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Plant water status, CO_2 assimilation, yield, and fruit quality of 'Pacific Rose™' apple under partial rootzone drying

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Abstract: Water resources are becoming more limited worldwide and there is an urgent need to explore efficient irrigation technologies. The present paper investigates the feasibility of partial rootzone drying (PRD) for 'Pacific Rose™'apple grown in a humid climate. The treatments were commercial irrigation (CI) as control and PRD. Only one side of tree row was irrigated in the PRD treatment with the other side left to dry to a volumetric soil water content of 0.18 to 0.22 m^3 m^{-3} before being irrigated subsequently. In general, diurnal leaf water potential was the same for CI and PRD treatments. Stomatal conductance and photosynthetic rate appeared unaffected. Yield, mean fresh weight of fruit, trunk cross-sectional area (TCSA), yield efficiency (yield/TCSA), and shoot growth were the same between CI and PRD. Water use efficiency was improved in PRD trees. Fruit quality at harvest, in terms of internal ethylene concentration, starch pattern index, flesh firmness, total soluble solids concentration, and fruit skin background colour, was the same between CI and PRD. Dry matter concentration of fruit was lowerin PRD fruit than in CI fruit. In summary, PRD did not adversely affect yield and fruit quality and improved water use efficiency by 120%, saving 0.14 mega litres of water per hectare.

1. Introduction

Irrigation is important for meeting both high yield and fruit quality demands in apple, but water is scarce in many regions where this fruit crop is grown (De Lötter *et al.*, 1985). Therefore, improving water-use efficiency is crucial in producing high quality apple while maintaining the yield, making the investigation of new irrigation technologies essential.

Partial rootzone drying is a relatively new water-saving irrigation strategy where at each irrigation time only a part of the rhizosphere is irrigated with the complement left to dry to a pre-determined level. The drying side is irrigated subsequently and the previously wet side left to dry down. PRD attempts to save water by 50% without compromising yield. The idea is that in PRD chemical signals (mainly abscisic acid, ABA) from roots (experiencing water deficit) are sent to leaves, inducing partial closure of stomata. Transpiration therefore decreases, leaf water potential is maintained, and water use efficiency improved (Gowing *et al.*, 1990; Dry and Loveys, 1998; Davies *et al.*, 2002).

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In grapevines PRD has been successfully tested in Australia (Loveys *et al.*, 2000; du Toit *et al.*, 2003) and Portugal (de Souza *et al.*, 2003; dos Santos *et al.*, 2003). Information about PRD in pome fruit trees is scant and controversial. For instance, higher yield in PRD trees than fully irrigated (FI) trees has been reported in pear by Kang *et al.* (2002). In contrast, no significant differences were found in yield or fruit quality of 'Pacific Rose™' apples grown either under PRD or FI (van Hooijdonk *et al.*, 2004). 'Fuji' apple grown in a semi-arid area produced inconsistent information on yield and fruit quality. In fact, PRD tended to increase yield in relation to FI trees while trees with ongoing deficit irrigation (where water is applied to all the rootzone) had reduced yield compared with FI and PRD (Leib *et al.*, 2005). These contradictory results may be associated with weather conditions during experimentation or differences among apple cultivars. There is, therefore, a need to clarify the effects of PRD on apple because if application of less water has no negative impact on yield and a possible positive effect on fruit quality, the information is of primary importance to the industry.

The objective of this research was to assess the effect of PRD relative to commercial irrigation on yield and fruit quality of 'Pacific Rose™' apple grown in a humid climate. Plant water status, stomatal conductance, and photosynthetic rate were also monitored to gain further knowledge about the effects of PRD on tree physiology. Because a large portion of the root system would be left to dry by using drip irrigation, we hypothesised that the yield might be reduced but fruit quality could be improved. We conducted this experiment using drip irrigation because water use and precision placement are more efficient in comparison with flood and/or micro-sprinkler irrigation (Hartz, 1993).

2. Materials and Methods

Experimental site, plant material, and treatments

The experiment was conducted at the Fruit Crops Unit, Massey University, Palmerston North (latitude 40° 2' S, longitude 175° 4' E) during the 2001-02 growing season. The area has a humid-temperate climate with an average annual rainfall of 960 mm. The orchard soil is a Manawatu fine sandy loam.

Two rows of five-year-old 'Pacific Rose™' apple trees growing on MM-106 rootstock and M9 interstock were used in this trial. The trees were spaced at 4 m between rows and 3 m within the row and trained as a central leader. Two treatments were randomly allocated to four trees (as experimental unit) and replicated four times. The treatments were: commercially irrigated (CI) control and partial rootzone drying (PRD). Trees were drip irrigated by using four emitters (two on each side of the tree row). The drippers, that emitted 4 l per hour each, were placed 500 mm away from the tree row and between pairs of trees. The automatic irrigation in PRD trees was applied to one side of the tree row and the other side was left to dry to a volumetric soil water content (θ) of between 0.18 and 0.22 $m^3 m^{-3}$ during the growing season. CI and the irrigated side of PRD trees were irrigated to maintain θ at or close to field capacity. For this soil, field capacity and permanent wilting point occurred, respectively, at a θ of 0.35 and 0.17 $m^3 m^{-3}$. Approximately 172 and 344 l per tree were applied to PRD and CI treatments, respectively, over five irrigation episodes. These were applied on 123, 144, 145, 176 and 179 days after full bloom (DAFB) which occurred on 3 October 2001. We selected two rows upslope to facilitate runoff after rain. The soil in the CI and PRD plots was covered with clear polythene from 55 DAFB to keep the rain out. This covered an inter-row area of 512 m^2 in total. Soil was uncovered periodically, according to the weather conditions, to facilitate aeration. Trees received standard cultural practices for local commercial fruit production including fertilisation, pest and disease control, and weed control. Crop load was adjusted by hand thinning to six fruit per cm^2 of trunk cross-sectional area (Tustin *et al.*, 1999). This was done on 50 days after full bloom (DAFB).

Measurements of volumetric soil water content

Volumetric soil water content was monitored once a week by time domain reflectometry (TDR, Trase System-Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Two pairs of TDR probes were installed permanently at a soil depth of 500 mm (one per each side of the row) at a distance of 250 and 500 mm from the drippers and tree trunk, respectively.

Measurements of photosynthesis and stomatal conductance

Photosynthetic rate, stomatal conductance, and photosynthetic photon flux were measured between 12:00 and 13:30 hr local time with a portable photosynthesis system (LI-6200, Li-Cor Inc., Nebraska, USA) on four mature and exposed leaves per plot from shoots in the middle and outer part of the trees. This was done on 146, 155, 176, and 184 DAFB.

Measurements of leaf water potential

Diurnal changes in leaf water potential (Y_{leaf}) were recorded using a Scholander pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, California, USA) on leaves in the vicinity of those used for photosynthesis and stomatal conductance determinations on the same sampling dates at 06:00, 09:00, 12:00, 15:00, and 18:00 hr.

Growth of shoot and tree trunk

Shoot growth was measured by selecting and tagging similar sized current-season shoots at the outer and middle part of the canopy. The final shoot length was measured at the end of the experiment. Tree trunk diameter was measured before and at the end of the experiment at 400 mm above ground level with a digital hand-calliper (Digimatic, model 50-321, Mitutoyo, Co., Japan). Tree trunk diameter was used to calculate trunk cross-sectional area (TCSA).

Yield and fruit quality

At harvest, which occurred on 196 DAFB, fruit from each tree were counted and weighed and the yield was recorded as the sum of individual weight of fruit from each tree (gross yield). Mean fresh weight of fruit (MFMF) was calculated by dividing the gross yield by the number of fruit per tree. Yield efficiency was calculated by dividing the yield per tree by the corresponding TCSA. Water use efficiency was obtained by dividing the gross yield of each tree by the litres of water supplied to the tree (kg per tree l^{-1} H_2O).

Six fruit per plot were randomly selected to assess fruit quality parameters. Samples of internal ethylene concentration were obtained from the core cavity from each fruit while submerged under water (Johnston *et al.*, 2002). One-ml gas sample was injected into a gas chromatograph (Pye Unicam GCD) fitted with a flame ionisation detector (set at 140°C with H_2 and air flow of 30 and 300 ml min^{-1}, respectively), an activated alumina column (set at 100°C with N_2 as the carrier gas at 30 ml min^{-1}), and a Hewlett Packard integrator (model 3390A) calibrated with external ethylene standards (certified as b-standard by B.O.C Gases New Zealand Ltd.). Skin background colour, in terms of hue angle, was determined using a chromameter (CR-200 Minolta, Osaka, Japan). This was done on two opposite sides of the middle part of each fruit. Then, after removing the fruit skin, two flesh firmness determinations were carried out on two opposite sides in the equatorial part of each fruit using a press-mounted Effegi penetrometer (model FT 327, Alfonsine, Italy) with an 11.1 mm head. Total soluble solids concentration was measured mixing some drops from each side of the fruit with a hand-held refractometer with automatic temperature compensation (ATC-1 Atago, Tokyo, Japan). Starch pattern index was determined by dipping cross-sectional fruit halves for 30 s into a solution of 20 g of potassium iodide plus 5 g of iodine in 2000 ml of water. Hydrolysis of starch was ranked on a scale of 0 (100% starch) to 6 (no starch) using an Export New Zealand Apple (ENZA) Starch Pattern Index Chart for apple (Reid *et al.*, 1982). Dry matter concentration of fruit was determined from 25-g fresh cortical tissue and oven-dried at 85°C to constant weight and it was expressed on a fresh weight basis.

Statistical analysis

Data were analysed by randomised complete block model using GLM procedure of SAS software. To stabilise the variance, the variables expressed in percentage, such as fruit skin colour, were arcsine-transformed. Number of fruit and starch pattern index were square root-transformed. Means are reported after back transforming. Treatment means were separated by the least significant difference (LSD) test at $P \leq 0.05$.

3. Results

Changes in volumetric soil water content and leaf water potential

Volumetric soil water content (θ) alternatively increased and decreased during the growing season as irrigation was shifted from the wetted side to the drying side of the tree row (Fig. 1). However, the difference of θ between wetted and drying sides of PRD was not significant during the growing season (Fig. 1). Significant differences of θ between CI and the drying side of PRD were only detected on 155, 169, 175, and 196 DAFB. Drying one side of the PRD tree row resulted in a significant reduction in leaf water potential (Ψ_{leaf}) at 06:00, 09:00, and 15:00 hours on 155 DAFB (Fig. 2B) and at 18:00 hours on 176 DAFB (Fig. 2C). In general, predawn Ψ_{leaf} (at 06:00 hr) showed full recovery in all treatments and midday Ψ_{leaf} did not become lower, on average, than -1.1 MPa on the four occasions that this parameter was measured.

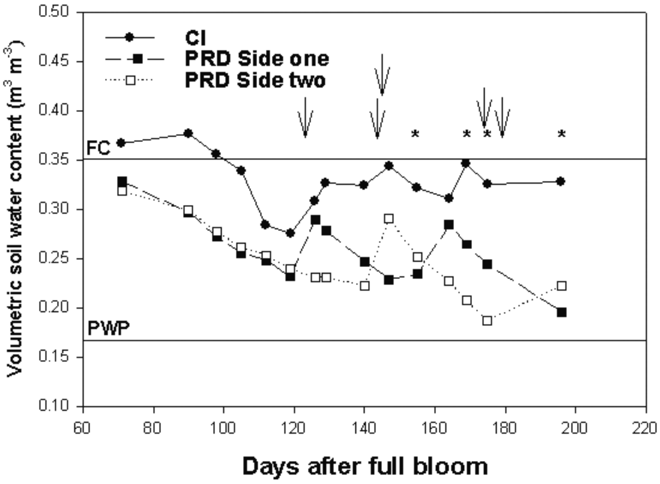

Fig. 1 - Changes in the volumetric soil water content (θ in the text) in commercially irrigated (CI) trees and in both sides of partial root zone drying (PRD) trees. Field capacity (FC) and permanent wilting point (PWP) values are also shown. Arrows represent irrigation episodes and the asterisks indicate significant differences at $P \leq 0.05$.

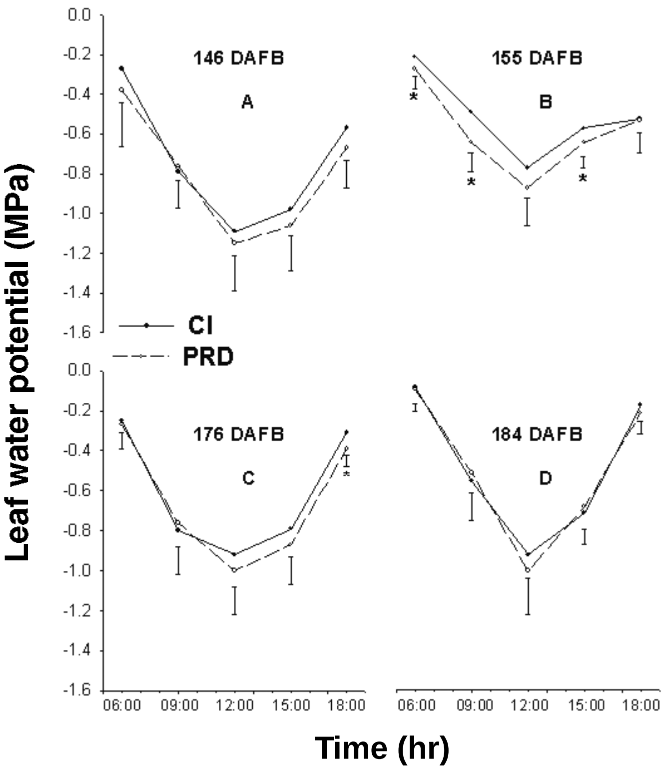

Fig. 2 - Diurnal changes in leaf water potential in commercially irrigated (CI) and in partial rootzone drying (PRD) apple trees. Vertical bars represent the Least Significant Difference and the asterisks indicate significant differences both at $P \leq 0.05$.

Photosynthesis and stomatal conductance

Stomatal conductance (g_s) did not differ between CI and PRD trees in all sampling dates. The same was true for the rate of photosynthesis (*A*), except for 176

DAFB when it was higher in PRD trees than in CI trees (Table 1).

Yield, yield components, and fruit quality

Yield, mean fresh weight of fruit, yield efficiency, trunk cross-sectional area, and final shoot growth were the same between treatments, but the water use efficiency improved in PRD trees relative to CI trees (Table 2). Except for fruit dry matter concentration, which was higher in CI than in PRD fruit, the remaining fruit quality attributes did not differ between the two groups (Table 3). The IEC, as physiological indicator of fruit maturity, was not significantly different between CI and PRD fruit. The mean IEC of fruit (LSD= 0.56 µl l^{-1}) was 0.63 and 0.83 for CI and PRD fruit, respectively.

4. Discussion and Conclusions

Volumetric soil water content was maintained, on average, at approximately 94% and 79% of the apparent field capacity in CI and PRD trees. However, when PRD trees were irrigated on the drying side of the tree row with half the amount of water given to the CI trees, their θ was still lower, but not significantly, than those of CI trees (Fig. 1). Fluctuations of θ on the two sides of the tree row in the PRD treatment were not reflected in significant differences of Ψ_{leaf} between CI and PRD trees (Fig. 2). Rain and long cloudy periods could override the effect of PRD by reducing transpiration (Green and Clothier, 1995) and therefore no consistent measurable effect of treatments on Ψ_{leaf}. The monthly precipitation (mm) during the experiment was 166 for December 2001 and 74, 102, 81, and 56 for, respectively, January, February, March, and April 2002. The data on Ψ_{leaf} and on gas exchange parameters (Table 1) were taken on sunny days.

The maintenance of Ψ_{leaf} in PRD trees may be explained by the increase in the rate of water absorption by the roots in the wetted soil as first observed in peaches (Tan and Buttery, 1982) and then in apple roots (Green *et al.*, 1997). Green and Clothier (1995) observed that water absorption was enhanced 10-fold upon re-watering in the roots of kiwifruit vines that had been previously water deprived. Furthermore, the root system of apple is explorative and therefore it is able to explore large volumes of soil and to extract water from regions where it is more freely available (Green *et al.*, 1997). Both mechanisms may take place in apple roots resulting in similar values of Ψ_{leaf} between PRD and CI trees. However, further research needs to be done on the spatial soil water distribution, availability, and plant root morphology and development under PRD. Most of

Table 1 - Effect of commercial irrigation (CI) and partial root zone drying (PRD) on stomatal conductance and photosynthesis of 'Pacific Rose™' apple

		Days after full blom				
Parameter	IT	146	155	176	184	Mean
Stomatal conductance	CI	1.0 a	1.4 a	0.8 a	0.7 a	1.0 a
(mol m^{-2} s^{-1})	PRD	1.1 a	1.3 a	0.6 a	0.7 a	1.0 a
Photosynthesis	CI	8.5 a	13.7 a	9.0 b	10.9 a	10.5 a
(µmol m^{-2} s^{-1})	PRD	10.2 a	11.5 a	11.6 a	10.8 a	10.8 a
PPF		1052	1126	1167	1185	
(µmol m^{-2} s^{-1} ± SD)		± 495	± 622	± 234	± 374	

IT= irrigation treatments.
Photosynthetic photon flux (PPF ± standard deviation, SD) values are also presented.
Means within columns followed by the same letter are not significantly different by the LSD test at *P*≤ 0.05.

Table 2 - Effect of commercial irrigation (CI) and partial rootzone drying (PRD) on mean fresh weight of fruit (MFMF), yield efficiency, trunk cross-sectional area (TCSA), final shoot length (FSL), and water use efficency (WUE) of 'Pacific Rose™'apples

IT	Gross yield (kg $tree^{-1}$)	MFMF (g)	Yield efficiency (kg $tree^{-1}/cm^2$ TCSA)	TCSA (cm^2)	FSL (mm)	WUE (kg l^{-1} H_2O)
CI	18.7 a	281.4 a	0.53 a	35.7 a	30.1 a	0.05 b
PRD	18.0 a	273.2 a	0.58 a	33.5 a	24.9 a	0.11 a

IT= irrigation treatments.
Means within columns followed by the same letter are not significant different by the LSD test at P≤ 0.05.

Table 3 - Effect of commercial irrigation (CI) and partial root zone drying (PRD) on dry matter concentration of fruit (DMCF), starch pattern index (SPI), flesh firmness (FF), total soluble solids concentration (TSSC), and fruit skin colour in terms of hue angle (HA°)

IT	DMCF (mg g^{-1} fresh weight)	SPI	FF (N)	TSSC (%)	HA°
CI	146 a	4.0 a	90.1 a	13.4 a	30.8 a
PRD	137 b	4.4 a	89.5 a	13.4 a	31.9 a

IT= irrigation treatments.
SPI's scale: 0=100% starch and 6= no starch.
Means within columns followed by the same letter are not significant different by LSD test at P≤ 0.05.

the knowledge on the soil-root interface has been obtained by Green *et al*. (2006) on a microscopic scale in kiwifruit and in apple trees undergoing PRD treatment.

Occasional significant differences in Ψ_{leaf} between CI and PRD leaves (Fig. 2) were not reflected in similar differences in their stomatal conductance (Table 1). Measurable stomatal closure in apple can occur when Ψ_{leaf} becomes -3.0 MPa or lower (Flore and Lakso, 1989). This did not occur in our experiment (Fig. 2). On 176 DAFB, a lower photosynthetic rate was observed in CI trees than in PRD trees (Table 1). The ratios of leaf internal CO_2 concentration to that of the air (Pi/Pa) was significantly higher in CI trees. The values were 0.90 and 0.86 for CI and PRD trees, respectively. Photosynthesis might have been biochemically limited when measurements were taken (Lauer and Boyer, 1992). We lack explanation for this possibility. Therefore, Ψ_{leaf}, stomatal conductance and photosynthetic rate responses to PRD suggest no evidence that PRD promotes a non-hydraulic effect (positive or negative signalling) (Davies *et al.*, 2002) on apple trees under our conditions. Recent research on olive trees by Fernández *et al.* (2006) and on apple trees by Zegbe *et al.* (2006, 2007) support this conclusion. Results presented by Fernández *et al.* (2006) and Zegbe *et al.* (2006) are interesting because these authors obtained similar results to ours in olive and apple trees grown, respectively, in a Mediterranean (southwest of Spain) and a North-Central climate where vapour pressure deficit is higher than in a humid climate. However, in humid areas like New Zealand, PRD could be recommended for the fruit tree production areas of Hawke's Bay and Marlborough where irrigation is required to meet high yields and fruit quality.

As the basic physiological parameters were not adversely affected by PRD, this accounts for the maintenance of yield and yield components compared to CI. Kang *et al.* (2002) observed that number of fruit was significantly increased in PRD trees relative to CI trees. In their experiment, however, there were on average 89 more fruit on PRD trees than on CI trees. In our experiment, there were eight more fruit, on average, on PRD trees than on CI trees. Therefore, in the experiment of Kang *et al.* (2002), the higher number of fruit in PRD trees suggests that the crop load was unadjusted at the start of their experiment. We calculated a 120% rise in water use efficiency in the PRD trees compared to CI trees (Table 2). This is higher than those observed in pear (79%) (Kang *et al.*, 2002) and in apple (94%) (van Hooijdonk *et al.*, 2004). At harvest, PRD treatment had saved 0.14 mega litres of water per hectare relative to CI treatment. Another benefit of PRD is the reduction of pruning cost by reducing shoot growth as shown for field-grown grapevine (du Toit *et al.*, 2003). We did not observe significant changes in shoot growth pattern in apple (Table 2). However, shoot growth tended to be lower (although not significantly) in PRD trees than in CI trees by about 17%. Although not significantly different, the higher IEC and SPI in PRD trees are indicative of their more advanced maturity (Kingston, 1991), hence their lower dry matter concentration (Table 3). However, fruit quality was generally similar between treatments.

This study showed that drip-irrigated PRD trees did not experience significant changes in Ψ_{leaf}, stomatal conductance, and photosynthetic rate. Yield and yield components were the same between treatments, and the water use efficiency improved by 120% in PRD trees over CI trees. Shoot growth was reduced by 17% in PRD trees. Fruit quality, in general, was not enhanced by PRD, but PRD seemed to advance fruit maturity. PRD treatment used 50% less water and saved 0.14 mega litres of water per hectare compared to CI treatment without compromising either yield or quality. Therefore, PRD irrigation could be suggested as a water saving practice for humid areas similar to our experimental conditions. Research should be done for semi-arid conditions where water is scarce and expensive for irrigation and the evapotranspiration demand is also higher.

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