



Fruit quality of 'Pacific Rose'TM apple grown under partial rootzone drying and deficit irrigation

Ben M. van Hooijdonk, Karma Dorji and M. Hossein Behboudian*

Horticultural Science Group, Institute of Natural Resources (INR 433), College of Sciences, Massey University, Palmerston North, New Zealand. *e-mail: M.Behboudian@massey.ac.nz

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Abstract

Water is limited world-wide and water saving irrigation practices are essential for crops, like apple, that are grown over wide acreages and within water limited regions. In a field experiment, we investigated plant water relations, yield and fruit quality of 'Pacific Rose'TM apple under the following irrigation treatments: commercially irrigated (CI) control, where soil was maintained near field capacity throughout the season; partial rootzone drying (PRD), where half of the irrigation volume of CI was applied to only one side of the rootzone; and no irrigation (NI), where water was withheld for the duration of the experiment. From 62 days after full bloom (DAFB), the volumetric soil water content of NI and the un-irrigated PRD side were significantly lower than CI and the irrigated PRD side. Leaf water potential of PRD was generally similar to CI throughout the season, whereas leaf water potential of NI was lower than CI from 123 DAFB. Fruit yield and quality at harvest were similar among the treatments. However, PRD and NI fruit were firmer and had less weight loss during postharvest storage. In addition to enhancement of fruit storage potential, water savings of 0.78 and 1.56 megalitres per hectare occurred for PRD and NI treatments, respectively. Both PRD and NI are suitable for humid environments similar to that of the experimental site, while PRD may also have potential to save water in arid climates.

Key words: Irrigation use efficiency, water relations, postharvest fruit quality.

Introduction

Global demand for water is going to increase due to rapid industrialisation and population growth^{3,28}. Increasing competition for water means that irrigation practices for food production must be efficient, especially because irrigated agriculture and horticulture presently use 75% of the world's total fresh water resource²⁹. Excessive use of irrigation for food production has led to environmental problems that include the degradation of fresh water quality through the leaching of biocides³. As a result, developed countries have introduced legislation to reduce the amount of water allocated for irrigation²⁵. Therefore, effective irrigation saving strategies are required to ensure crop yield and quality are not compromised.

Water saving strategies are important for apple because it is commonly grown in regions of the world where water resources are limited¹⁸. Deficit irrigation (DI) has been researched extensively in apple¹ and involves irrigating the entire rootzone with less water than prevailing evapotranspiration. DI was reported to improve fruit quality^{16, 22, 23}. However, DI may affect yield by reducing fruit size¹⁴. Partial rootzone drying (PRD) is a new irrigation saving strategy that involves applying water to one half of the rootzone at each irrigation time, while the other half is left to dry to a predetermined level of soil moisture. During PRD, soil drying is expected to stimulate root to leaf chemical signalling⁶ that reduces stomatal conductance¹¹ and transpiration⁹. Other benefits of PRD include the maintenance of plant water potential¹⁹, reduced shoot growth⁹ and decreased soil evaporation¹³. To date, PRD studies of perennial fruit crops have focused on

grape^{9, 19, 27}, pear¹³ and pot-grown apple¹¹. Caspari *et al.*⁴, Lombardini *et al.*¹⁷ and Einhorn and Caspari¹⁰ have published abstracts based on their PRD research in apple. However, information for apple concerning PRD effects on seasonal plant water relations and postharvest fruit quality does not exist to the best of our knowledge. The aim of this research was to compare commercial irrigation with PRD and with no irrigation for their effects on water relations, yield and postharvest fruit quality of field-grown 'Pacific Rose'TM apple.

Materials and Methods

The study was conducted in the 2002-2003 season at the Fruit Crops Unit, Massey University, Palmerston North (lat. 40°22'S, lon. 175°42'E), New Zealand. The experimental site is humid and temperate with an average annual rainfall of 960 mm. Seven-year-old 'Pacific Rose'TM apple trees (*Malus x domestica* Borkh.) grafted on MM.106 rootstock and trained as a central leader (4.5 m between rows and 2 m between the trees) were used. The experiment was a completely randomised design with four replicates. Each replicate contained three subplots (each consisting of two experimental trees) that were separated by a guard tree. To exclude rainfall, clear plastic covers (extending 1.7 m on each side of the row) were installed under the trees two months before full bloom which occurred on 14 October 2002.

The irrigation system consisted of two 20-mm alkathene lines (one per side of the row) placed 250 mm from the trunk on a bare herbicide strip. Plastic tap valves were positioned on the lines to

control irrigation in each subplot and side of the tree. Within each subplot, one micro-jet sprinkler covering 180° was positioned on each line between the two experimental trees. Irrigation treatments commenced on 7 DAFB and included a commercially irrigated (CI) control, where soil moisture was maintained near field capacity throughout the season; partial rootzone drying (PRD), where half of the irrigation volume of CI was applied to only one side of the rootzone at each irrigation; and no irrigation (NI), where water was withheld for the duration of the experiment while the soil covers were on (14 August 2002 to 5 May 2003). With the exception of irrigation, cultural practices were the same as other commercial orchards in New Zealand.

Volumetric soil water content was measured at weekly intervals to a depth of 500 mm using Time Domain Reflectometry (TDR) (Model 1502c; Tektronix, Redmond, USA). TDR probes were installed 500 mm from the trunk (between the experimental trees) on both sides of each subplot. Leaf water potential (LWP) was measured on two fully exposed leaves per tree using a Scholander pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, California, USA) within 30 seconds of leaf removal. Predawn and midday LWP were measured between 04:30 - 05:00 hours and 12:00 - 13:00 hours, respectively.

Fruit were hand thinned on 35 DAFB to adjust the crop load in each treatment to 6 fruit per cm² of trunk cross sectional area. Fruit were harvested on 183 (Harvest 1), 194 (Harvest 2) and 201 (Harvest 3) DAFB. They were colour-picked to commercial standards (66% red blush), and then counted, weighed and graded to determine colour development and yield. At each harvest, 5 fruit (each weighing 220–250 grams) per tree were randomly selected for quality assessment. Flesh firmness was measured to a depth of 7.9 mm using a press-mounted Effegi penetrometer (model FT 327, Alfonsine, Italy) with an 11.1 mm head. Total soluble solids were measured with an Atago refractometer (0–20% Brix; ATC-1, Atago, Tokyo). Starch pattern index was determined by dipping cross sectional fruit halves for 30 seconds into a solution of 20 grams of potassium iodide plus 5 grams of iodine in 2000 ml of water. Starch hydrolysis was ranked 0 (100% starch) to 6 (no starch) using an Export New Zealand Apple (ENZA) Starch Pattern Index Chart for apples. At Harvest 2, fruit dry matter concentration was determined from 50 grams of cortical tissue by drying at 71°C to a constant mass.

Fruit soluble sugars were measured in five fruit per treatment at Harvests 1 and 2. Five grams of cortical tissue were placed in 20 ml of 95% ethanol to inactivate invertase, thereby preventing the conversion of starch into soluble sugars. Samples were stored at –18°C for one month to allow precipitation of the cell component. After storage, a 1 ml aliquot of clear supernatant was taken from each sample and dried down using a concentrator (Model RH 40-11, Savant Instruments, Farmingdale, NY, USA). The remaining residue was dissolved in 3 ml of Barnstead nano-pure water and filtered through a 0.3 µm nylon membrane filter. Concentrations of sugars were determined from 15 µl samples using high performance liquid chromatography (Waters, Milford, MA, USA) with a carbohydrate analysis and deashing column (Aminex HPX87C, Life Science Group, Hercules, CA, USA) maintained at 85°C. The detector (Optilab 5922 RI Chromatography Module, Tekator AB, Högnäs, Sweden) temperature and flow rate were maintained at 40°C and 0.6 ml min⁻¹, respectively. A b-Ram software package was used to compute peak areas under the curves. The concentration

of each sugar sample was calibrated with individual sugar standards of known concentration. Results are presented as milligrams of sugar per gram of fruit fresh mass.

Aroma volatile concentrations were measured on five fruit per treatment at Harvest 2, and then again after storage at 0°C for 10 weeks. Aroma volatiles were extracted from 10 ml juice samples using 10 ml of diethyl ether: n-pentane (2:1 v:v) containing 10 ppm of n-decane and 10 ppm of octyl acetate as internal standards⁷. The samples were vortexed and then frozen at –18 °C for 3 days. The clear solvent phase was decanted and concentrated to 200 µl using an oxygen free N₂ gas stream. Aroma volatiles were analysed by injecting 1 µl samples into a gas liquid chromatograph (Hewlett-Packard 5890 Series II Plus, Hewlett-Packard Co., Avondale PA, USA) connected to an FID detector with a capillary column (0.32 mm i.d. x 30 m DB WAX, 0.5 µm film thickness). Column oven temperature was programmed at 40°C for 5 minutes, 120°C (increasing at 5°C per minute), 190°C (increasing at 20°C per minute) and 190°C for 2 minutes. Injector and detector temperatures were maintained at 150 and 250°C, respectively. The flow rate of the hydrogen carrier gas was 1.39 ml per minute set on constant flow mode at 29 kPa and 40°C. The flow rate of hydrogen and air for the detector were 30 and 400 ml per minute, respectively⁷. Quantification and identification of aroma volatiles within each sample was by comparison with the peak area and the retention time of known external standards made up in diethyl ether: n-pentane. Volatile concentrations, expressed as ppm of juice, were normalised for losses during extraction and on drying against decane and octyl acetate internal standards as described by Dixon⁷.

At Harvest 2, a total of 240 fruit per treatment (each fruit weighing 230–240 g) were randomly selected and divided into six groups (40 fruit per group). Fruit were stored at 0±0.5°C and changes in quality attributes were measured at fortnightly intervals over 10 weeks. At each measurement, one group of fruit was removed from cool storage and measured for firmness, total soluble solids and starch pattern index. Group 6 was used to measure weight loss during the entire storage period. Following storage, fruit from Group 6 were transferred to storage at 20°C (relative humidity 65%) to measure post-storage weight loss. Weight loss was calculated as the percentage of initial fruit fresh mass.

Data were analysed using the Proc GLM procedure of SAS software (Version 8.2, SAS Institute, Cary, N.C.). Mean comparisons were made using the LSD test at the 5% level of significance. Where appropriate, data were transformed and has been back transformed for presentation.

Results and Discussion

The irrigated PRD side had the same volumetric soil water content as CI throughout the growing season (Fig. 1). From 62 DAFB, volumetric soil water content of NI and the un-irrigated PRD side were significantly lower than CI and the irrigated PRD side. Yet, NI's predawn LWP values were not significantly different from those of CI until 123 DAFB (Fig. 2A). Clothier *et al.*⁵ reported that roots positioned deeper in the soil profile progressively contributed to more soil water extraction as the water supply at the soil surface was depleted. Because rainfall was excluded from the rootzone with soil covers in all treatments, a similar predawn LWP between NI and CI up until 123 DAFB was a probable result of NI roots using water from deeper in the soil profile beyond our

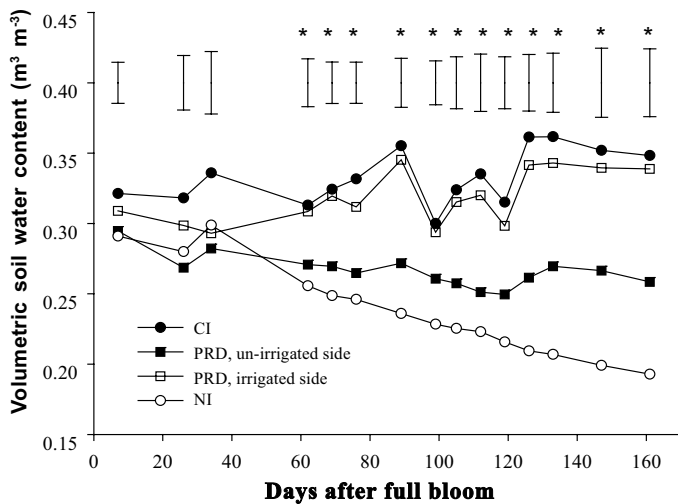


Figure 1. Changes in volumetric soil water content under CI, PRD, and NI. Vertical bars represent the LSD and asterisks denote significant differences at $P \leq 0.05$.

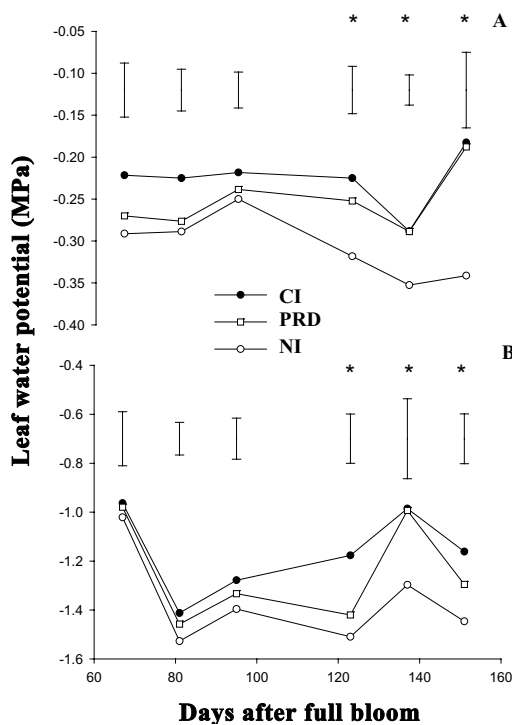


Figure 2. Seasonal predawn (A) and midday (B) leaf water potentials under CI, PRD, and NI. Vertical bars represent the LSD and asterisks denote significant differences at $P \leq 0.05$.

TDR probes. However, from 123 DAFB, midday LWP in NI trees was significantly reduced, whereas that of PRD was mostly similar to CI throughout the season (Fig. 2B). There were no significant differences in predawn LWP between PRD and CI trees throughout the season (Fig. 2A). Studying the root sap flow in ‘Braeburn’ apple, Green *et al.*¹² reported that water uptake from the wetted root increased by two fold and compensated for the reduced uptake by roots located in dry soil. Therefore, the maintenance of predawn LWP by PRD trees could be attributed to the ability of roots to absorb water at higher rates from wetted soil areas.

Irrigation use efficiency, defined as the gross yield per tree (grams)

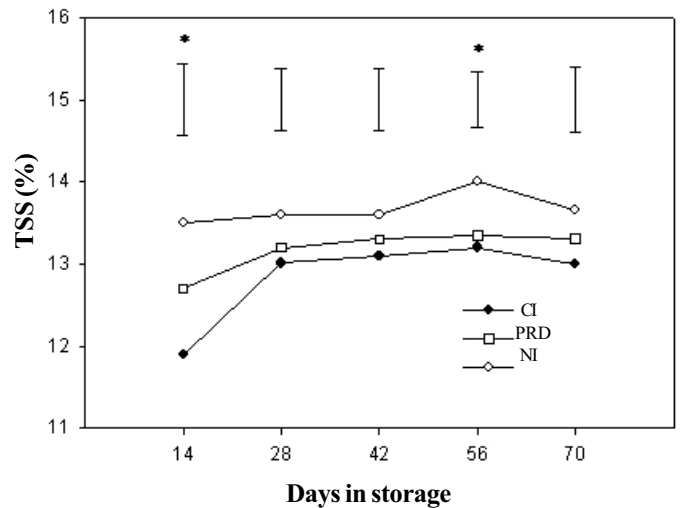


Figure 3. Changes in total soluble solids under CI, PRD, and NI for fruit stored at $0 \pm 0.5^\circ\text{C}$ for 10 weeks. Vertical bars represent the LSD and asterisks denote significant differences at $P \leq 0.05$.

divided by the total volume of irrigation water applied per tree (litres), was significantly improved ($P \leq 0.05$) over the growing season by PRD compared to CI (Table 1). Final values ($\text{g/L H}_2\text{O}$) were 91 and 47 for PRD and CI, respectively. In contrast, NI saved 100% irrigation water compared to CI. At a density of 1111 trees per hectare, seasonal water savings for PRD and NI were approximately 0.78 and 1.56 megalitres of water per hectare, respectively.

The adjustment of crop load to 6 fruit per cm^2 of trunk cross sectional area and a similar mean fruit mass meant that gross yield per tree did not significantly differ among the treatments at harvest (Table 1). Despite significant water savings by NI and PRD, fruit quality at harvest was similar to CI (Table 1). Total fruit sugar composition was not significantly different among treatments, although NI fruit had greater ($P \leq 0.05$) fructose than CI and PRD at Harvest 2 (Table 2). Simple reducing sugars such as fructose contribute to fruit flavour³⁰ and are reported to increase^{15,23} or remain unchanged²¹ at harvest under reduced irrigation. Kilili *et al.*¹⁵ and Mpelasoka *et al.*²³ reported that deficit irrigation significantly improved fruit sugars of ‘Braeburn’ apple. Midday LWP in their studies ranged from -2.0 to -2.5 MPa, which is much lower than the -1.5 MPa measured in our experiment (Fig. 2B). Similarity in fruit quality at harvest among the treatments suggests that quality changes may depend on the degree of water deficit experienced during fruit growth and development¹.

Alcohols, aldehydes and esters are the major group of volatile compounds considered important for apple flavour. The biogenesis of fruit volatiles involves complex pathways that depend on the availability of precursors, temperature and metabolic enzymes⁸. Increased production of volatile compounds coincides with an increase in internal fruit ethylene production²⁶. During storage, total concentrations of fruit volatiles increased by two fold in all treatments (Table 3). Behboudian *et al.*² reported a similar increase in fruit volatile production after storage, which coincided with a rise in fruit ethylene production. No statistical differences in total volatile concentrations were detected among the treatments at harvest or after 10 weeks of cool storage (Table 3). Concentrations of individual compounds including methyl hexanoate and 2-methyl butyl acetate were significantly

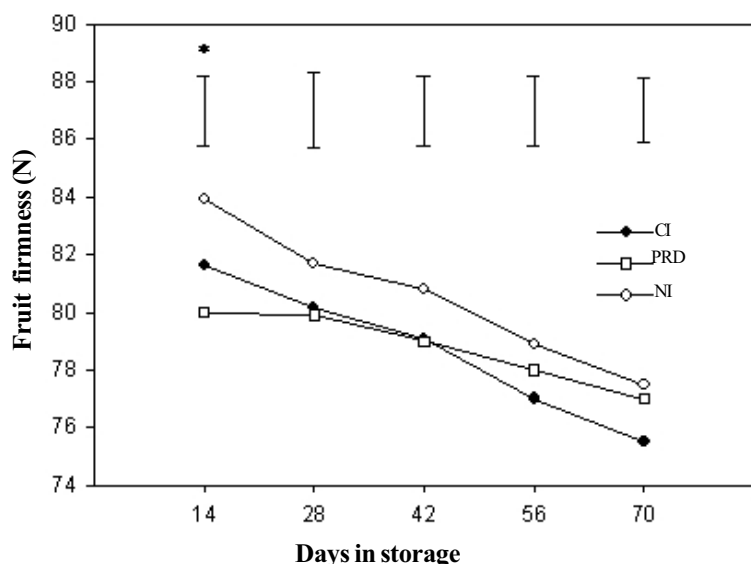


Figure 4. Changes in flesh firmness under CI, PRD, and NI for fruit stored at $0\pm 0.5^{\circ}\text{C}$ for 10 weeks. Vertical bars represent the LSD and asterisks denote significant differences at $P \leq 0.05$.

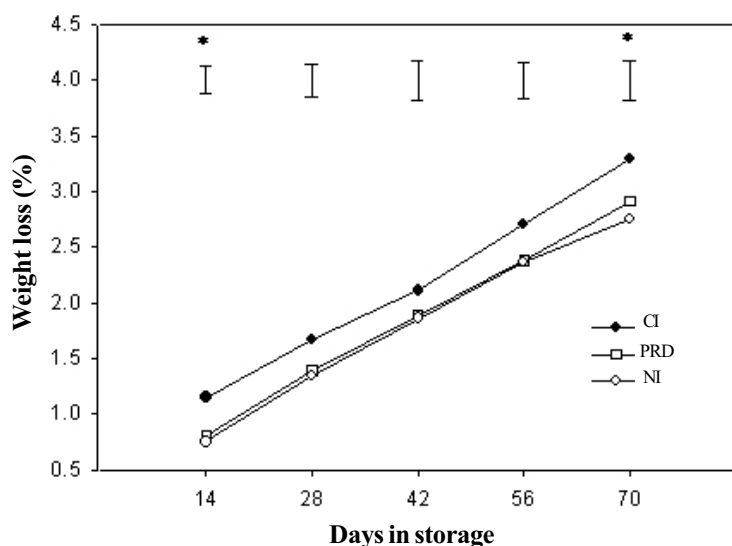


Figure 5. Cumulative weight loss (% of initial fruit fresh mass) under CI, PRD, and NI for fruit stored at $0\pm 0.5^{\circ}\text{C}$ for 10 weeks. Vertical bars represent LSD and asterisks denote significant differences at $P \leq 0.05$.

lower ($P \leq 0.05$) for CI and PRD fruit than NI fruit at Harvest 2 (Table 3). However, after 10 weeks in cool storage, PRD and NI fruit contained greater ($P \leq 0.05$) concentrations of 2-methyl butyl acetate than CI fruit, whereas methyl and ethyl hexanoate concentrations were significantly lower in PRD fruit compared to both CI and NI. Butyl acetate was absent at Harvest 2, but appeared after storage with significantly greater ($P \leq 0.05$) concentrations occurring in NI fruit. NI fruit also had higher T, 2-hexenal concentrations than PRD fruit after storage. Short chain alcohol compounds (butanol and pentanol) were not detected after storage. Volatiles such as T-2-hexenal are reported to be important for aroma intensity²⁴, whereas the ester 2-methyl butyl acetate is reported to be characteristic of red skinned cultivars³¹. Overall, these results indicate that reduced irrigation maintains total fruit volatiles and sometimes may improve the concentration of

individual compounds. Further research using taste panels would be needed to determine if the observed compositional changes are reflected in fruit flavour.

Values of fruit total soluble solids during storage were highest for NI, intermediate for PRD, and lowest for CI (Fig. 3). This is similar to the trend observed at fruit harvest (Table 1). TSS values for NI were significantly higher than CI fruit on days 14 and 56 (Fig. 3). No statistical differences in fruit starch pattern index occurred at harvest or throughout storage. There was, however, a strong trend that greater starch hydrolysis in NI and PRD fruit was responsible for higher TSS values. For example, mean fruit starch pattern index after storage was 5.6, 5.3, and 5.1 for NI, PRD and CI, respectively. Fruit firmness in all treatments decreased during cool storage with NI fruit retaining more firmness than PRD and CI throughout most of the storage period (Fig. 4). Despite differences being very small, on day 14 PRD fruit were softer ($P \leq 0.05$) than NI fruit. However, by day 70 fruit firmness in these treatments did not differ, whereas there was a trend that CI fruit had begun to soften at a greater rate (Fig. 4). Subsequently, during storage at 20°C , NI and PRD fruit were significantly firmer ($P \leq 0.05$) than CI fruit. These differences, however, were relatively small (77.6, 77.0 and 75.5 Newtons, respectively). Improved firmness during cool storage was also reported for deficit-irrigated 'Braeburn' apple² and has important implications for producers exporting to distant markets, especially because fruit firmness contributes to postharvest shelf life and eating quality.

Throughout storage, NI and PRD exhibited less weight loss compared to CI fruit with significant differences occurring on days 14, 28, and 70 (Fig. 5). Differences in weight loss could be related to skin permeance to water vapour²⁰ due to changes in cuticular properties induced under reduced irrigation^{16,23}. Cuticular cracks, the open calyx, and skin lenticels are the major routes by which fruit lose water to the atmosphere during cool storage²⁰. Fruit water loss is a major cause of product weight loss and is detrimental to fruit quality because it can cause fruit shrivel that affects fruit marketability. Given the commercial importance of reducing fruit weight loss, further investigation into the physico-chemical changes in cuticle composition is needed to explain the observed behaviour of PRD and NI fruit during storage.

Conclusions

Reduced irrigation saved water and improved aspects of postharvest fruit quality. The benefits included an increase in some individual fruit aroma volatiles, less fruit weight loss, and a slower loss of fruit firmness during storage. Although PRD reduced water applied by 50%, it did not adversely alter seasonal LWP, fruit quality and yield at harvest. PRD could be used in preference to CI to improve irrigation efficiency, maintain fruit quality at harvest, and improve postharvest fruit storage potential. No irrigation, especially under similar climatic conditions to ours, is highly effective in saving water. Commercial irrigation regimes could use NI to strategically withhold water and PRD as an efficient application method to replenish soil water as required, thereby preventing the development of severe plant water stress.

Table 1. Effects of irrigation treatment on yield, irrigation use efficiency, and fruit quality of ‘Pacific Rose’TM apple at harvest. Means within columns sharing the same letter are not significantly different at $P \leq 0.05$ using the LSD test.

Treatment	Yield (kg tree ⁻¹)	IUE/tree (g l ⁻¹ H ₂ O)	MFM (g fruit ⁻¹)	CF (%)	TSS (% Brix)	FF (Newtons)	SPI	FDC (mg g ⁻¹)
CI	65.5a	47a	220a	85.7a	11.5a	81.6a	2.9a	129.7a
PRD	63.7a	91b	220a	84.5a	11.8a	81.5a	2.9a	135.1a
NI	57.1a	NA	220a	76.5a	12.0a	82.4a	2.7a	140.3a

IUE: irrigation use efficiency; MFM: mean fruit mass; CF %: colouration of fruit (defined as the number of fruit (with a minimum of 66% red blush) per tree divided by total number of fruit per tree); TSS: total soluble solids; FF: flesh firmness; SPI: starch pattern index, (FDC): fruit dry matter concentration.

Table 2. Fruit sugar concentration under CI, PRD, and NI. Means within columns sharing the same letter are not significantly different at $P \leq 0.05$ using the LSD test.

Treatments	Soluble sugars (mg g ⁻¹ fresh mass)				
	Glucose	Fructose	Sucrose	Sorbitol	Total sugars
<i>Harvest 2</i>					
CI	6.6a	47.3b	22.7a	0.5a	77.1a
PRD	6.7a	49.7ab	25.3a	0.7a	82.4a
NI	7.5a	54.0a	25.0a	0.8a	87.3a
<i>Harvest 3</i>					
CI	7.9a	67.3a	31.6a	1.6a	108.4a
PRD	9.8a	67.5a	32.7a	1.8a	111.8a
NI	8.5a	71.8a	34.3a	2.1a	116.7a

Table 3. Concentrations of fruit aroma volatiles (μmole l⁻¹) under CI, PRD, and NI. Volatiles were analysed at Harvest 2 and after 10 weeks of storage at 0±0.5°C. Across the row, means sharing the same letter are not significantly different at $P \leq 0.05$ using the LSD test.

Volatile	At harvest			After storage		
	CI	PRD	NI	CI	PRD	NI
<i>Alcohols</i>						
Butan-1-ol	460.8a	655.1a	513.6a	ND	ND	ND
Pentan-1-ol	134.4a	95.1a	306.9a	ND	ND	ND
Hexan-1-ol	63.4a	41.9a	111.0a	297.4a	272.6a	330.4a
2,3, Methyl butan-1-ol	438.3a	523.5a	466.3a	110.0a	253.6a	279.4a
<i>Aldehydes</i>						
Hexenal	180.0a	ND	205.0a	145.2a	162.0a	183.0a
T,2-Hexenal	301.4a	382.8a	338.9a	280.0ab	137.4b	513.4a
<i>Esters</i>						
Ethyl butanoate	362.0a	578.5a	1052.8a	127.2a	211.4a	158.0a
Ethyl pentanoate	386.7a	299.7a	332.2a	4670.0a	6713.0a	5425.0a
Ethyl hexanoate	ND	ND	ND	83.0a	73.0b	102.2a
Ethyl-3-hydroxy hexanoates	ND	ND	ND	828.1a	951.1a	871.8a
<i>Acetates</i>						
Butyl acetate	ND	ND	ND	973.5b	712.5b	1824.3a
Hexyl acetate	1.7a	8.3a	23.6a	67.8a	84.4a	144.1a
2-Methyl butyl acetate	8.5b	3.4b	69.5a	1388.7b	2028.9a	1939.0a
Methyl hexanoate	21.5b	20.1b	86.7a	881.6a	400.1b	711.0a

ND: not detected due to low concentration (< 0.1 μmole l⁻¹).

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