Abstract

The effect of regulated deficit irrigation (RDI) on fruit growth was studied for pear trees (Pyrus communis L. ‘Barlett’) grown in 120 l isolated containers. Two irrigation treatments were applied in consecutive seasons (1996 and 1997) but on different trees each year. The Control treatment was watered to non-stress conditions using stem water potential (Ψstem) and Penman ETo as a guide for the application of water. The RDI treatment received an average of 15% of the Control applied water from 32 to 60 DAFB (days after full bloom), the latter part of pear fruit development Stage I. Before 32 DAFB and after 60 DAFB, RDI was irrigated as the Control. Tree water status (leaf and stem water potential, leaf conductance and net assimilation rate at midday) and fruit growth parameters were measured periodically during both years. Additionally, in 1997, anatomical measurements of fruit growth (radial distance along fruit cortex tissue, cell number per radial distance and cross-sectional area) were made at the end of the deficit period and at harvest. Minimal Ψstem values during the RDI deficit period were about −1.4 MPa, indicative of moderate stress, and fruit growth was less in RDI than in the Control. The integral of water stress during the deficit period was linearly correlated with smaller cell size in the fruit cortex, whereas cell number was unaffected. When full irrigation was resumed and during Stage II fruit development, the fruit growth rate remained higher in the Control than in RDI, despite fruit osmotic adjustment and slightly higher tree water status of RDI. At harvest, RDI fruit size was smaller than the Control. The apparent contradiction between these results and studies which report a recovery of fruit growth
after deficit irrigated period may be caused by differences in growth conditions. © 2000 Elsevier Science B.V. All rights reserved.

**Keywords:** Pyrus communis; Fruit cell size; Fruit volume; Stem water potential

### 1. Introduction

Regulated deficit irrigation (Chalmers et al., 1981) has been reported by Mitchell et al. (1989) as a successful irrigation management strategy in ‘Bartlett’ pear orchards (*Pyrus communis* L.). When deficit irrigation was applied during Stage I of fruit development, excessive tree growth was controlled without negatively affecting fruit growth (Mitchell et al., 1989). A phenomenon which might explain this success is the accelerated growth which fruits sometimes experience after a specific period of water stress, as observed for peach (Chalmers et al., 1981), pear (Chalmers et al., 1986), Asian pear (Behboudian et al., 1994) and grapefruit (Cohen and Goell, 1988). Such increased fruit growth rates have been attributed to osmotic adjustment (Behboudian et al., 1994; Mills et al., 1996). A secondary advantage of mild stress may be the suppression of excessive vegetative growth, which can limit fruit growth or flower bud formation by shading (Giulivo and Xiloyannis, 1988; cited by Faust, 1989). For pear trees, though, the processes related to adaptation to water stress in leaves seem to be more important for tree survival than for maintaining productivity (Marsal and Girona, 1997).

Stage I of pear fruit development, corresponding to the main cell division period, takes place during the first 7–8 weeks after bloom (Bain, 1961; Westwood, 1978). The major increase in cell volume occurs during Stage II, the remainder of fruit development (Bain, 1961). Cell expansion, however, is also active during Stage I, but its effect is masked by the simultaneous occurrence of cell division. Thus deficits applied during Stage I could potentially affect cell division, cell enlargement or both of these processes.

Greater understanding of the fruit growth response can increase the success of RDI. If fruit recovery after RDI depends mainly on the intrinsic physiology of fruit growth, then the apparently successful application of RDI techniques could be reproduced in more general conditions than those reported for vigorous high-density orchards. In contrast to field conditions, working with containers, such as in this experiment, allows more precise control of the timing and level of plant water stress imposition in a deficit period. The objective of this study was to determine if these positive results obtained by Mitchell et al. (1989) could be repeated under conditions initially less favorable to RDI. Those conditions were achieved by using wide tree spacing and restricting root spread to an allotted volume, converting each tree in an isolated unit. The experiment was replicated
over 2 years, with different trees used between years to avoid carry-over effects. In the second year, fruit anatomical analyses were carried out to complement the fruit growth parameters.

2. Material and methods

2.1. Plant material and growth conditions

The experimental site, at the Experimental Station of Lleida (Catalunya, Spain), is located in a semiarid zone 41.38°N, 0.35°E, 250 m above sea level, with almost no rain in summer. In 1995, two-year-old pear trees were planted in thirty 120 l plastic containers and arranged in a spacing of 5×4 m². The soil depth inside the containers was 35 cm, four holes in each container base allowed adequate drainage, and the root system appeared homogeneously distributed throughout the effective volume at the end of the experiment.

A localized drip irrigation system was installed using two pressure-compensating 4 l/h drippers per container, increased to eight drippers in summer to assure uniform wetting in the containers. The system was controlled with a timer and solenoid valves. The trees were managed according to common commercial practices, with weeds eliminated manually.

During 1995, the trees were used to study leaf physiological response to both spring and summer drought cycles. This preliminary study served to establish the boundaries of plant water stress for local conditions. During the spring and summer seasons, non-stressful conditions were established by relating leaf conductance to plant water status measured with a pressure chamber. Maximum leaf conductance values were obtained at midday stem water potential ($\Psi_{stem}$) values above $-0.8$ MPa. Moderate water stress was considered to be at around $\Psi_{stem}$ values of $-1.4$ MPa, which induced about 40% reduction in net leaf assimilation rate at midday (IRGA system model ADC LCA-2; Analytical Development, Hoddesdon, Herts, UK). These two boundaries based on $\Psi_{stem}$ seemed to show a reasonable reliability due to their lesser dependence on weather conditions in comparison to midday or predawn leaf water potential (Marsal, 1997). Similar $\Psi_{stem}$ values for well-watered field pear trees have been reported (Ramos et al., 1993). In consequence, midday $\Psi_{stem}$ was adopted to aid in scheduling irrigation. The actual study began in spring, 1996, and was repeated in 1997.

2.2. Irrigation treatments and experimental design

Two treatments were applied: Control, and RDI. The Control was irrigated to provide non-stress conditions, using midday stem water potential ($\Psi_{stem}$) and
Penman reference evapotranspiration (ETo) (Doorenbos and Pruitt, 1977), to maintain the average $\Psi_{stem}$ above $-0.8$ MPa. Additionally, ETo was used to estimate seasonal changes in tree water needs. The ETo was obtained from the nearest automated weather station (Xarxa Agrometeorològica de Catalunya) (Lletjós et al., 1998) located 13 km from the study field. The RDI treatment was irrigated as the Control, except during the deficit irrigation period when the applied water was progressively reduced until the values of $\Psi_{stem}$ reached around $-1.4$ MPa. The RDI containers were covered with plastic in the event of rainfall episodes during the deficit period to eliminate rain intake. The deficit irrigation period elapsed from 34 to 59 DAFB, within the latter part of fruit growth Stage I. Full bloom occurred in the first week of April (calendar day 96) in 1996 and somewhat sooner in 1997 (calendar day 81). Harvest took place during the first week of August (calendar day 215).

In 1996, 22 trees were selected for homogeneity of fruit load and randomly assigned to each irrigation treatment. To eliminate carry-over effects from the 1996 deficit irrigation, the 1997 experiment utilized trees from the 1996 Controls, assigning five of the 11 available trees to the 1997 Control treatment and five other trees to the 1997 RDI treatment. A completely randomized design was used with each tree representing an experimental unit. Fruit harvest data were based on a nested analysis of variance (with tree nested to irrigation treatment variable). The PDIFF option of least square means (LSMEANS) was used to obtain $t$-tests for mean comparison (SAS, 1988, SAS Institute, Cary, NC). Significant differences were based on $p\leq 0.1$ and $p<0.05$.

2.3. General measurements

Data were collected from May until harvest. During the deficit period average air temperature and relative humidity were 17.2°C and 67%, respectively. Rainfall, totaling 20 mm, occurred at the beginning and end of the deficit period. Average temperature and relative humidity during Stage II were 26.4°C and 61.3%. Volumetric soil water content ($\theta_v$) was determined using a time domain reflectometry (TDR) system (Dalton et al., 1984), according to the equations proposed by Topp et al. (1980) and calibrated for the site by means of gravimetric measurements. TDR probes consisted of three 0.35 m deep parallel stainless steel rods. Two sets of TDR probes were placed opposite to each other in each container; the average of both sets was used to calculate the weekly $\theta_v$. Midday stem water potential ($\Psi_{stem}$) and midday leaf water potential ($\Psi_{md}$) were measured every week. In order to facilitate comparisons between this study and others, predawn leaf water potential ($\Psi_{stem}$) was also measured in 1996. Leaf water potential was determined by the pressure chamber technique (Scholander et al., 1965) following the recommendations of Turner and Long (1980). Readings were taken with a plant water status console (Model 3005, Soil
Moisture Equipment Corporation, Santa Barbara, CA). The oldest fully-expanded sunlit mature leaves were used for leaf water potential measurements. To determine $\Psi_{stem}$, leaves located near the trunk were enclosed in a plastic bag covered with aluminum foil 4 h before the measurements. Then, at midday leaf conductance ($g_s$) and net CO$_2$ assimilation rate ($A$) were determined under lightsaturating conditions using a portable IRGA system (Model ADC LCA-2, Analytical Development, Hoddesdon, Herts, UK). Leaf conductance was calculated according to the equations of von Caemerer and Farquhar (1981). Water stress integral was calculated by summing up “$t$” measurements of $\Psi_{stem}$ during the deficit period at intervals of “$n$” days. This can be estimated by multiplying the average of consecutive measurements $(\bar{\Psi}_{t+1})$ by the number of days between measurements ($n$).

$$S\Psi = \sum_{i=0}^{i=t} \Psi_{t+1} \ast n.$$  

### 2.4. Vegetative and fruit growth measurements

Trunk cross-sectional area (TCSA) was calculated from circumference measurements made in winter and after harvest, at 20 cm above the graft union. Shoot elongation was measured for six (1996) and 10 (1997) randomly tagged non-terminal shoots per tree during Stage I.

Fruit length (Le) and maximum width (Wi) of eight (1996) and 12 (1997) tagged fruits per tree were measured weekly with digital calipers. Due to fruit drop produced by strong winds during the summer, only 60% of the tagged fruits reached harvest. Fruit volume was estimated from fruit length and fruit width, assuming the fruit to have a composite shape of a hemisphere (bottom region) and a truncate cone (upper region) and using volume=$\frac{2}{3}\pi(Wi/2)^3 + \frac{1}{3}\pi(Le−Wi/2)(b^2+bWi/2+(Wi/2)^2)$, where the parameter $b$ represents the smaller base of the truncate cone. The value for $b$, obtained by minimizing the square difference between predicted volume (PV) and measured volume (MV) from an experimental sample of 114 fruits (least-square procedure), was 11.4 in 1996 and 25.1 in 1997. Different $b$ values in the different years corresponded to different fruit shapes because of the application of gibberellic acid in 1996. The predictions of real volumes obtained by using this formula were of acceptable accuracy in a broad range of values ($MV=−0.181+0.979*EV; R^2=0.983$). Relative growth rate was calculated as RGR=$\frac{\ln V_1−\ln V_0}{(t_1−t_0)}$; where $V_1$ and $V_0$ are the fruit volume at time $t_1$ and $t_0$, respectively (Hunt, 1982). Fruit osmotic content at full turgor was measured at the end of the deficit period in 1997 for 18 fruits per treatment. The fruits were collected at midday, allowed to rehydrate 16 h overnight and then frozen. Fruit sap was mechanically expressed from the
previously unfrozen fruits and osmotic content was determined with a vapor pressure osmometer (Model 5520, Wescor, Logan, UT).

At harvest, fruit fresh weight, fruit dry weight and flesh firmness were determined for all tagged fruits. Firmness was measured using a penetrometer (Fruit Pressure Tester, FT-327, Italy) fitted with an 8 mm plunger. For dry weight, the fruits were oven dried at 70°C. Fruit soluble solids were measured at harvest on a sample of 20 fruits per treatment. Total juice was expressed individually and filtered. A portion of the juice was used for the determinations of sugar percentage with a refractometer (Atago, ATG-1, Tokyo).

2.5. Anatomical fruit measurements

In 1997, 5 mm transverse slices were taken at the widest portion of the fruit and placed in formalin: acetic acid: 60% ethanol = 2:1:17 v/v (Berlyn and Miksche, 1976) at the end of Stage I and at harvest. The transverse slices were submerged in 70% ethanol with a few drops of toluidine blue 2–3 h in order to show the vascular bundles, and rectangular radial samples extending from inside the sepal vascular bundle to the fruit exterior were cut from the slices as pictured in Fig. 1. The radial samples were then dehydrated in tertiary butyl alcohol, embedded in paraffin, sectioned at 12 μm and stained with toluidine blue (Sakai, 1973).

The anatomical preparations were measured with the aid of a VIDS V (Ai Cambridge) image analysis system connected to either a binocular or ocular microscope, depending on the measurement. Radial distance from the external boundary of the sepal bundle to the exterior of the fruit and number of cells along

![Diagram of the pear fruit cross-section indicating the area used for anatomical studies: a rectangular radial sample extending from inside the sepal bundle to the fruit exterior. Diagram based on Bain (1961) and Essau (1997).](image-url)
this distance were determined using a binocular microscope (Fig. 1). Radial cell length was calculated as radial distance divided by cell number. Cross-sectional area of the cells was determined, using an ocular microscope, by counting the number of cells in precisely measured areas. These areas were 2500 μm² for the end of Stage I and 10 000 μm² for harvest, chosen in order to contain approximately 200 cells. In order to reduce any effect due to differences in cell enlargement within the fruit, cell area was assessed in both internal and external zones of each radial section; no difference was found, however, between the two zones.

All parameters were determined for one radial section per fruit for 12 (Control) or 14 (RDI) fruits/treatment at the end of Stage I (2–4 fruits per tree in four trees per treatment), and three radial sections per fruit for six fruits/treatment (2–4 fruits per tree in two trees per treatment) at final harvest. Statistical analyses were performed as for other fruit growth parameters. In addition an index of cell cross-sectional area was calculated as the percentage of each value with respect to the highest value for that date (100×actual value/highest value).

3. Results

Total water applied to each Control tree ranged from 709 l in 1996 to 790 l in 1997. Annual water savings with RDI can represent about 10% that of the Control. During the deficit period in 1996 (about 25 days in May), the RDI treatment received 21% of the Control dose and in 1997 10% of the Control.

As a consequence of the smaller doses and the use of plastic covers in the RDI containers during the spring rains (deficit period), soil water content was markedly lower in RDI than in the Control (Fig. 2A). Once full irrigation was resumed, differences between treatments in $\theta_v$ rapidly disappeared. Average

![Fig. 2. Seasonal patterns of volumetric soil water content measured with TDR (A), in 1996 and (B), 1997 season in response to irrigation treatments. Each point represents the mean of 20 (A), and 10 (B) measurements±standard error.](image)
values during the deficit period in 1996 were around 0.19 and 0.12 m\(^3\) m\(^{-3}\) for Control and RDI, respectively. However, during the same period in 1997, both treatments reached higher \(\theta_v\) values than in 1996: 0.27 and 0.15 m\(^3\) m\(^{-3}\) for Control and RDI, respectively (Fig. 2B). After the deficit period soil water content increased notably, but with the onset of the summer, \(\theta_v\) values from 0.25 to 0.30 m\(^3\) m\(^{-3}\) were needed to maintain \(\Psi_{stem}\) values above −0.8 MPa. During Stage II in both years \(\theta_v\) values for RDI were somewhat higher than in the Control (Fig. 2A and B).

In 1996, midday stem water potential was maintained as planned. Only on 53 DAFB did Control \(\Psi_{stem}\) values drop below −0.8 MPa, but this was immediately corrected the following day (Fig. 3A). Differences between treatments during the deficit period were significant for all water status parameters measured, and were always more highly negative for the RDI treatment (Fig. 3). The imposition and relief of plant water stress was rapid, with treatment differences occurring or disappearing in as little as 1 week (Fig. 3). Average minimum \(\Psi_{stem}\) values for RDI during the deficit treatment reached −1.4 and −1.3 MPa in 1996 and 1997, respectively. After the deficit period, values of \(\Psi_{stem}\) and \(\Psi_{md}\) were maintained at
high level for both treatments, and a tendency to exhibit higher $\Psi$ values in RDI than in Control was also clear for $\Psi_{\text{stem}}$ and $\Psi_{\text{md}}$ (Fig. 3). During Stage II, especially in 1997, it was very difficult to maintain values higher than $-0.8$ MPa in the Control treatment and values around $-0.95$ MPa were frequently observed (Fig. 4C). In general $\Psi_{\text{stem}}$ reflected differences between treatments sooner and measurements varied less than $\Psi_{\text{md}}$ (Fig. 4). For predawn leaf water potential, well-irrigated trees exhibited values from $-0.15$ MPa in spring to $-0.25$ MPa in summer; and average minimal $\Psi_{\text{pd}}$ values for I-RDI corresponded to $-0.47$ MPa.

There were significant treatment differences in leaf gas exchange during the deficit period; $A$ values were 35% lower for RDI than for Control during 1996, and in 1997 20% lower (Table 1). Shoot growth for RDI was 30% less than Control in both years (Table 2). Shoot growth ceased approximately 1 week...
before the onset of fruit development Stage II. Trunk cross-sectional area also presented lower values for RDI than for Control, but this was significant only in 1997 (Table 2).

The first productive year for the young trees was 1996 and fruit numbers (Table 2) and fruit size (Table 4, Fig. 4) were notably less than in 1997, but fruit loads were homogeneous between treatments (Table 2). Nevertheless, seasonal trends in fruit growth consistently showed different tendencies between treatments during both the years (Fig. 4). Early in the deficit period, estimated volumes in RDI were lower than in Control (Fig. 4A), with treatment differences becoming more pronounced as the season progressed (Fig. 4A). The average fruit volume growth rate (ml per day) for the whole deficit period indicated significantly less growth for RDI fruits in both years and also significantly lower rates for RDI during Stage II in 1997 (Table 3, Fig. 4B). The week after the resumption of irrigation, RDI estimated fruit growth seemed to momentarily recover normal Control rates, however, in subsequent weeks, well into Stage II, fruit volume growth rates in RDI again appeared consistently lower than Control (Fig. 4B). Averaging both years, higher reductions in growth rates in RDI were

### Table 1

Means and LSD probabilities of leaf gas exchange parameters during the most stressed day of the RDI period in different years (52 and 61 DAFB in 1996 and 1997, respectively) at midday in response to the irrigation treatments (each mean is obtained from n=16)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>An (μmol m⁻² s⁻¹)</td>
<td>7.16</td>
<td>4.69</td>
<td>0.0008</td>
<td>11.2</td>
<td>9.1</td>
<td>0.0014</td>
</tr>
<tr>
<td>gs (mmol m⁻² s⁻¹)</td>
<td>112</td>
<td>74</td>
<td>0.0004</td>
<td>281</td>
<td>235</td>
<td>0.015</td>
</tr>
<tr>
<td>Ci (μmol mol⁻¹)</td>
<td>195.9</td>
<td>206.8</td>
<td>n.s. ᵃ</td>
<td>238.4</td>
<td>249.9</td>
<td>0.006</td>
</tr>
</tbody>
</table>

ᵃ Not significant (p>0.1).

### Table 2

Means and LSD probabilities of fruit load and vegetative parameters in different years in response to the irrigation treatments

<table>
<thead>
<tr>
<th>Tree parameters</th>
<th>1996</th>
<th>1997</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>RDI</td>
</tr>
<tr>
<td>Fruit load (# fruits/tree)</td>
<td>7.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Shoot length increase in Stage I (mm)</td>
<td>75.6</td>
<td>53.1</td>
</tr>
<tr>
<td>TCSAᵃ at full bloom (cm²)</td>
<td>8.2</td>
<td>8.4</td>
</tr>
<tr>
<td>TCSA at harvest (cm²)</td>
<td>12.7</td>
<td>11.9</td>
</tr>
</tbody>
</table>

ᵃ Trunk cross-sectional area.
ᵇ Not significant (p>0.1).
observed during Stage I (16.5%) than in Stage II (approximately 9.5%) (Table 3). Fruit size at harvest in RDI was significantly smaller than in the Control, but only at a confidence level close to \( p < 0.1 \) (Table 4).

Fruit osmotic content just before the end of the deficit period in 1997 for RDI was 745 mmol kg\(^{-1}\), whereas Control values were significantly lower (572 mmol kg\(^{-1}\)) (\( t \)-student test, \( p < 0.0001 \)). Those determinations were made after 16 h rehydration, during which the RDI fruits absorbed 6% more water than those of the Control. In 1996, fruit firmness at harvest, was apparently not affected by RDI, but in 1997 the RDI fruits were slightly and significantly softer than Control fruits, perhaps indicating accelerated maturity (Table 4). For both years Control fruits at harvest contained significantly higher percentage sugars than RDI fruits for both the years (Table 4).

The anatomical measurements (Table 5) indicated no differences between treatments for fruit radial distance, cell number per radial distance and radial cell length. Cell cross-sectional area was slightly lower for the RDI treatment at the

<table>
<thead>
<tr>
<th>Fruit growth parameter</th>
<th>Year</th>
<th>Deficit period</th>
<th>Stage II</th>
<th>Deficit period</th>
<th>Stage II</th>
<th>Deficit period</th>
<th>Stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control RDI</td>
<td>Pr&gt;T</td>
<td>Control RDI</td>
<td>Pr&gt;T</td>
<td>Control RDI</td>
<td>Pr&gt;T</td>
</tr>
<tr>
<td>Growth rate (ml per day)</td>
<td>1996</td>
<td>0.657 0.568</td>
<td>0.022</td>
<td>2.481 2.288</td>
<td>n.s.(^a)</td>
<td>2.481 2.288</td>
<td>n.s.(^a)</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>1.254 1.017</td>
<td>0.012</td>
<td>4.318 3.855</td>
<td>0.016</td>
<td>4.318 3.855</td>
<td>0.016</td>
</tr>
<tr>
<td>Relative growth rate  (ml ml(^{-1}) per day)</td>
<td>1996</td>
<td>0.0537 0.0485</td>
<td>0.024</td>
<td>0.0295 0.029</td>
<td>n.s.(^a)</td>
<td>0.0264 0.0275</td>
<td>n.s.(^a)</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>0.0459 0.0468</td>
<td>n.s.(^a)</td>
<td>0.0264 0.0275</td>
<td>n.s.(^a)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( ^a \) Not significant \( (p>0.1) \).

Table 3
Fruit growth parameters for the deficit irrigation period and fruit development Stage II in different years for the irrigation treatments (each value is the LSmean \( n=74 \) and 66 in 1996 and \( n=44 \) and 46 in 1997 for Control and RDI, respectively) and the probability corresponds to the \( t \)-test significance.

<table>
<thead>
<tr>
<th>Harvest fruit fresh mass (g)(^a)</th>
<th>1996</th>
<th>141.2 131.8</th>
<th>0.107</th>
<th>255.7 228.6</th>
<th>0.101</th>
<th>141.2 131.8</th>
<th>0.107</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of dry matter(^b)</td>
<td>1996</td>
<td>17.51 17.78</td>
<td>n.s.(^c)</td>
<td>21.2 20.2</td>
<td>n.s.(^c)</td>
<td>17.51 17.78</td>
<td>n.s.(^c)</td>
</tr>
<tr>
<td>Firmness (N)(^b)</td>
<td>1996</td>
<td>110.7 109.5</td>
<td>n.s.(^c)</td>
<td>94 86</td>
<td>0.003</td>
<td>110.7 109.5</td>
<td>n.s.(^c)</td>
</tr>
<tr>
<td>Sugars (%)</td>
<td>1996</td>
<td>12.8 12.4</td>
<td>0.031</td>
<td>13.6 12</td>
<td>0.001</td>
<td>12.8 12.4</td>
<td>0.031</td>
</tr>
</tbody>
</table>

\( ^a \) Total sample at harvest.
\( ^b \) Tagged sample at harvest.
\( ^c \) Not significant \( (p>0.1) \).

Table 4
Fruit size and quality parameters at harvest in different years for the irrigation treatments (each value is the LSmean and the probability corresponds to the significance of \( t \)-test).
end of Stage I, but there was no significant difference between treatments for Stage II. There were no significant changes in cell number between Stage I and Stage II, while there was an approximately fivefold increase in cell area. When the fruit cell cross-sectional area was examined on a per tree basis, a strong linear relationship was revealed between this parameter and tree water status as indicated by stress integral of $\Psi_{stem}$ for both Stages I and II (Fig. 5). Fruit cell area was consistently lower with greater tree stress, although this relationship was much stronger for Stage I than for Stage II.

4. Discussion

In this study, using large containers, it was possible to impose precise timing of water stress within the last 30 days of Stage I fruit development. Water stress was easily managed because the imposition and relief of water deficit was rapid, as
evidenced from plant-based indicators ($\Psi_{stem}$, $\Psi_{md}$) (Fig. 3A–C). Non-stress conditions were apparently maintained during the first 30 days of Stage I and throughout the entire Stage II (Fig. 3).

The soil water content values corresponding to the presumably optimal $\Psi_{stem}$ levels were quite variable and depended on the season. In 1996, for instance, Control values in $\theta_v$ were smaller during spring than summer (Fig. 2A). This is not surprising because when changing from low to high evaporimetric demand wetter soil conditions are needed to support maximum plant evapotranspiration (Denmead and Shaw, 1962; cited by McCutchan and Shackel, 1992). Nevertheless, in 1997 Control soil water content was similar for spring and summer, and, with minor exceptions, was almost always close to container capacity (Fig. 2B). It should also be considered that in 1997, and especially during the summer, $\Psi_{stem}$ fell below $-0.8$ MPa and $\theta_v$ could not be raised further despite the substantial increase in irrigation. (Fig. 3C). The differences between years could be explained by the rapid development of these young trees, indicated by a doubling of TCSA and a fourfold increase in fruit load (Table 2), creating a presumable increase in tree water use in 1997 compared to 1996 (Faust, 1989; Wullschleger et al., 1998) while the container available volume for root growth remained unchanged. If this assumption holds, then 1996 $\theta_v$ were lower because additional water was not needed to maintain the determined $\Psi_{stem}$ value. Therefore, soil water content should be interpreted here in the context of $\Psi_{stem}$ irrigation scheduling and its absolute values were not necessarily related to plant water deficits. These observations and the fact that the average maximum summer $\Psi_{stem}$ in 1997 was about $-0.95$ MPa, suggest that a change in the optimum plant water balance occurred. A reasonable $\Psi_{stem}$ for indicating operative unstressed conditions in 1997 could be $-0.95$ MPa. This information reveals that despite the advantages of using $\Psi_{stem}$ as a plant–water–stress indicator (McCutchan and Shackel, 1992; Naor et al., 1995), some further modification is still required to establish a specific value of $\Psi_{stem}$ to determine the time when more irrigation is needed.

Plant parameters ($\Psi_{stem}$, $\Psi_{md}$) indicated that water stress developed during the deficit period (Fig. 3), although leaves never wilted. Photosynthesis during the most-stressed part of the deficit period in RDI trees fell to nearly 40% of Control, and leaf conductance decreased in a similar fashion (Table 1), indicative of moderate water stress. As a consequence, shoot growth decreased approximately 30% on RDI trees (Table 2). During Stage II, and even though all trees were receiving the same quantity of water, both water status parameters ($\Psi_{stem}$, $\Psi_{md}$) tended to be less negative for the RDI treatment (Fig. 3A–C). This phenomenon could be related, in part, to reduced vegetative growth in RDI trees, thus inducing lower tree water use during Stage II, as suggested by Buwalda and Lenz (1995). The soil water content in RDI also tended to be slightly greater throughout Stage II (Fig. 2A and B).
Small fruit size in 1996 was as expected in the first bearing year. Fruit size was normal as in an adult tree in the second year. In both years, however, fruit growth was apparently reduced by RDI. Seasonal patterns of fruit-size values were consistently slightly smaller during Stage I for RDI, with differences between treatments becoming more accentuated in the last 30 days of Stage II (Fig. 4). Those differences were even more evident in 1997 (Fig. 4). At harvest, RDI fruits were significantly smaller than Control in fresh mass (Table 4). In contrast, Chalmers et al. (1986), in studies with ‘Bartlett’ pear, and Caspari et al. (1993), with Asian pear, detected no decreases in fruit growth during the RDI period, and Chalmers et al. (1986) observed a significant increase in RDI fruit growth after resuming full irrigation. In Asian pear, osmotic adjustment of the fruit could contribute to this kind of recovery (Behboudian et al., 1994). Nevertheless, even though RDI fruits seemed to adjust osmotically at the end of the 1997 deficit period, no clear enhancement of fruit growth was observed during Stage II.

Water stress during Stage I could affect fruit development and thus limit the potential size to be achieved during Stage II. Fruit cell number, though, was not affected under the stress conditions produced in this study, since Stage I values were similar for both treatments (Table 5). Also, Stage I cell number was maintained unchanged in Stage II, in agreement with the timing for cell division in pear fruit established by Bain (1961). Stage I fruit cell size, however, was reduced under the RDI treatment (cell cross-sectional area, Table 5) and seems to correspond with the degree of stress, as indicated by the strong correlation with individual tree water status (Fig. 5). In Fig. 5, the higher values and reduced slope for Stage II as compared to Stage I possibly indicate a stronger stress effect during Stage I, the time of both early fruit growth and application of RDI, and a possible partial recuperation of cell size during Stage II. It should be noted that the anatomical studies were of transverse sections of the fruit flesh exterior to the sepal vascular bundles (Fig. 1). While this zone forms the major edible portion of the pear fruit, growth of the fruit internal to the sepal vascular bundles, including the core, was not included. Possibly growth in those internal zones was reduced by RDI, affecting total fruit volume (Fig. 4) or fruit growth rate (Table 3).

Reduction in fresh fruit mass (average of the two-year experiment) due to RDI treatment was 9%; whereas the decrease in shoot length was 33%, confirming the lower sensitivity of fruit to water stress compared to vegetative growth (Chalmers et al., 1986; Higgs and Jones, 1991; Berman and DeJong, 1996, 1997). The slightly higher \( \theta_v, \Psi_{stem}, \) and \( \Psi_{md} \) values in RDI during Stage II, however, were not related to greater fruit growth rates, probably because the differences between treatments were too small to limit expansive fruit growth. Chalmers et al. (1986) obtained significantly greater \( \Psi_{pd} \) for the RDI treatment after resuming full irrigation, similar to the tendency here toward greater leaf water potentials during Stage II. Contrary to our study, however, they found greater differences between treatments for midday leaf water potential. They report, for example, Stage II leaf
Ψ_{md} for Control of −1.92, −1.79 and −1.56 MPa, chronologically, as compared to −1.69, −1.44 and −1.47 MPa for the most-stressed RDI on the same days. That superior leaf water status of the RDI treatment during Stage II was not observed in our study (Fig. 3A,C). Also, Chalmers’ experiment was managed so that RDI treatments included a withholding period soon after full bloom to dry out the root zone of pear trees; During that time, Ψ_{pd} and Ψ_{md} fell as low as −0.46 and −1.91 MPa, respectively (Chalmers et al., 1986), that could have a decisive impact on shoot and fruit performance. The possible advantages and drawbacks of this withholding period cannot be evaluated from the scope of our data.

Fruit maturity in 1997, evaluated as fruit firmness at harvest (Table 4), indicated apparent earlier maturation in RDI. Commonly, maturity is correlated with higher soluble solids, but in our case RDI was characterized by less firm fruit and lower percentage sugars (Table 4). The slightly higher water status during Stage II in RDI may have induced a dilution effect.

Possibly the success of RDI strategies depends more on growth conditions than on intrinsic fruit physiology. Chalmers et al. (1981), with peach, obtained better results at high tree density. Under saline conditions, though, Boland et al. (1993, 1996) reported that deficit irrigation during Stage II of peach development resulted in smaller fruits. In this study we show that RDI fruit size was reduced in container-grown pear trees. Under our specific growth conditions and with separated trees, there is no competition for light among tree canopies, so no advantage is gained by reducing excessive vegetative growth. Under conditions that favor canopy shading, however, such as vigorous rootstocks, narrow tree spacing or high soil fertility, reduced canopy growth in RDI might allow increased light penetration into the canopy and an opportunity for RDI fruit recovery.

Acknowledgements

The research was supported by the council of Lleida LA PAERIA. The authors thank Boland and Connor for their helpful comments on the manuscript. They also thank Mercè Mata and Amadeu Arbonèes for their assistance in field-work.

References


