Reduced Irrigation Maintains Photosynthesis, Growth, Yield, and Fruit Quality in ‘Pacific Rose™’ Apple

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ABSTRACT. Apple is grown in areas where water for irrigation is often limited. New water-saving irrigation methods are therefore needed for production in a sustainable system. Here we have compared commercial irrigation (CI) with partial rootzone drying (PRD) for their effects on ‘Pacific Rose™’ in a humid climate during the growing season of 2000-2001. In our PRD treatment only one side of the tree row was watered at each irrigation time and the other side was kept un-irrigated for

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the entire growing season. In general, diurnal leaf water potential values were the same for CI and PRD trees, and so were the gas exchange parameters of photosynthesis, transpiration, and stomatal conductance. Yield, mean fresh weight of fruit, trunk cross sectional area (TCSA), yield efficiency (yield/TCSA), and shoot growth were the same for CI and PRD. But the irrigation water use efficiency was higher by 133% for PRD trees compared to the CI trees. Fruit quality at harvest; in terms of dry matter concentration, flesh firmness, total soluble solids concentration, and background skin colour was the same for the treatments. Besides maintaining fruit yield and quality, the PRD treatment led to a saving of 0.151 megalitres of water per hectare. PRD could therefore be recommended where water resources are limited for apple production.
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KEYWORDS. *Malus pumila*, partial rootzone drying, water relations, yield, fruit quality, water saving technology

INTRODUCTION

Apple is grown in a wide range of climates worldwide often with limited water availability for irrigation (Westwood, 1993). With the higher demands for water from increasing world population and growing industries, water is becoming increasingly limited for irrigation (Postel, 1998; Bouwer, 2003). New water saving irrigation methods would therefore have to be explored for food production. This is true especially for apple production as apple has the second highest acreage of any fruit crop in the world after grapes (FAO, 2005).

So far, there are two methods of reduced irrigation for saving water in fruit production. One is deficit irrigation (DI) where a certain percentage of evapotranspiration is replaced by irrigation applied over the entire rootzone. The other, which is a variation of DI, is partial rootzone drying (PRD) where at each irrigation time only one side of the tree row is watered with the other side is left to dry, to a pre-determined level, before being irrigated next. Apple has been extensively researched under DI but, to our best knowledge, there is only one literature report (van Hooijdonk et al., 2004) on its responses to PRD, which is a relatively new technology. Roots in drying soil are expected to send chemical signals (mainly abscisic acid, ABA) to leaves inducing partial closure of stomata, and thereby reducing transpiration rate and improving water use efficiency, because photosynthesis is expected to decrease to a lesser extent than does transpiration (Gowing et al., 1990; Dry and Loveys, 1998; Davies et al., 2002). This potential of PRD has been realised in grape (Loveys et al., 2000; du Toit et al., 2003; de Souza et al., 2003; dos Santos et al., 2003). Yield and berry quality for two grapevine cultivars were the same between PRD vines and fully irrigated vines, but irrigation water use efficiency improved in the former vines (Loveys et al., 2000).

However, PRD has had different effects on yield and fruit quality in various fruit trees. While Kang et al. (2002) reported a significant increase in the yield of pear under PRD, a similarity of yield and fruit quality between PRD and fully irrigated trees was reported for peach (Goldhamer et al., 2002) and for apple (van Hooijdonk et al., 2004). The potential of PRD as an effective water saving irrigation practice will have to be further explored. Our objective therefore was to investigate the effect of PRD on plant and fruit water status, photosynthesis, yield, fruit quality, and irrigation water use efficiency of 'Pacific Rose™' apple. Because one part of the rootzone is always moist during PRD and plant water status is expected to equilibrate with this part as observed in a split root experiment on apple by Gowing et al. (1990), we hypothesised that PRD would not significantly reduce the fundamental physiological processes, and therefore yield and fruit quality would be similar to trees fully irrigated.

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 growing season of 2000-2001. The area has humid temperate climate with an average annual rainfall of 960 mm. The orchard soil is a Manawatu fine sandy loam.

The experimental block consisted of four rows of four-year-old 'Pacific Rose™' apple growing on M9 interstem and on MM-106 rootstock. The trees were spaced at 4 m between rows and 3 m within the row and trained as a central leader. Sixteen experimental trees were divided into four blocks. Each block had two plots of two experimental trees each. Two guard trees at each end surrounded the experimental plots.

Two treatments were randomly allocated within each block. They were commercial irrigation (CI), considered as control, and PRD. The CI trees were irrigated to maintain the soil moisture at or close to field capacity. The irrigation water in PRD trees was applied only to one side of the tree row, while the other side was kept un-irrigated during the entire growing season. To exclude the rain, soil in the PRD plots was covered with clear polythene a month before full bloom, which occurred on October 23, 2000. Trees received standard cultural practices for local commercial fruit production including fertilization, pest and disease control, and weed control. Trees were hand-thinned at 53 days after full bloom (DAFB) to 6 fruit per cm^2 of trunk cross sectional area (TCSA) (Tustin et al., 1999).

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 pair on each side of the row) at distances of 250 and 500 mm away from the emitters and tree trunk, respectively. Field capacity and permanent wilting point for this soil are reached at volumetric soil water contents of 0.35 and 0.17 $m^3\ m^{-3}$, respectively.

Measurements of Leaf Water Potential

Diurnal leaf water potential was measured on six fully expanded leaves per plot by using a Scholander pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Measurements were taken at 05:00, 09:00, 13:00, 17:00, and 20:00 hours on 52, 87, 115, and 142 DAFB.

Measurements of Gas Exchange Parameters

Data on stomatal conductance and rates of photosynthesis and transpiration were collected between 12:00 and 13:30 hours with a portable photosynthesis system (LI-6200, Li-Cor Inc., Nebraska, USA) on eight mature and exposed leaves per plot. These were taken on the same sampling days as for leaf water potential.

Measurement of Growth in Trunk, Shoot, and Fruit

Shoot growth was measured by selecting and tagging similar-size current season shoots at the outer and middle part of the canopy at the start of the experiment on 37 DAFB. The shoot length was measured at the end of the growing season. Shoot length values (mm $\pm$ standard deviation) at the start of the experiment were: 10.2 ± 1.1 and 9.4 ± 2.0 for CI and PRD trees, respectively. Fruit growth was recorded at weekly intervals, in terms of fruit diameter of the equatorial region of each fruit, on 10 fruit randomly sampled at the outer and middle part of one tree canopy with a digital caliper (Digimatic, model 50-321, Mitutoyo, Co., Japan) commencing on 37 DAFB and until growth ceased. Fruit volume was estimated by assuming a spherical shape. Tree trunk diameter was measured before and at the end of the experiment at 400 mm above the ground level with the same digital caliper. Tree trunk diameter was expressed in terms of TCSA.

Yield, Irrigation Water Use Efficiency, and Fruit Quality

At harvest, which occurred on 179 DAFB, fruit from each tree were harvested, counted, and total weight of all fruit measured as gross yield. Mean fresh weight of fruit was calculated by dividing the gross yield by number of fruit per tree. Yield efficiency was calculated by dividing the yield of each tree by TCSA of the same tree. Irrigation water use efficiency was obtained by dividing the gross yield by litres of water applied to the tree (kg per tree L^{-1} H_2O).

Six fruit per plot were randomly selected to assess quality. Skin background colour of fruit, 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. After removing the fruit skin, two flesh firmness determinations were done 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 with a hand-held refractometer with automatic temperature compensation (ATC-1 Atago, Tokyo, Japan) by mixing some drops from each side of the fruit. Dry matter concentration of fruit was determined from 25 g fresh cortical tissue oven-dried at 85°C to constant weight and it was expressed on a fresh mass basis.

Return Bloom

Return bloom was determined as follows. Four 2-year-old shoots (25 cm length) per tree were selected a month before full bloom which occurred on October 10, 2001. The basal diameter of each shoot was determined and shoot cross sectional area (SCSA) calculated. The flowers on each shoot were recorded and the bloom density was calculated as the number of open flower clusters divided by SCSA.

Statistical Analysis

Data were analysed by complete randomised block model using GLM procedure of SAS software (SAS Institute, Cary, North Carolina, USA). To stabilise the variance, the variables that were expressed in percentage (such as skin background colour of fruit and volumetric soil water content) were arcsine-transformed. Number of fruit was squareroot-transformed (Fernandez, 1992). Means are reported after back transforming. Treatment means were separated by the least significant difference (LSD) test at $P \leq 0.05$.

RESULTS AND DISCUSSION

In PRD, the rootzone is simultaneously exposed to both wet and drying soil. In our experiment, θ in the wet side of PRD and in CI was kept close to field capacity. In contrast, θ in the drying side of PRD slowly decreased from 44 DAFB and it tended to stabilise from 100 DAFB to the end of the growing season (Figure 1). The slow drying of the soil did not necessitate alternating the irrigation in both sides of the root system in the PRD treatment. We do not discount the possibility of water movement from the wet side to the dry side of PRD plots. However, a stronger possibility is water uptake from the deeper soil profile and the occurrence of 'hydraulic lift' (as defined by Atwell et al., 1999) contributing to the stabilisation of θ in the dry side of PRD trees.

In our PRD treatment the expected hormonal changes, mentioned earlier, might not have been realised. Stomatal conductance and the rates of transpiration and photosynthesis were the same between CI and PRD (Table 1). This might be due to the fact that ψ_{leaf} was similar between CI and PRD trees, except for two times at 13:00 and 05:00 hours on 52 and 115 DAFB (Figure 2). However, most of the time, ψ_{leaf} in PRD trees was slightly lower than in CI trees at midday, possibly due to evaporative

FIGURE 1. Changes in volumetric soil water content (θ in the text) in commercially irrigated (CI) trees and both sides of partial rootzone drying (PRD) trees. Vertical bars represent the least significant difference (LSD) at $P \leq 0.05$ and the asterisks indicate significant differences at the $P \leq 0.05$.

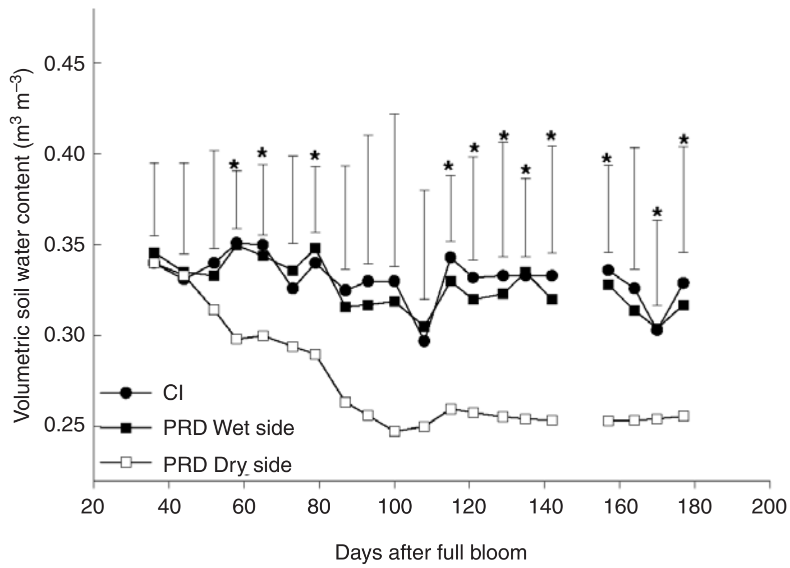


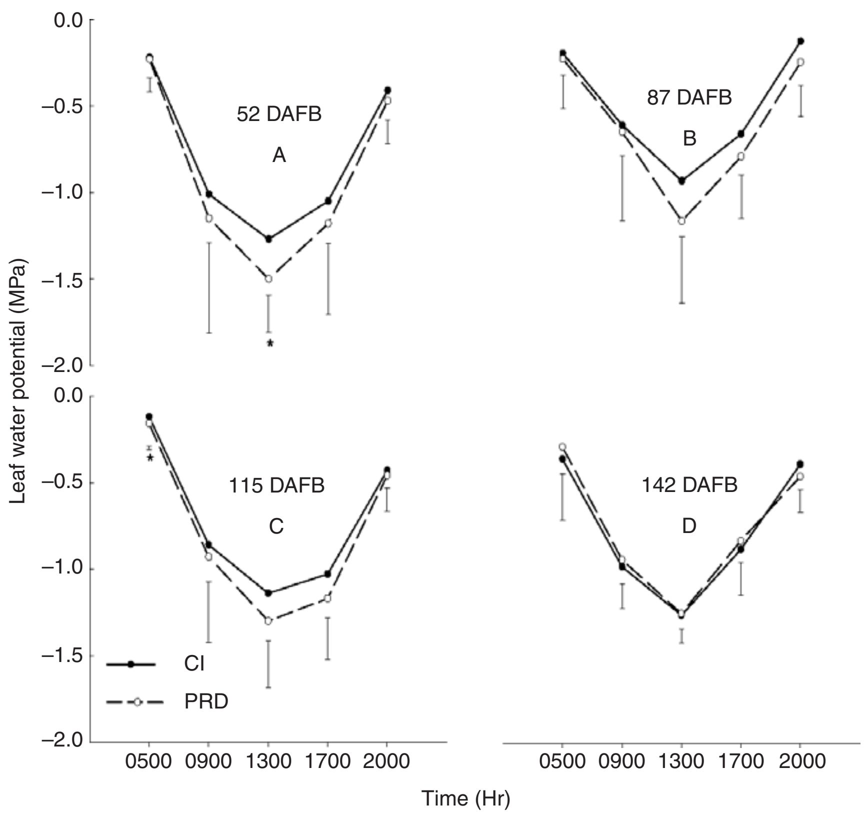
TABLE 1. Stomatal conductance, rates of transpiration, and photosynthesis in response to irrigation treatments (ITs). CI and PRD stand for commercial irrigation and partial rootzone drying, respectively. Photosynthetic photon flux (PPF) is given for each occasion. Standard error of the mean (SEM) and standard deviation (SD) are provided for each mean value.

Parameter	ITs	Days after full bloom			
		52	87	115	142
Stomatal conductance	CI	13.8 ± 1.6	13.8 ± 1.2	14.2 ± 0.8	13.4 ± 1.2
(cm s^{-1} ± SEM)	PRD	11.8 ± 0.9	17.3 ± 0.7	12.9 ± 0.9	13.1 ± 0.8
Transpiration rate	CI	2.2 ± 0.1	5.6 ± 0.2	9.6 ± 0.6	2.5 ± 0.1
(mmol m^{-2} s^{-1} ± SEM)	PRD	2.0 ± 0.1	6.5 ± 0.2	8.8 ± 0.3	2.5 ± 0.1
Photosynthetic rate	CI	14.9 ± 0.7	19.2 ± 0.3	33.4 ± 1.1	16.1 ± 0.6
(μmol m^{-2} s^{-1} ± SEM)	PRD	15.1 ± 0.4	20.9 ± 0.4	34.4 ± 0.7	16.6 ± 0.3
PPF (μmol m^{-2} s^{-1} ± SD)		1764 ± 389	1627 ± 582	1225 ± 667	1313 ± 583

demand. The maintenance of ψ_{leaf} in PRD trees could be explained, in part, by an increase of water absorption from the roots in the wet soil as observed by Green and Clothier (1999). These authors observed that when a portion of the apple root system is irrigated, this portion has the capacity to transfer water from the soil at higher rates than when the whole root system is irrigated. Flore and Lakso (1989) have shown that stomata of apple leaves close when ψ_{leaf} become −3.0 MPa or lower. Leaf water potential did not decrease to this level in our experiment (Figure 2).

Fruit growth of PRD trees, in terms of volume, was reduced significantly from 80 to 120 DAFB (Figure 3) possibly, because of a temporary

FIGURE 2. Diurnal changes in leaf water potential in commercially irrigated (CI) and partial rootzone drying (PRD) trees. Vertical bars represent the LSD at $P \leq 0.05$ and the asterisks indicate significant differences at the $P \leq 0.05$.



water deficit that is not reflected in our measurements of Figure 2. Although not significant, fruit growth remained slightly lower than that of CI fruit until the end of the growing season (Figure 3). Yield and yield components were also similar between irrigation treatments (Table 2). Our results disagree with those of Kang et al. (2002) who reported a significant increase in the yield of pear under PRD. They also reported higher number of fruit (111 more fruit) in PRD trees than in CI trees. In their experiment, maybe the crop load was not properly adjusted. In our experiment, at harvest, mean number of fruit (LSD = 56) was 104 and 124 for CI and PRD trees, respectively. Similar results were found in 'Golden Delicious' apple trees undergoing PRD in semi-arid environment (Zegbe, 2005).

Compared to CI, PRD had an increase of 133% in irrigation water use efficiency (Table 2). Values quoted from the literature are: 27% for pear (Kang et al., 2002), 89-100% for grape (du Toit et al., 2003; dos Santos et al., 2003), and 93% for apple (van Hooijdonk et al., 2004). Another benefit of PRD is the reduction of pruning cost by reducing shoot growth as shown for field-grown grapevine (Dry et al., 2000; du Toit et al., 2003). We did not observe changes in growth pattern in apple (Table 2). In fact, shoot growth tended to be higher (although not significantly) in PRD trees than in CI trees by *ca* 15%. Return bloom, recorded in the spring of 2001, was the same between the treatments. The values (number of open flower clusters per cm^2 of SCSA $\pm$ twice the standard error of the mean) were 4.1 $\pm$ 1.2 and 2.8 $\pm$ 0.8 for CI and PRD trees, respectively.

Although PRD trees received only 50% of water given to CI trees, fruit quality, in terms of higher total soluble solids concentration, flesh firmness, dry matter concentration, and skin colour of fruit, was the same in both treatments (Table 3). There was a trend for an increase in dry matter concentration of PRD fruit by *ca* 4%. It is reported that red colour of 'Pacific Rose™' apple can be hampered or delayed by water deficit (Tustin et al., 1999). However, here red colour tended to increase by 10% in PRD fruit relative to CI fruit. A benefit of reduced irrigation is the improvement of fruit quality in apple, but this improvement depends on the extent of water deficit developed and the timing of it (Behboudian and Mills, 1997). For instance, ψ_{leaf} reduction by -1.5 to -2.5 MPa is accompanied by increase in sugars, flesh firmness, aroma volatiles, and storage potential (Ebel et al., 1993; Mills et al., 1996; Kilili et al., 1996; Mpelasoka et al., 2000). This lowering of ψ_{leaf} did not occur here in the PRD treatment (Figure 2).

FIGURE 3. Cumulative fruit growth, in terms of fruit volume, of 'Pacific Rose™' apple under partial rootzone drying (PRD) and commercial irrigation (CI). Vertical bars represent the LSD at $P \leq 0.05$ and the asterisks indicate significant differences at $P \leq 0.05$.

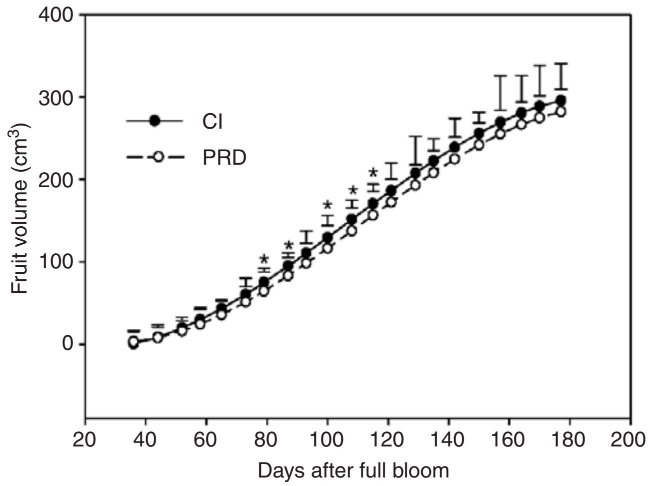


TABLE 2. Effect of commercial irrigation (CI) and partial rootzone drying (PRD) on mean fresh weight of fruit (MFMF), trunk cross-sectional area (TCSA), final shoot length (FSL), and irrigation-water-use efficiency (IWUE) of 'Pacific Rose™' apple. IT = irrigation treatments. Means within columns followed by the same letter are not significant different by LSD test at $P \leq 0.05$.

IT	Gross yield (kg tree^{-1})	MFMF (g)	Yield efficiency (kg tree^{-1}/cm^2 TCSA)	TCSA (cm^2)	FSL (mm)	IWUE (kg L^{-1} H_2O)
CI	23.80a	216.04a	1.22a	20.33a	142a	0.06b
PRD	24.38a	187.47a	1.20a	19.82a	163a	0.14a

CONCLUSIONS

PRD did not alter plant water status and gas exchange parameters during the entire growing season in the 'Pacific Rose™' apple. Yield, yield components, and fruit quality were not adversely affected by PRD. This irrigation method improved irrigation water use efficiency by 133% and saved 0.151 megalitres of water per hectare. Although

TABLE 3. Fruit quality attributes of 'Pacific Rose™' apples at harvest as influenced by commercial irrigation (CI) and partial rootzone drying (PRD). Means within rows followed by the same letter are not significantly different by LSD test at $P \leq 0.05$.

Fruit quality attributes	Irrigation treatments	
	CI	PRD
Dry weight concentration of fruit (mg g^{-1} fresh weight)	126.1a	130.8a
Flesh firmness (N)	82.8a	81.5a
Total soluble solids concentration (%)	12.7a	12.1a
Hue angle (fruit skin colour)	24.6a	22.2a

PRD could be suggested as a water saving practice in a humid environment, research in dry environments needs to be conducted.

REFERENCES

Atwell, B.J., P.E. Kriedemann, and C.G.N. Turnbull. 1999. *Plants in action: Adaptation in nature, performance in cultivation*. Macmillan Education Australia, Melbourne, Australia. 664 pp.

Behboudian, M.H. and T.M. Mills. 1997. Deficit irrigation in deciduous orchards. *Hort. Rev*. 21:105-131.

Bouwer, H. 2003. Integrated water management for the 21st century: Problems and solutions. *Food, Agric, & Environ*. 1:118-127.

Davies, W.J., S. Wilkinson, and B. Loveys. 2002. Stomatal control by chemical signalling and the exploitation of the mechanism to increase water use efficiency in agriculture. *New Phytol*. 153:449-460.

de Souza, C.R., J.P. Maroco, T.P. dos Santos, M.L. Rodrigues, C.M. Lopes, J.S. Pereira, and M.M. Chaves. 2003. Partial rootzone drying: Regulation of stomatal aperture and carbon assimilation in field-grown grapevines (*Vitis vinifera* cv. Moscatel). *Func. Plant Biol.* 30:653-662.

dos Santos, T.P., C.M. Lopes, M.L. Rodrigues, C.R. de Souza, J.P. Maroco, J.S. Pereira, J.R. Silva, and M.M. Chaves. 2003. Partial rootzone drying: Effects on growth and fruit quality of field-grown grapevines (*Vitis vinifera*). *Func. Plant Biol.* 30:663-671.

Dry, P.R. and B.R. Loveys. 1998. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. *Australian J. Grape and Wine Res*. 4:140-148.

Dry, P.R., B.R. Loveys, and H. Düring. 2000. Partial drying of the rootzone of grape. I. Transient changes in shoot and gas exchange. *Vitis* 39:3-7.

du Toit, G., P. Dry, and B. Loveys. 2003. A preliminary investigation on partial rootzone drying (PRD) effects on grapevine performance, nitrogen assimilation and berry composition. *South Africa J. Enol. & Vitic*. 24:43-54.

Ebel, R.C., E.L. Proebsting, and M.E. Patterson. 1993. Regulated deficit irrigation may alter apple maturity, quality, and storage life. *HortScience* 28:141-143.

Fernandez, G.C.J. 1992. Residual analysis and data transformation important in statistical analysis. *HortScience* 27:297-300.

Flore, J.A. and A.N. Lakso. 1989. Environmental and physiological regulation of photosynthesis in fruit crops. *Hort. Rev.* 11:111-157.

Food and Agriculture Organization of the United Nations (FAO). 2005. FAOSTAT database (http://faostat.fao.org).

Goldhamer, D.A., M. Salinas, C. Crisosto, K.R. Day, M. Soler, and A. Moriana. 2002. Effects of regulated deficit irrigation and partial rootzone drying on late harvest peach tree performance. *Acta Hort*. 592:343-350.

Gowing, D.J.G., W.J. Davies, and H.G. Jones. 1990. A positive root-sourced as an indicator of soil drying in apple, *Malus* × *domestica* Borkh. *J. Exp. Bot*. 41:1535-1540.

Green, S.R. and B.E. Clothier. 1999. Roots water dynamics of water uptake by a mature apple tree. *Plant Soil* 206:61-77.

Kang, S., X. Hu, I. Goodwin, and P. Jerie. 2002. Soil water distribution, water use, and yield response to partial root zone drying under shallow groundwater table condition in a pear orchard. *Scientia Hort*. 92:277-291.

Kilili, A.W., M.H. Behboudian, and T.M. Mills. 1996. Composition and quality of 'Braeburn' apple under reduced irrigation. *Scientia Hort*. 67:1-11.

Loveys, B.R., P.R. Dry, M. Stoll, and M.G. McCarthy. 2000. Using plant physiology to improve the water use efficiency of horticultural crops. *Acta Hort*. 537:187-197.

Mills, T.M., M.H. Behboudian, and B.E. Clothier. 1996. Water relations, growth and the composition of 'Braeburn' apple fruit under deficit irrigation. *J. Amer. Soc. Hort. Sci.* 121:286-291.

Mpelasoka, B.S., M.H. Behboudian, J. Dixon, S.M. Neal, and H.W. Caspari. 2000. Improvement of fruit quality and storage potential of 'Braeburn' apple through deficit irrigation. *J. Hort. Sci. & Biotechnol.* 75:615-621.

Postel, S.L. 1998. Water for food production: Will there be enough in 2025? *BioScience* 48:629-637.

Tustin, S., J. Hughes, and P. Brookfield. 1999. *Pacific Rose™*. Technical Bulletin. ENZA New Zealand Apple and Pear Marketing Board.

van Hooijdonk, B.M., K. Dorji, and M.H. Behboudian. 2004. Responses of 'Pacific Rose'™ apple to partial rootzone drying and deficit irrigation. *Europ. J. Hort. Sci*. 69:104-110.

Westwood, M.N. 1993. *Temperate zone pomology–Physiology and culture*. Timber Press, Portland, Oregon, USA. 535 pp.

Zegbe, J.A. 2005. Partial rootzone irrigation in 'Golden Delicious' apple trees grown in a semi-arid environment. Personal communication. Campo Experimental Zacatecas-INIFAP. Zacatecas, Mexico.

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