Regulated deficit irrigation during the kernel-filling period and optimal irrigation rates in almond

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Abstract

The use of Regulated deficit irrigation (RDI) in almond, applied during the kernel-filling phase, was evaluated over four consecutive years. To determine the reference optimal irrigation rate, three treatments were applied: T-100, which was irrigated by replacing crop evapotranspiration; T-130, which was irrigated by applying 30% more water than in T-100 and T-70, which received 30% less water than T-100. The RDI treatment received the same irrigation rate as T-100, but during the kernel-filling period irrigation was reduced to 20% of T-100. The optimum yield response was observed in treatment T-100, while T-130 trees never improved on T-100 kernel production over the 4 years of the study. During the first two experimental years, kernel dry matter accumulation did not decrease with drought in the RDI treatment. However, both cropping and kernel growth were reduced during the third and fourth years of the experiment. A possible explanation for this decrease could be found in a hypothetical depletion of the carbohydrate reservoir in RDI trees and also to the negative soil water balance that was evident in the T-70 and RDI treatments during winter and spring of the last 2 years. Although yield reductions for RDI trees were significant (20% with respect to T-100), the water savings obtained (about 60% of that applied with respect to T-100), may help to promote the adoption of RDI in areas, where water availability has been reduced. Bearing in mind the water conservation aspect in almond, RDI, as applied in this case, seemed more interesting than a seasonal sustained deficit irrigation strategy like T-70.

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1. Introduction

The limited availability of water for irrigation in semi-arid zones means it is necessary to develop water conserving irrigation techniques. Almond orchards in Mediterranean regions are mainly found in dry areas because of their capacity to withstand water stress (Castel and Fereres, 1982; Marsal et al., 1997; Wartinger et al., 1990), salinity (Franco et al., 2000; Nightingale et al., 1991) and other adverse conditions. The adoption of irrigation techniques in these areas can increase production by as much as 10-fold (Girona, 1992), whereas traditional non-irrigated almond orchards are being abandoned because of low profitability. New irrigation techniques that permit significant increases in production with limited irrigation are therefore, of great interest. Regulated deficit irrigation (RDI) strategies are based on only reducing irrigation during certain periods of the annual plant cycle. These periods are selected when ongoing growth processes are less sensitive to water stress and when the derived effects of water stress are advantageous for yield, as in the case of reducing vigor in high density orchards (Chalmers et al., 1981). In almond orchards, intensification is not an issue and thus, RDI strategies should primarily focus on reducing irrigation during periods of annual development with a low sensitivity to water stress. A successful design for deficit irrigation scheduling should produce the maximum possible yield for the minimum possible rate of water application.

Dry matter accumulation is one of the processes that is least sensitive to water stress. In peaches, this process usually remains unchanged when applying deficit irrigation during pit hardening and the phase of expansive fruit growth (Li et al., 1989; Girona et al., 1993, 2003). In the case of almond, for the majority of cultivars, the period of kernel dry matter accumulation occurs during late summer, when the evaporative demand is at its maximum and while other growth processes are very much reduced (Girona, 1992; Kester et al., 1996). Goldhamer and Viveros (2000) reported a slight reduction in kernel dry weight for severe drought conditions (withholding irrigation) during a period of 50 days before harvest, whereas under less severe conditions no negative effect on kernel dry weight was observed (Girona et al., 1997; Goldhamer and Viveros, 2000; Esparza et al., 2001a). Nevertheless, little has so far been reported on the effect of drought on kernel growth and the limiting effect of its container – the shell – has also rarely been considered (Girona et al., 1997). Long term experiments on the application of RDI during the kernel-filling period are also needed, since changes in flowering (Goldhamer and Viveros, 2000) and carbohydrate reservoirs may have a long-term impact on almond yield components (Esparza et al., 2001b). A recent report indicated that water deficit immediately prior to harvest induced an increase in flowering during subsequent years, whereas drought after harvest produced the opposite effect and reduced flowering (Goldhamer and Viveros, 2000). This indicates that when analyzing water deficits, rather than looking at their effects on kernel filling, over 1 or 2-year period, their long-term effects on cropping should also be studied in order to understand their putative variations on yield components. Along these lines, besides producing a reduction in flowering and/or fruit set as a result of water stress, a reduction in the renewal of fruiting positions may also explain reductions in cropping, as in the case cited by Esparza et al. (2001a), after a 3-year drought during harvest.
This experiment was designed to test the hypothesis that irrigation can be dramatically reduced during the kernel-filling period without affecting final kernel dry matter. The possibility of maintaining cropping after 4 years of irrigation treatments was also studied, since drought was applied during the period prior to harvest and minimized during postharvest.

2. Material and methods

The experiment was conducted from 1990 to 1993 at a 4-year-old almond (Prunus amygdalus L.) plot located at the IRTA – Centre de Mas Bové (Reus, Spain) experimental fields. The soil (Xerochrept calcixerollic) (SSS, 1975) had a root zone depth of about 1 m. A total of 192 “Ferragnes” (the main cultivar with 50% of total plot almonds) trees were used in this experiment, in which the pollinizers were “Ferraduel” (25%) and “Cristomorto” (25%) and all trees were grafted onto “GF-677” rootstock. Tree spacing was 5 m × 6 m.

A localized micro-sprinkler irrigation system was installed to irrigate the plot. Two micro-sprinklers (35 l/h) were used per tree in order to wet about 35% of the soil surface. In each treatment, the system was individually controlled using an electronic irrigation controller and solenoid valves. The plot was managed according to normal commercial practices, which implied full herbicide control, but no soil cultivation.

Four irrigation treatments were defined in this experiment: T-100, T-130, T-70 and Regulated deficit irrigation. T-100 was managed to fully satisfy tree water requirements based on soil water content (SWC), predawn leaf water potential (Ψpd) and the water budget approach, by subtracting effective rainfall from theoretical crop evapotranspiration (ETc). ETc was calculated from a modified Penman-determined reference crop water use (ET0) (Doorenbos and Pruitt, 1977), using data from a weather station located 1 km from the plot, with estimated crop coefficients (Ke) adapted from Goldhamer and Snyder (1989) (ETc = ET0 × Ke × Kc). T-130 and T-70, respectively, received 30% more and 30% less water than T-100. RDI was irrigated as T-100 from March to late (about 20th) June and from harvest (≈15th September) to leaf-out (end of November). For the remaining period (from late June to harvest – equivalent to the kernel-filling period) applied irrigation water was 20% of T-100.

A randomized complete block design with three replications was used in this experiment. Each treatment-block consisted of 16 trees (4 × 4), in which the middle four (all “Ferragnes”) were used for experimental measurements and the rest served as non-experimental guard trees.

Applied water was determined from weekly water-meters readings for each irrigation treatment. Gravimetric soil water content (θ) was determined using a neutron probe (Hydroprobe 503, Campbell Pacific Corp., Martinez, CA, US), which was previously calibrated for the site. Two 2 m access tubes were located in each treatment-block, at 60 cm from the trunk, on the tree row wetted area. θ was determined on a weekly basis and measured at 20 cm intervals down to the soil profile, to a maximum depth of 180 cm.
Trunk circumference measurements were taken during the non-dormant period to evaluate the increase in trunk cross sectional area (TCSA). This was done using a metallic tape toll designed by K.A. Shackel (personal communication). Measurements were taken on each of the 192 experimental trees at a height of 40 cm above the soil. Each year, winter pruning was weighted for each individual tree.

Leaf water potential ($\Psi_l$) was monitored according to the pressure chamber technique (Scholander et al., 1965) and using a plant water status console (Model 3005, Soil Moisture Equipment Co., Santa Barbara, CA, US). Predawn leaf water potential ($\Psi_{pd}$) was determined before sunrise, on two leaves per tree, and for two trees per treatment-block. Leaves were covered with plastic bags just before excision and readings were taken within a few seconds in order to prevent leaf water loss during measurements: the process followed the recommendations given by Turner and Long (1980).

During the growing season, 45 fruits per treatment (15 fruits per treatment-block) were collected on a weekly basis. Hulls and shells were separated from their respective kernels for each treatment-block and fruits were immediately weighted to determine fresh weight. The hulls, shells and kernels for each treatment-block were oven dried at 72 °C until permanent weight and weighed immediately after removal from the oven to determine dry weight. At harvest time, yield was determined for each individual control tree (four per treatment-block) by weighting the nuts after removing the hulls from the rest of the fruit. One sample of 150 fruits per tree was collected to determine the following values: fruit, kernel and shell fresh and dry weights, and humidity. Nut counts per tree were determined by dividing the gross yields for each tree by the average fruit fresh weight. To analyze comparable data, yields were normalized to 8% humidity.

### Results

Water meter readings indicated that the average volume of water applied in the T-100 treatment during the 4-year experiment (1990–1993) was 537 mm per year. Even so, the normal dose for full season irrigation conditions should be derived from the average for the period 1991–1993, which was 608 mm (Table 1). The irrigation rates for T-130 and T-70

<table>
<thead>
<tr>
<th>Years</th>
<th>Rainfall Annual (mm)</th>
<th>Rainfall PreH (%)</th>
<th>Rainfall PostH (%)</th>
<th>Irrigation treatments T-100 (mm)</th>
<th>Irrigation treatments T-130 (mm)</th>
<th>Irrigation treatments T-70 (mm)</th>
<th>Rain + irrigation rates T-100 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 1989–1990</td>
<td>439</td>
<td>178</td>
<td>262</td>
<td>325</td>
<td>100</td>
<td>425</td>
<td>71</td>
</tr>
<tr>
<td>1991</td>
<td>505</td>
<td>281</td>
<td>224</td>
<td>617</td>
<td>100</td>
<td>798</td>
<td>129</td>
</tr>
<tr>
<td>1992</td>
<td>600</td>
<td>368</td>
<td>233</td>
<td>550</td>
<td>100</td>
<td>682</td>
<td>124</td>
</tr>
<tr>
<td>1993</td>
<td>440</td>
<td>269</td>
<td>171</td>
<td>656</td>
<td>100</td>
<td>758</td>
<td>115</td>
</tr>
<tr>
<td>Average 1990–1993</td>
<td>496</td>
<td>274</td>
<td>223</td>
<td>537</td>
<td>100</td>
<td>666</td>
<td>124</td>
</tr>
<tr>
<td>Average 1991–1993</td>
<td>515</td>
<td>306</td>
<td>209</td>
<td>608</td>
<td>100</td>
<td>746</td>
<td>123</td>
</tr>
</tbody>
</table>

Note: Pre-H: Pre-harvest.
Post-H: Post-harvest.
Fig. 1. Seasonal patterns of full profile (0–160 cm) gravimetric soil water content for each irrigation treatment over the last 3 years of experiment. Each point is the average of 48 measurements (six access tubes by eight depths). Vertical bars are the mean ± S.E.
approached the pre-planned 30% over an infra with respect to the T-100 applied water, respectively (Table 1). The application of the proposed RDI strategy led to average savings of around 60% with respect to the T-100 treatment (Table 1).

The seasonal patterns of gravimetric soil water content ($\theta$) indicated clear differences in humidity between different irrigation treatments according to irrigation rates: these were most evident in summer (Fig. 1). The only exception was the T-130 treatment, which had slightly lower values than T-100 (Fig. 1). For deficit-irrigated treatments, T-70 and RDI, soil water content decreased gradually with time. This decrease was always more accentuated in RDI than in T-70. After harvest, soil water content in T-70 and RDI recovered sharply but never equaled that of T-100 and T-130 (Fig. 1A and C). Particularly in early spring 1993, soil water content values dramatically differed between irrigation treatments, with the lowest values being associated with the RDI treatment (Figs. 1C and 2A). Although the long-term effects on soil water content profiles were visible in 1993 (fourth year of the experiment), most of the water was taken from the top 80–100 cm of the profile throughout the season (Fig. 2).

While soil water depletion in T-100 was nearly zero (Fig. 3A), in RDI, soil water depletion affected the whole profile, with the most evident effects being appreciated in the top 80–100 cm (Fig. 3B).

Predawn leaf water potential ($\Psi_{pd}$) values during the deficit-irrigated period indicated a faster development of water stress for the RDI than for T-70 treatment (Fig. 4). Minimum values for predawn apparently varied between the 1991 and 1993 season, but they were always associated with the RDI treatment (Fig. 4). In 1991, the lowest $\Psi_{pd}$ value was close to $-1$ MPa, whereas in 1993 this reached $-1.7$ MPa (Fig. 4). On the other hand, $\Psi_{pd}$ values for T-100 and T-130 trees varied from $-0.4$ to $-0.5$ MPa, regardless of the experimental year. $\Psi_{pd}$ averages for the T-70 treatment were almost always between the values associated with the RDI and T-100 treatments (Fig. 4).

Accumulated growth in trunk cross sectional area from 1991 to 1993 indicated a significant reduction in growth for RDI trees (Fig. 5). These differences were already statistically significant as early as the end of the first measured year (1991). There were no statistical differences in trunk growth among T-130, T-100 and T-70 trees; however, growth associated with different irrigation treatments was related to the amounts of applied water (Table 1 and Fig. 5). The observed irrigation effects on winter pruning weights were evident (Table 2): the 4 year average analysis not only ordered the treatments with respect to applied irrigation water, but also clearly differentiated between them.

<table>
<thead>
<tr>
<th>Irrigation treatments</th>
<th>Kernel yield (kg ha$^{-1}$)</th>
<th>Fruit count (#fruit tree$^{-1}$)</th>
<th>Kernel dry W. (g)</th>
<th>Shell dry W. (g)</th>
<th>Fruit load (# fruit cm$^{-2}$)</th>
<th>Pruning W. (kg tree$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-100</td>
<td>1756 a$^a$</td>
<td>3436 a</td>
<td>1.49</td>
<td>2.22</td>
<td>14.4 a</td>
<td>13.78 a</td>
</tr>
<tr>
<td>T-130</td>
<td>1555 ab</td>
<td>3058 ab</td>
<td>1.48</td>
<td>2.23</td>
<td>12.6 b</td>
<td>12.54 ab</td>
</tr>
<tr>
<td>T-70</td>
<td>1479 ab</td>
<td>2947 b</td>
<td>1.46</td>
<td>2.10</td>
<td>12.9 b</td>
<td>11.10 bc</td>
</tr>
<tr>
<td>RDI</td>
<td>1408 b</td>
<td>2864 b</td>
<td>1.45</td>
<td>2.13</td>
<td>12.6 b</td>
<td>10.01 c</td>
</tr>
</tbody>
</table>

$^a$ Means within column followed by different letters were significantly different at $P < 0.05$ using Duncan’s test (SAS Institute, 1998).
The effect of the irrigation treatments on kernel yield over the 4 years of the experiment was marginally significant. There was a 20% reduction in kernel yield for the RDI treatment with respect to T-100. The latter had an annual average of 1756 kg ha\(^{-1}\) (Table 2). The yield reduction associated with the RDI treatment was related to a decrease in the number of fruits per tree (Table 2). Fruit load varied according to irrigation treatment and the highest fruit loads were found with treatment T-100 (Table 2). Unlike fruit count and kernel yield, the effect of irrigation treatment on individual kernel and shell dry weight was not evident (Table 2).
Yield increased steadily in all irrigated treatments from 1990 to 1993 seasons, but T-70 yields tended to only slightly vary with respect to those associated with the other irrigation treatments (Fig. 6A). In general, RDI trees had significantly lower kernel yields from 1991 onwards, whereas yield reductions for T-70 with respect to T-100 depended very much on the year in question and, in the end, were only significant in 1992 (Fig. 6A). The yearly patterns of fruit counts mirrored those of kernel yield and as occurred with the latter, differences in counts associated with T-70 depended on the year in question (Fig. 6B). There were no significant differences between irrigation treatments in terms of kernel and

Fig. 3. Soil water depletion profiles for the last 3 years of experiment, for T-100 and RDI treatments. Each point is the average of six values.
shell + hull dry mass over the 1990–1992 period, though in the last year (1993), T-100 showed significantly greater values in terms of kernel and shell + hull dry weight than RDI and T-70 fruits (Fig. 6C and D).

The growth of kernels and shells + hulls in dry mass appeared to follow a similar pattern throughout the developmental period during the years 1991 and 1992 (Fig. 7A and B). However, in April 1993, the shell + hull dry weight for RDI and – to a lesser extent – for T-70 seemed to lag behind those of T-100 and T-130 (Fig. 7C). Once the shell growth period
Fig. 6. Variation of almond yield components during the 4 years of experiment in response to the irrigation treatment. Different letters indicate significant differences between irrigation treatments according Duncan’s test, $P < 0.05$ (SAS Institute, 1998).
Fig. 7. Seasonal patterns of kernel and shell + hull dry weights in response to the irrigation treatments during the last 3 years of experiment. Each point is the average of 45 measurements. Vertical bars are the mean ± S.E. for kernel measurements.
was over (around the end of July), there was a clear tendency for RDI fruits to exhibit lower shell dry weights (Fig. 7C). The growth of kernel dry weight also appeared to decline for the RDI and T-70 treatments in 1993, but this only became evident in the case of RDI trees after the application of 3 weeks of deficit irrigation (Fig. 7C).

4. Discussion

The fact that applying the T-130 irrigation treatment produced no improvements in kernel yield for the average of the 4 years of the experiment supports the use of T-100 as a reference (Table 2). Additionally, soil water depletion for T-100 during the last 3 years of the experiment was very close to zero (Fig. 3). Average yield data indicated that any attempt to save water with either of the T-70 and RDI treatments produced a decrease in kernel yield (Table 2). However, there was a major difference between strategies T-70 and RDI in that RDI implied savings of about twice the amount of applied water (60%) than T-70 (34%), yet with only a 5% reduction in yield (Tables 1 and 2). While, the reduction in yield for T-70 with respect to T-100 (about 15%) was less advantageous in relation to its water savings (Table 2).

Long-term effects derived from deficit irrigation (T-70 and RDI) were evident in the form of reductions in yield apparent from the third year of applying these irrigation treatments (1992) (Fig. 6A and B). These reductions increased progressively with time and during the fourth year of the experiment (1993) were also accompanied by reductions in individual kernel dry mass (Fig. 5C). Apparently, the accumulation of kernel dry mass was very resistant to water stress in the first 2 years. In subsequent years, the observed reduction in leaf photosynthesis in treatments T-70 and RDI (Marsal et al., 1997) probably resulted in a reduction in the amount of carbohydrates available for fruit growth (Esparza et al., 2001b). Other possible explanations for this reduction in kernel dry mass, such as fruit competition, are to be excluded since fruit load in deficit irrigation treatments were even lower than in T-100 (Table 2). As vegetative growth, is more sensitive to water stress than carbohydrate transport (Hsiao, 1973), reductions in trunk growth tended to relate to drought from the first year of the RDI treatment (Fig. 5). However, the only short-term effect observed on yield components was the reduction in cropping for T-130 trees in 1990. This was perhaps due to the combined effect of excessive irrigation and the youth of the almond trees at that time (Fig. 6B and C). Fruit counts for T-130 later seemed to approach the optimum values observed for T-100 (Fig. 6B and C).

Deficit irrigation scheduling that do not guarantee the complete replacement of crop water consumption, such as T-70 and RDI, base part of their water savings on this lack of replacement. In the area in which the experiment was carried out, it is commonly assumed that winter and spring rainfall should compensate previous soil water depletion. However, the sustainability of such irrigation strategies can be compromised if this rainfall does not occur and if a chronic soil water deficit progressively develops. In the case of our study, the replenishment of soil water content after the expected winter–spring rainy season was far from complete, especially in spring 1993 (Figs. 1C and 2A). As the rainfall regime expected in this study had not anticipated this chronic deficit, no specific plant water status measurements were taken for the non-deficit irrigated periods. Even so, it is likely that
Fig. 8. Seasonal patterns of dry weight kernel/(shell + hull) ratio in response to the irrigation treatments during the last 3 years of experiment. Each point is the average of 45 measurements.
water stress occurred in early spring and that this may have produced a reduction in vegetative growth. This could have predominantly affected the RDI trees, as reflected in the significant reduction in TCSA growth (Fig. 5) and winter pruning weights (Table 2). As a result, it is more probable that the reduction in cropping for the RDI trees was related to a reduction in bearing positions and tree size, because the other components of cropping; flower initiation and fruit set, were apparently not reduced for almond in the case of water deficits occurring before harvest (Goldhamer and Viveros, 2000).

Consistent with the presumption that a certain level of water stress in spring occurred, was the reduction of shell + hull dry matter for T-70 and RDI fruits in spring 1993 (Fig. 6D). Accordingly, kernel growth for RDI and T-70 could also have been the result of a reduction of the space available for kernel growth, since the shells associated with these treatments were smaller than usual (Fig. 6C). The ratio between kernel dry weight to shell + hull dry weight was calculated in order to shed further light upon this last hypothesis (Fig. 8). A greater increase in this ratio during the kernel-filling period accompanied by smaller shells would be indicative of a physical limitation upon kernel growth. This was demonstrated in another experiment in which water stress was deliberately applied during shell growth period and in later stages of development, but stress was relieved during the kernel-filling phase (Girona et al., 1997). In the case of this study, and also that conducted in 1991, the kernel to shell + hull ratio tended to increase at the same rate in all treatments (Fig. 8A). However, unlike in 1991, in both the 1992 and 1993 seasons, and particularly during the final weeks of the kernel-filling phase, a slowing was observed in the rate of increase of T-70 and RDI with respect to T-100 (Fig. 8B and C). This suggested that the main limitation upon kernel growth was not primarily related to smaller shells. Since this event did not occur during the first years of the experiment, when the carbohydrate pool is supposed to be generally equal for all irrigation treatments (1991), the most likely mechanism for explaining a reduction in kernel dry weight for T-70 and RDI would be source limitation due to the long term impact of deficit irrigation on the carbohydrate reservoir (Fig. 8). Despite the negative long-term effects of the RDI treatment on cropping and kernel growth, the irrigation rates applied to RDI trees were as low as 200 mm. This makes the adoption of RDI very appealing in areas, where water available for irrigation is very limited or when a change from dry land to supplemental irrigation is under study. Taking into account the fact that average almond yields on un-irrigated lands in Spain are about 200 kg ha$^{-1}$ (Girona, 1992), the simple measure of applying RDI would imply an eight-fold increase in yield.

The high yields recorded in this experiment contrast with other results presented in the literature (Franco et al., 2000; Hutmacher et al., 1994; Torrecillas et al., 1989). Some of these experiments (Hutmacher et al., 1994; Shackel et al., 1998; Torrecillas et al., 1989) reported that applying more irrigation water than the presumed full water requirement promoted extra vegetative growth, while this experiment no extra vegetative growth was observed in T-130 in relation to T-100. The main difference between this experiment and the others was the irrigation system used (micro-sprinklers in our experiment and drips in most of the others). This may have affected the wetted soil volume and influenced the holding capacity of the soils. Hutmacher et al. (1994) discussed the possibility of obtaining better results using micro-sprinklers and Franco et al. (2000) also found that leaching was greatly influenced by the irrigation treatment applied (up to 3 mm/day). All of this seems to
indicate that the wet soil volume is a very important factor for almond, especially due to its high ability to use water and to promote extra growth until full water requirements are met.

In summary, T-100 irrigation scheduling based on the water balance technique and the use of previously published $K_c$'s (Goldhamer and Snyder, 1989) led to an optimum yield response. Kernel growth during the kernel-filling phase seemed to be relatively resistant to water stress. However, the carry over effect of three consecutive years of deficit irrigation reduced the capacity to accumulate dry matter in the kernel. This perhaps also combined with early water deficits to influence cropping efficiency. On the other hand, when compared to an optimum irrigation scheduling, an RDI strategy of the type proposed in this study offered potential savings of up to 60% of the quantity of water applied with only a 20% reduction in yield.

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