g^{-1}, among others, as was reported by Yada *et al*. (2011). Lipan *et al*. (2019a) with cv. Vairo under deficit irrigation found a significant effect on Ca, K, and Mn contents. And the K increased (7.7 g kg^{-1}) with moderate RDI respect to the non-stressed control trees, however, as recommend these authors the stress intensity has to be controlled due to the importat impact on fruit quality.

Lipan *et al*. (2020) highlighted the effect of irrigation amount on mineral content of different almond cultivars (Guara, Marta, and Lauranne). According to their findings the K content was affected neither by the irrigation treatment nor by type of cultivar. Comparably, Ca, Mg, and Mn contents under RDI_{65} were similar to control trees, while RDI_{65} and 150% ET_C lightly augmented Cu. For the three almond cultivars studied the K content was lower than values reported for cv. Vairo (Lipan *et al*., 2019a), however, with mean values of 508 mg 100 g^{-1} higher than minimum threshold defined in the Annex to Directive 90/496/ECC (300 mg 100 g^{-1}). The Ca levels for three almond cultivars were higher than those found for cv. Vairo (Lipan *et al*., 2019a).

Important increments for Ca and Zn contents for pistachio nuts yielded with water stress conditions was stated by Carbonell *et al*. (2015). This differ from results revealed by Alimohammadi *et al*. (2012), reporting no significant effects of deficit irrigation on almond mineral contents, and similar conclusions were found by Nakajima *et al*. (2004) with other woody crops (grapes, olive, and apple).

In relation to sugars and organic acid contents important effects were found by Lipan *et al*. (2020) for different almond cultivars due to deficit irrigation treatments. In this line, higher organic acids and sugars concentrations were fixed by RDI_{65} with cv. Lauranne, however, the lowest sugar level were recorded by cv. Guara, therefore, this suggest that organic acids as well as sugars were more influenced by type of almond cultivar. In addition, cv. Marta contained high levels of oxalic acid, cv. Guara of malic acid, while cv. Lauranne of citric, tartaric, and fumaric acids. Regarding to sugars, cvs. Marta and Guara displayed lower sucrose and higher glucose levels, in contrast with cv. Lauranne.

The impact of water stress on total organic acids content was divided into groups with "strong relationship" by Lipan *et al*. (2019a) and "no relationship" by Sánchez *et al*. (2008) and Egea *et al*. (2009). What is indisputable is that the water stress encreases sugars (glucose) and therefore, sweetness as a result of the osmotic adjustment (Yakushiji *et al*., 1996). In other words, this fact activated the accumulation of solutes in hydroxyl groups such as sugars in the fruit cytoplasm, and consequently, as a mechanism in coping water stress (Ripoll *et al*., 2014).

IRRIGATED PISTACHIO PLANTATION

Pistachio cultivation is feasible in marginal rainfed agricultural areas because its ability to fit under water shortages such as Mediterranean basin conditions (Spiegel *et al*., 1977). However, it is well-known that when pistachio tree is grown with plenty water availability both productivity and profitability can be upgraded (Goldhamer, 1995). Many studies have defined the positive impact of irrigation on pistachio yield and quality (Goldhamer *et al*., 1985; Polito & Pinney, 1999; Goldhamer, 2005; Iniesta *et al*., 2008). Indeed, pistachio has a great productive potential and long-living tree under irrigated conditions, that is, with 250 tree ha^{-1} the nut yield could be amounted to 2,500 kg ha^{-1}, roughly 60-70% more than under rainfed conditions.

According to Kanber *et al*. (1993) the most important feature limiting pistachio productivity is its proclivity toward biennial fluctuations in yield which can be aggravated by failures in pollination and long periods of water stress. Studies have shown that this problem may be related to an imbalance between carbohydrate supply and demand because of shoot growth alternating with cropping cycles (Spann *et al*., 2009). Although alternate bearing can be considered as innate process in most woody-fruit crops, normally it affects only the crop load. But in pistachio trees it is an overall process reflected both in fruit production and in flower and branch formation (Couceiro *et al*., 2013). Initially it was suggested that the competition for metabolites between developing seeds and flower buds was responsible for bud abscission and thus a main factor for alternate bearing (Crane & Nelson*et al*., 1972).

The studies regarding to the impact of irrigation on biennial bearing demonstrated that irrigated trees presented a lower yield variation over the years, with cumulative yields being improved by as much as 200% respect to rainfed orchards (Kanber *et al*., 1993; Goldhamer *et al*., 1984, 1985).

Today in many pistachio country producers the reduced water resources is the main trouble for development of irrigated plantations. In this context, as is for almond the deficit irrigation strategies could be essential in order optimize the irrigation water without significantly impact on nut productivity. However, a successful deficit irrigation program requires a knowledge respect to critical crop phenological periods and how water stress impacts on each of them in both quantitative and qualitative terms.

In Spain, pistachio orchards demand relatively high elevations (600 m a.s.l.) to achieve the accumulation of cold hours needed to ensure good bud break and an optimum production of flowering buds, these values ranging between 700 and 1200 hours depending on the variety. In this line, the deficiency of cold hours would not involve the vegetative development of pistachio tree, but flowering would be highly committed (Couceiro *et al*., 2000).

There are three main critical phenological stages in pistachio as shown in Figure 5 (Gijón *et al*., 2011; Gijón, 2013). The stage I begins with flowering and leafing out and involves the nut growth until the maximum size; stage II, starting about six weeks after flowering, initiating the phase of shell hardening, with slowly increase of fruit weight and continue vegetative growth; and phase III defines the period of seed growth. Before stage I is the sprouting period and after stage III occurs the post-harvest period when reserves are accumulated and buds differentiated for the next season. Thus, the water stress can have different effects, depending on the phenological stage in which is applied (Goldhammer, 1995).

Figure 6 displays the crop coefficients for Mediterranean pistachio trees, being these values similar to other nut trees such as almond or walnut, reaching about 1.2 during the maximum evapotranspiration demand (Fereres & Goldhamer, 1990). Consequently, under water scarcity scenario would be essential to

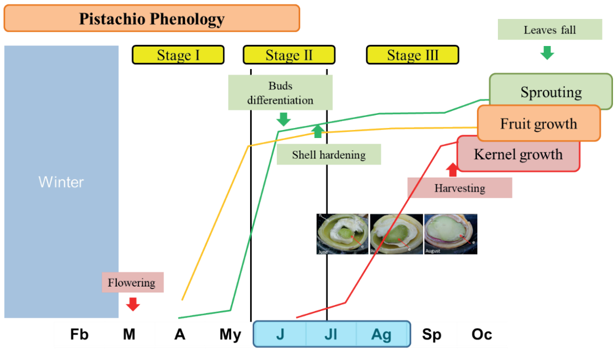

Figure 5 - Main phenological stages for pistachio trees throughout the production cycle (own development).

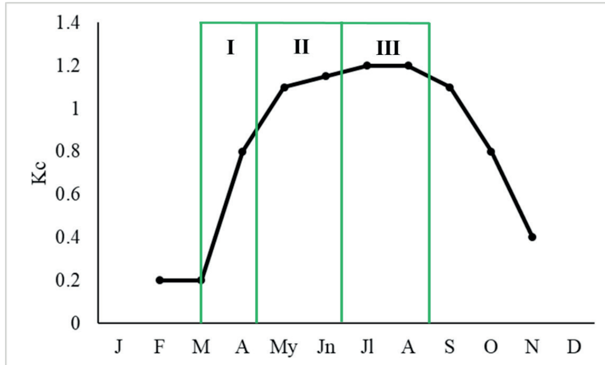

Figure 6 - Pistachio crop coefficient (K_C) at each phenological stages (I, II, and III) throughout the production cycle (Goldhamer 1995; Couceiro *et al*., 2013).

Table 1 - Impact of water stress on pistachio nut yield

Authors	Phenological period	Impact on productivity
Goldhamer *et al*. (1987), Phene *et al*. (1987)	Stage II	Low
Goldhamer *et al*. (2004)	Stage II + Postharvest	Low
Goldhamer & Beede (2004)	Stage I	Early splitting, increasing the percentage of split nuts
Goldhamer *et al*. (2004, 2005, 2006b), Doster & Michailides (1997, 1998)	Stage I	Early and before harvest splitting, delayed harvest
Goldhamer et al. (2004)	Stages I and II	Low, early and before harvest splitting
Gijón *et al*. (2009)	Stages I and II	Low, control of bi-annual pattern
Gijón *et al*. (2009)	Stages I, II, III (50% ET_C)	Significant yield loss
Gijón *et al*. (2009)	Stages I, II, III (65% ET_C)	Low, even with an improvement in seasons with lower yields

ET_C, Crop evapotranspiration

integrate the information from the pistachio physiological response and the thresholds values derived from water stress vs. deficit-irrigation situations.

Table 1 presents the findings from studies regarding the impact of water stress on pistachio yield for concrete phenological stages. Although, in some cases the results are contradictory, which could be attributed to differences in edafo-climatic conditions of the experimental zones. This fact justifies the importance to extend and adapt the experiments performed so far to new areas where pistachio cultivation is being considered.

PISTACHIO RESPONSE TO WATER STRESS

The pistachio drought resistance ability presumably depends on extensive root system development as was stated by Germana (1997), although it is a commonly xerophyte characteristic, it does not present the morphological features of such in the leaves, however, pistachio trees reach high values of net photosynthesis (P_N) and leaf conductance.

According to Pérez *et al*. (2018) the pistachio nut yield could be reduced appreciably as a result of a higher percentage off lower buds dropped during seasons with higher yield or when a severe water stress was took place during stage II. The pistachio trees subjected to water stress develop stress prevention and stress tolerance mechanisms (Memmi *et al*., 2016a,b). In this sense, during stages I and II, if the soil-water content is quite high and the evaporative demand is low, pistachio reach higher P_N and g leaf rates. In contrast, during fruit stage III, with higher evaporative demand the pistachio could be able to register lower P_N and g_s values. It is well-known that the plant response to water stress by decreasing the g_s in order to avoid the water loss through transpiration, and therefore, registering maximum rates in the morning and decreasing gradually throughout the day. The water stress during stages I and III are considered as the most critical periods that affects significantly on pistachio yield as was stated by Pérez *et al*. (2018).

Pistachio trees are able to pursue their photosynthetic activity even when leaf registers extraordinary low water potential (Ψ_{leaf}) values from -5.0 to -6.0 MPa (Behboudian *et al*., 1986). That is, pistachio has an unusual capability for leaf thermoregulation, even at severe water stress levels, because its canopy can transpire water at rates far higher than those normally found in mesophytes. Germana (1997) highlighted the great ability of pistachio to swiftly compensate water losses without displaying visible water stress symptoms.

As stated by Gijón *et al*. (2010), the rootstock *P. terebinthus* could be considered as appropriate option for rainfed or deficit irrigated orchards, as it is able to retain a greater leaf area than non-stressed trees with lower Ψ_{stem} and g_s rates. And for irrigated plantations the hybrid from crossbreeding *P. atlantica* Desf. × *P. vera* L. since this rootstock promotes a highest leaf conductance and vigour. Additionally, Memmi *et al*. (2016b) considered that rootstock *P. atlantica* as adequate for deficit irrigated plantations due to its reputation as permissive to water stress under rainfed system.

Goldhamer *et al*. (1983) observed that water-stressed trees showed partial defoliation, a regulation of g_s (60% reduction), a decrease in water potential (Ψ_{stem} < -2.0 MPa), and rising leaf temperatures (4-5ºC). Tavallali *et al*. (2009) for pistachio trees reported a significant relationships between the g_s and the relative water content (R^2 = 0.95), and between g_s and Ψ_{leaf} (R^2 = -0.98), establishing threshold values for Ψ_{leaf} in non-water-stressed trees close to -0.4 MPa. According to Gijón *et al*. (2011) water stress applied during stages II (shell hardening) and III (kernel growth) were the most adversely circumstances for the plant physiological response. And the reference values defined for non-stressed trees by these authors for Ψ_{stem} and g_s ranged between -1.2 and -1.5 MPa, and 500 and 700 mmol m^{-2} s^{-1} at solar noon, respectively. Memmi *et al*. (2014) monitored the pistachio response to water deficit and timing of application, revealing that irrigation when kernel weight is rising (stage III) results in a higher fruit size than when the same amount of irrigation water is dispensed between I and III stages. Also, the shell hardening (stage II) starts as the fruit reaches maximum external diameter and completes before the kernel reach its final weight.

On the other hand, Sedaghati & Alipour (2006) pointed out that early hull splitting reduced the pistachio nut quality and the properly plant--water status from late April to early June played an important role. It is undoubted that irrigation increases yield, nut size and splitting, decreases the alternate bearing pattern and presence of blank nuts, but has not impact on the hull to kernel ratio (Ak & Agackesen, 2006).

The application of RDI (with Ψ_{stem} threshold value of -1.5 MPa) during stage II or postharvest period decreased the tree growth but not impacted significantly on nut yield (Memmi *et al*., 2016b). Gijón *et al*. (2009) concluded that SDI strategies lowered total yield and kernel size, without alterations in kernel dry weight. In addition, in order to prevent adverse effect of water stress during stage III, irrigation should be augmented at the end of stage II or be higher than non-stressed trees (100% ET_C) from the beginning of stage III (Guerrero *et al*., 2006).

The nuts from the RDI_{65} and RDI_{50} pistachio trees were smaller in diameter and their total yield was reduced compared to control trees (100 ET_C) (Gijón *et al*., 2009). However, no significant differences in kernel dry weight were found, and RDI trees showed a total yield and percentage of split nuts similar to those of the non-stressed, even though they received around 20% less water. The research studies regarding to the impact of water stress on pistachio yield are listed at the end of this section.

In relation to response of pistachio fruit quality of different pistachio cultivars, Okay & Sevin (2011a,b) reported that the differences were more significant under non-irrigated conditions than for irrigated. Qualitative parameters affected by water stress are related to weight and final fruit size, percentage of open and empty nuts, moisture content of the nut, and the content of unsaturated fatty acids (Kashaninejad *et al*., 2006). A premature opening of the nut could reduce nut quality although if this process occurs shortly before harvest this effect would be positive, since the nut opening previous to the harvest is considered as one of the most important quality factor in commercial terms. In this sense, when the nut opening does not take place properly, the final value of the product is significantly lower (Gijón *et al*., 2009). Many authors argued that when a moderate water-stress is applied during the first stage, this promotes a little decrease of fruit size. If after this stage, a partial recovery of water stress is applied (during the kernel growth period), it can encourage a mechanical pressure into the shell, providing the fruit opening previous to the harvest (Doster *et al*., 1998; Couceiro *et al*., 2000; Goldhamer *et al*., 2005; Gijón, 2013).

According to Goldhamer *et al*. (2005, 2006a) a severe water stress during fruit growth promoted an early split nut, and this provide fungal infections reducing the fruit quality. In addition, Goldhamer & Beede (2004) argued that moderate water stress during the fruit growth would promote a higher number of splits nuts at the end of the kernel--growth period, and this could be improved the fruit quality. In any case, as split nut is a positive factor, climatic conditions previous to harvest such as rains, high levels of relative humidity, or moderate air temperature are responsible of an aflatoxins production into the nuts.

The pistachio water status influences significantly on the kernel fatty acid content, according to Okay & Sevin (2011a), well-irrigated trees increased the oleic acid but decreased the linoleic acid content. However, a moderate RDI during stage II considerably augmented the oil content, while more severe RDI reduced the oil content in pistachio nuts, encouraging in both cases a significant rise in linoleic acid content as was reported by Carbonell *et al*. (2015). In addition, a visual analysis of pistachios evidenced that moderate RDI throughout stage II leads to an intense green pistachio colour with higher intensities of nutty and pistachio notes in harder, crunchier nuts with a longer aftertaste. Carbonell *et al*. (2015) and Noguera *et al*. (2016) from a consumer study regarding to judgment of pistachios grown under RDI concluded that the kernels from moderate RDI applied during stage II acquired a higher intensities of characteristic sensory attributes and a greater level of satisfaction among consumers than kernels from non-stressed and severe RDI during stage II.

Pistachio deficit irrigation studies and their effect on yield are listed nextly.

<u>Monastra *et al*. (1998)</u>

Objective and DI strategies: A study to determine the long term effects of various irrigation regimes on pistachio trees (*Pistacia integerrima* grafted with cv. Larnaka). The irrigation treatments replaced 75, 50, 25, and 0% of daily evaporation (Class A evaporimeter).

Main findings: Growth patterns indicated that irrigation equal to 50 % of evaporative demand could support trunk growth equal to that in the fully irrigated trees. Flowering process development in irrigated trees was two years earlier than in non--irrigated. Irrigation induced a greater branch growth with presence or absence of inflorescences. This fact was beneficial in reducing alternate bearing that is especially strong in non-irrigated trees. Productivity demonstrated that irrigation increased fresh and dry kernel yield without effect on hull to kernel ratio.

<u>Goldhamer & Beede (2004)</u>

Objective and DI strategies: Assess the impact of RDI on different pistachio phenological stages throughout of the season, aiming to determine which period was most stress tolerant in terms of nut production.

Main findings: The best yield occurred with deficit irrigation during stage II at 50% ET_C and at 25% ET_C after harvest. This RDI regime saved about 180 mm of water (23.2% respect to control) and WUE was significantly higher (4.69 vs. 3.61 kg marketable fruit per mm for RDI and control trees, respectively). Thus, the application of RDI during stage II and postharvest was a viable irrigation strategy to save irrigation water while maintaining pistachio yields.

<u>Guerrero *et al*. (2006)</u>

Objective and DI strategies: Field experiment of recovery of water status in water-stressed pistachio trees under: RDI irrigated at 60% ET_C during stages I and II followed by full irrigation (100% ET_C) during stage III (kernel-filling) and control trees irrigated at 100% ET_C throughout stages I, II, and III.

Main findings: In RDI the lowest Ψ_{stem} of -1.8 MPa was at the end of this period, and the corresponding for control trees was of -1.1 MPa. Although RDI affected g_S later than Ψ_{stem}, and the greatest reduction in g_S (60% of control) was at the end of RDI period. Even though water status recovered within 20 days of resuming irrigation, trunk diameter variation (TDV) indicated a longer period for complete recovery. Recovery of g_s was faster than Ψ_{stem}, albeit differences in TDV between control and RDI indicated that g_s recovered later than Ψ_{stem}. The slow recovery of pistachio trees during stage III from water stress imposed during stages I and II suggests that irrigation should exceed 100% ET_C during stage III or that more extensive irrigation should commence before the end of stage II.

<u>Gijón *et al*. (2009)</u>

Objective and DI strategies: An irrigation experiment in pistachio over a 4-year period to determine the effect on nut yield and quality under: control trees irrigated to supply full water needs, except for the post-harvest period, SDI at 65% (SDI_{65}) and SDI at 50% (SDI_{50}) of control irrigation, and RDI provided water stress during stages I and II but no during stage III.

Main findings: The pistachio nuts from SDI_{65} and SDI_{50} trees were smaller in diameter and their total yield was reduced compared to the control trees, however, no significant differences in kernel dry weight were found. The RDI trees showed a total yield and percentage of split nuts similar to those of control trees, even though they received around 20% less water. In addition, RDI did not show the alternate bearing pattern (which was clearly manifested in the control trees). The reduction in the alternate bearing in the RDI was probably a result of a balance between flower buds induced during stages I and II (water stress period) and the assimilation capacity during bud fall in stage III (water recovery period).

<u>Memmi *et al*. (2014)</u>

Objective and DI strategies: The effect of deficit irrigation strategies on pistachio fruit quality under two RDIs with different levels and moments of water stress throughout the phenological cycle compared with a full irrigated control trees.

Main findings: The pistachio fruit growth pattern has been characterized by a continuous shell lignification throughout the period of fruit growth. The lack of irrigation supply during stage I and II has shown better results in fruit diameter than a lower input distributed between stage I and III.

<u>Carbonell *et al*. (2015)</u>

Objective and DI strategies: A study to evaluate the effects of irrigation treatments on the quality of pistachio nuts: control trees irrigated without water stress (T_0), RDI at stage II and irrigation was suppressed until Ψ_{stem} < -1.3 MPa, then was irrigated to maintain the threshold ≤ Ψ_{stem} (T_1), and RDI with the same irrigation protocol as T_1 but with Ψ_{stem} threshold of -1.5 MPa (T_2).

Main findings: The application of RDI in pistachio trees had no significant impact on nut yield, weight, size, colour, water activity, and mineral composition. Additionally, T_1 resulted in an overall increase in total fatty acid composition, in particular, linoleic acid with higher intensities of characteristic sensory attributes, and a greater level of satisfaction among consumers. Thus, the application of RDI (T_1) contributes to an increase in overall product quality and reduced water consumption during pistachio cultivation, which carries a lower environmental and economic cost.

<u>Memmi *et al*. (2016a)</u>

Objective and DI strategies: The response of pistachio trees during 3-year monitoring period to two RDI strategies subjected to water stress during stage II of fruit growth with Ψ_{stem} threshold values of -1.5 MPa (T_1) and -2.0 MPa (T_2), both compared to control trees fully irrigated.

Main findings: A midday Ψ_{stem} threshold of -1.5 MPa could be recommended as stress level during stage II for pistachio trees that does not reduce yield or causes any undesirable effects. A Ψ_{stem} threshold of -2.0 MPa seems to be tolerated by trees during stage II, as the yield was not affected. The influence of this stress level on g_S indicated that a long term stress could be detrimental for pistachio production. The combination of the Ψ_{stem} and the RDI regime saved 43-70% in T_1 and 48-73% in T_2 of water compared to control trees.

Kola *et al.* (2018)

Objective and DI strategies: Field study to determine the effects of irrigation on some chemical characteristics and fatty acid composition of two pistachio varieties (Kirmizi and Siirt). The irrigated trees received water once a week between June and September, and these were compared with non-irrigated pistachio trees.

Main findings: Irrigation increased nut yield, crude fibre, ash, and oil content of the nuts, however, decrease in protein content; it had no effect on kernel, nut sizes, and dry matter contents. In general, variety effected the major fatty acid composition, but irrigation did not. The oil of Kırmızı had the highest linoleic acid content (17.7%) under irrigated conditions. Finally, irrigation increased the yield by 33.9 and 53.9% for two studied varieties respect to non-irrigated trees.

Marino *et al.* (2018)

Objective and DI strategies: A study to examine the effects of supplemental micro-irrigation on water status, gas exchange, and productivity of rainfed pistachio trees. The treatments were a control of rainfed and irrigated trees with supplemental irrigation of 100 mm.

Main findings: The results demonstrated that supplemental irrigation (100 mm) significantly and positively improved rainfed pistachio productivity. The major effect was during the ON-year by longer shoots, reduced leaves and bud drop and higher assimilation rates. Both g_S and maximum photosynthesis increased with irrigation during stage III. The Ψ_{stem} appeared less sensitive than g_S in detecting differences in water stress. Thus, the findings demonstrated that pistachio production is environmentally and economically sustainable in Mediterranean areas having 500 mm rainfall, with as little as 100 mm of irrigation water.

Sedaghati & Hosseinifard (2018)

Objective and DI strategies: The effects of deficit irrigation (DI) on early splitting pistachio nuts and aflatoxin contamination in two irrigation intervals (25 and 45 days) and five omissions of irrigation time compared with trees under regular irrigation.

Main findings: Long irrigation intervals and DI in late April until early June were critical, increasing early splitting (up to 90%) respect to regular irrigation. The highest frequencies of early split pistachios were in treatments with water stress at early June ranging from 7.7 to 9.6%. DI in July increased the number of pistachio hull cracking significantly. In addition, average of hull early splitting and cracking formation were 37 and 18.5% higher in 45 days irrigation intervals than those in 25 days, respectively. The content of B1 and B2 aflatoxins in hull early splitting and cracking were 223.4 and 25.4 μg kg^{-1}, and in hull cracking fruits 111.0 and 9.7 μg kg^{-1}, respectively.

Noguera *et al.* (2020)

Objective and DI strategies: A study to determine the influence of RDI on quality pistachio nuts and sensory properties (trained panel): control trees fully irrigated at 100% ET_C (T_0), RDI during stage II with Ψ_{stem} maintained around -1.5 MPa (T_1), and RDI during phase II with Ψ_{stem} < -2.0 MPa (T_2).

Main findings: The use of moderate RDI (T_1) led to pistachio nuts with higher weight, smaller size, similar fatty acid profile and higher total polyphenol content (TPC) (1,284 and 1,192 g GAE kg^{-1} d.m., respectively), and comparable antioxidant activity (AA) and sensory profile than control treatment. Thus, moderate RDI (T_1) produced nuts with a good functional quality (high values of TPC and AA), without affecting their sensory quality, but being environmental friendly and having reduced economic cost due to a lower use of irrigation water.

CONCLUSIONS

Climate change and related water stress are having, and will in future continue to have, impacts on agricultural activity. Today almond and pistachio cultivation continue in marginal rainfed areas of the Mediterranean basin, although under more adverse climatic conditions quite different compared with those many decades ago. Under current changing climate the productivity of these rainfed crops has been greatly declined, and presumably many of rainfed areas would need to convert to irrigation, at great cost. After the various studies carried out regarding to the behavior of almond and pistachio under water scarcity scenarios, and the introduction of new cultivars and rootstocks with tolerant features to drought, deficit-irrigation techniques would be a potential suitable strategy in irrigated plantations with reduced water allocations. This favorable response to water stress advises that almond and pistachio could be valuable crops for areas where water is restricted, and therefore, redesigning the traditional irrigation system is urgent in addressing a sustainable intensification. And probably in many areas where at least scarce water resources are available, the rainfed fruit trees would have to be converted to deficit-irrigation systems in order to ensure their productivity and profitability. In general, for both crops when moderate and properly timed deficit-irrigation restrictions were used throughout the growing season, no important effects provoked on nut yield.

In short, to procure an effective water conservation scheme in the Mediterranean region, some key aspects should be considered. Firstly, it has been shown that irrigation at full-water requirements by ET_C could be not sustainable in the long term, requiring a new paradigm in order to face the current climatic circumstances. Secondly, the deficit-irrigation techniques could be a sustainable option to guarantee a better balance in irrigated agriculture in saving water and producing with reasonable yield reductions. That is, the implementation of deficit-irrigation practices as a mechanism to mitigate climate change, attaining environmental, social and economic benefits. Finally, food security is currently facing peculiar challenges in which will be essential under changing climate to ensure food production and its quality, in this line, deficit irrigation is able to not only to maintain but also to improve the content of health-promoting phytochemicals. Thus, the yield reduction provoked by deficit irrigation could be compensate by the healthy and economic value of the fruits with improved quality.

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