



The effects of contrasted deficit irrigation strategies on the fruit growth and kernel quality of mature almond trees

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ABSTRACT

The aim of this study was to quantify and compare the effects of two different deficit irrigation (DI) strategies (regulated deficit irrigation, or RDI, and partial rootzone drying, PRD) on almond (*Prunus dulcis* (Mill.) D.A. Webb) fruit growth and quality. Five irrigation treatments, ranging from moderate to severe water restriction, were applied: (i) full irrigation (FI), irrigated to satisfy the maximum crop water requirements (ET_c); (ii) regulated deficit irrigation (RDI), receiving 50% of ET_c during the kernel-filling stage and at 100% ET_c throughout the remaining periods; and three PRD treatments – PRD₇₀, PRD₅₀ and PRD₃₀ – irrigated at 70%, 50% and 30% ET_c , respectively, during the whole growth season. The DI treatments did not affect the overall fruit growth pattern compared to the FI treatment, but they had a negative impact on the final kernel dry weight for the most stressed treatments. The allocation of water to the different components of the fruit, characterized by the fresh weight ratio of kernel to fruit, appeared to be the process most clearly affected by DI. Attributes of the kernel chemical composition (lipid, protein, sugar and organic acid contents) were not negatively affected by the intensity of water deprivation. Overall, our results indicated that PRD did not present a clear advantage (or disadvantage) over RDI with regard to almond fruit growth and quality.

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1. Introduction

Almond trees (*Prunus dulcis* (Mill.) D.A. Webb) represent a major tree-nut crop in the Mediterranean area. The fruit load and kernel dry weight are the most important almond yield determinants (Kester et al., 1996; Esparza et al., 2001). The fruit size and composition (protein, sugar and fat contents) are the most reliable indicators of fruit quality, and contribute substantially to the economic value of almond nuts (Nanos et al., 2002; Kodad and Socias, 2006). Among the cultural practices influencing crop yield and quality, irrigation has been recognized as the most important factor (Hutmacher et al., 1994), in spite of the well-known capacity of almond trees to withstand water stress (Ferreira and Goldhamer, 1990; Hutmacher et al., 1994). For several fruit tree species, reducing the amount of irrigation water below the full requirements (i.e., deficit irrigation) has been proven to increase the fruit quality (Mpelasoka et al., 2000).

Deficit irrigation (DI) strategies are currently practiced to increase the efficiency with which crops use water. Regulated deficit irrigation strategies (RDI), as defined by Chalmers et al. (1981), are based on reducing irrigation during certain periods of the growth cycle where the crops have a low sensitivity to water stress. For almonds, a water deficit is generally applied during kernel-filling (stage IV) because of its moderate impact on almond productivity (Girona et al., 1997; Goldhamer and Viveros, 2000). The application of RDI to almond trees has allowed for a decrease in water usage with little or no impact on the crop yield (Romero et al., 2004; Girona et al., 2005). However, Goldhamer et al. (2006) found that kernel growth was reduced as a function of the severity of pre-harvest water stress, leading to both lower kernel weight and yield. The former is an important quality indicator for almonds, and the industry prefers large kernels (Kodad and Socias, 2006).

Partial rootzone drying, or PRD (Dry et al., 1996), is a DI management technique that has been extensively studied in recent years. The hypothesis underlying PRD is that root-to-shoot signaling regulates the plant response to drying soil (Stoll et al., 2000; Dodd, 2005). PRD has been reported to provide similar water

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savings to RDI with the advantage of providing greater control over plant vegetative growth. PRD also avoids the negative impacts of severe water stress periods on crop yield and quality, a disadvantage of RDI (Dry and Loveys, 1998; Loveys et al., 2000). Reports on the advantages of PRD vs. RDI have been inconsistent. For some species, PRD appeared to improve the fruit quality, as found for grapevines by several authors (Loveys et al., 2000; Dos Santos et al., 2007; Du et al., 2008), while others did not report a significant effect on the grape yield and chemical composition (Bravdo et al., 2004; De la Hera et al., 2007; Intrigliolo and Castel, 2009). PRD has also been applied to other fruit tree species, including apple (Leib et al., 2006; O'Connell and Goodwin, 2007; Talluto et al., 2008; Zegbe and Hossein Behboudian, 2008), mango (Spreer et al., 2007), olive (Wahbi et al., 2005), peach (Goldhamer et al., 2002) and pear trees (Kang et al., 2002). These investigations reported either little or no improvement in crop yield and fruit quality when PRD was used instead of conventional DI. To the best of our knowledge, no studies have examined the impact of PRD on the yield components and fruit quality attributes of almond trees. Elucidating the influence of PRD on these traits in comparison to other irrigation strategies is relevant for almond production in water-restricted regions. To this aim, a three-year long experiment was carried out on almond trees to (i) determine the influence of three levels of water restriction under PRD (70%, 50% and 30% of full water requirements) on almond fruit growth and quality and (ii) to compare the almond fruit responses to PRD to that observed under a classical RDI strategy for almond trees (Girona et al., 2005) and under full irrigation.

2. Materials and methods

2.1. Plants and experimental conditions

The study was carried out from 2004 to 2006 at a 1 ha experimental almond orchard located at the Agricultural Experimental Station of the Technical University of Cartagena (37°35'N, 0°59'W). Almond trees (*P. dulcis* (Mill.) D.A. Webb cv. Marta) were grafted on 'Mayor' rootstock and planted in December 1999 with a spacing of 6 m × 7 m. The soil was a deep silt-clay-loam with a low amount of available potassium and organic matter and a high amount of phosphorus. The bulk density varied within the range 1.3–1.55 g cm⁻³ and the soil available water content was about 0.18 m m⁻¹. The electrical conductivity (EC) of the irrigation water was 1.2 dS m⁻¹, chloride and sodium contents of 4.6 and of 5.4 meq L⁻¹, respectively. The weather is Mediterranean semiarid, characterized by scarce annual rainfall and high amounts of annual reference evapotranspiration (ET_o) (364 ± 28 mm and 1173 ± 49 mm, respectively, where both values are averaged over the period of study). An automatic weather station located at the Experimental Station, next to the orchard, provided the climatic data. The trees were fertilized with 35–35–57 kg ha⁻¹ year⁻¹ of N, P₂O₅ and K₂O, respectively. No weeds were allowed to grow within the orchard for the duration of the experiment. Our pest control methods were the same as those used by growers and pruning was performed manually in December.

2.2. Irrigation treatments

Five irrigation treatments were applied to the experimental plots (full irrigation (FI), RDI, and three treatments under PRD) following a randomized block statistical design with three blocks, one replicate per block and twelve trees per replicate. A single pipe per row with six 4 L h⁻¹ drippers per tree (spaced 1 m apart starting at 0.5 m from the tree trunk) was used for FI and RDI irrigation. For the PRD treatments, two laterals per tree row were used, each equipped with six 4 L h⁻¹ pressure compensating drippers. Each

lateral had the drippers at a different side of the tree (spaced 1 m apart, starting at 0.5 m from the tree trunk, and separated 0.5 m from the drip line by microtubes), to supply irrigation independently to only one side of the root system. The crop water requirements (ET_c) were determined using six drainage lysimeters located in the FI plots. For FI, an extra amount of water, equivalent to 20% of ET_c, was applied to ensure well-watered conditions. For RDI, the trees were irrigated at 50% ET_c during kernel-filling (stage IV) and at 100% ET_c throughout the remainder of the growth period. For PRD, the irrigation was supplied at 70%, 50% and 30% ET_c (PRD₇₀, PRD₅₀ and PRD₃₀, respectively) during the whole growth season. For all of the PRD treatments, only one side of the row received water while the opposite side was left to dry. Assuming that the physiological benefits of PRD are likely to disappear with the completion of the soil drying process (Dry et al., 2000), the PRD cycle was achieved by switching the wetting zones on a variable time basis (6–9 days), once the process of soil drying was about finishing.

2.3. Soil and tree water status

Volumetric soil water content (θ_v) was measured from 0.1 m to 1 m depth every 0.1 m with an *in situ* calibrated frequency domain reflectometry (FDR) probe (Diviner 2000[®], Sentek Pty. Ltd., South Australia). In FI and RDI, three access tubes per treatment were installed within the emitter wetting area under the canopy and along the tree drip line for three randomly selected trees. In PRD, a total of six access tubes per treatment were installed (three in each side of the root system of three randomly selected trees). Measurements were taken between 10.00 and 12.00 h (solar time) every 2–3 days throughout the growing season. Mean θ_v values through the monitored soil profile were used to calculate the level of relative extractable water (REW) as a fraction of maximum extractable water, defined by the equation (Granier, 1987):

$$REW = \frac{R - R_{\min}}{R_{\max} - R_{\min}} \quad (1)$$

where R (mm m⁻¹) is the actual soil water content, $R_{\min}$ is the minimum soil water content measured in a rainfed plot within the orchard (220 mm m⁻¹), and $R_{\max}$ is the soil water content at field capacity (410 mm m⁻¹).

Predawn leaf water potential (Ψ_{pd}) was monitored fortnightly with a pressure chamber (Model 3000, Soil Moisture Equipment, Santa Barbara, CA) on 9 leaves per irrigation treatment. Measurements of Ψ_{pd} were carried out before dawn on mature leaves taken from the middle third of the branches.

2.4. Vegetative growth

Trunk circumference was measured annually with a tape-measure at the end of each year during winter dormancy on ten trees per replicate and three replicates per treatment ($n = 30$). The total increase in trunk cross-sectional area ($\Delta TCSA$) was determined from these measurements.

2.5. Fruit sampling

During the period of the study, 15 fruits per replicate (45 per treatment) were randomly chosen and collected from the tree on a weekly basis for fruit analyses throughout the whole growing cycle. Immediately after harvest, almond fruits from each sampled tree (12 per treatment) were mechanically hulled, weighed, sun-dried for about 3–4 days and weighed again. A nut (in-shell) subsample of ca. 500 g was collected from each tree to calculate kernel yield per tree and to characterize the fruit.

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