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Responses of 'Pacific Rose'™ Apple to Partial Rootzone Drying and to Deficit Irrigation

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Summary

Water resources for irrigation are becoming increasingly limited, therefore, reducing irrigation is a sensible strategy to save water and possibly improve fruit quality in apple production. We investigated plant water relations, growth, yield, and fruit quality of 'Pacific Rose'™ apple subjected to 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. Volumetric soil water content of NI and the un-irrigated PRD side were significantly lower than CI and the irrigated PRD side from 62 days after full bloom (DAFB). Leaf water potential (ψ) of PRD was similar to CI on most occasions, whereas ψ of NI was generally lower than CI from 95 DAFB. Neither irrigation treatment significantly affected shoot growth, fruit growth, photosynthesis, and stomatal conductance. However, NI leaves discriminated significantly less against $^{13}CO_2$ late in the season. At harvest, PRD and NI had saved 0.78 and 1.56 megalitres of water per hectare compared to CI, respectively, and did not significantly reduce fruit quality or yield.

Zusammenfassung

Reaktionen von Äpfeln der Sorte 'Pacific Rose'™ auf partielle Wurzelzonentrockenheit und Mangelbewässerung. Weil die Wasservorräte immer begrenzter sind, ist die Reduzierung der Bewässerung eine vernünftige Methode, um Wasser zu sparen und dabei möglicherweise die Qualität der produzierten Äpfeln zu erhöhen. Wir untersuchten die Pflanze-Wasser-Beziehungen, das Wachstum, die Erntemenge und Fruchtqualität von Äpfeln der Sorte 'Pacific Rose'™, die hinsichtlich der Bewässerung wie folgt behandelt wurden: (i) die im Erwerbsanbau übliche Bewässerung (CI) als Kontrolle, hierbei wurde die Erde über die ganze Saison nahe der Feldkapazität gehalten, (ii) partielle Wurzelzonentrockenheit (PRD), hierbei wurde die Hälfte der CI-Menge auf nur einer Seite der Wurzelscheibe ausgebracht sowie (iii) keine Bewässerung (NI), hierbei wurde während des Versuchs kein zusätzliches Wasser gegeben. Die Volumeterwerte des Wassergehalts der NI-Variante und der nichtbewässerten Seite der PRD-Variante waren ab 62 Tage nach Vollblüte (DAFB) signifikant niedriger als die der CI-Variante und der bewässerten Seite der PRD-Variante. Das Blattwasserpotential (ψ) der PRD-Variante war fast gleich, das ψ der NI-Variante ab dem 95 DAFB im Allgemeinen geringer als das von CI. Keine der Bewässerungsvarianten hatte deutlichen Einfluss auf das Spross- und Fruchtwachstum, die Photosynthese oder die stomatäre Leitfähigkeit. Allerdings unterschieden NI-Blätter zum Saisonende hin weniger deutlich bezüglich $^{13}CO_2$. Zum Zeitpunkt der Ernte hatten PRD und NI 780 bzw. 1560 m^3 Wasser pro Hektar im Vergleich zu CI gespart, ohne dass signifikante Unterschiede bei der Fruchtqualität und Erntemenge auftraten.

Key words. Fruit quality – irrigation use efficiency – plant water relations

Introduction

Irrigated agriculture and horticulture use 75 % of the world's total fresh water resource (WALLACE and GREGORY 2002). This has created a crisis because fresh water is also required by non-agricultural industries and for domestic use. Domestic demand for fresh water will increase as the world's population doubles by 2050 (BOUWER 2000). Rapid population growth could result in water shortages for 66 % of the world's population (WALLACE and GREGORY 2002). To tackle this crisis, irrigation has to be efficiently managed.

Water saving strategies are particularly important for apple production as it commonly occurs in regions of the world where water resources are limited (LOTTER et al. 1985). Deficit irrigation (DI) has been widely researched and it involves irrigating the entire rootzone with less water than prevailing evapotranspiration. For apple, DI was reported to save water (MPELASOKA et al. 2001a), increase fruit total soluble solids (KILILI et al.

1996), firmness (MPELASOKA et al. 2001b), and skin colour at harvest (KILILI et al. 1996).

Partial rootzone drying (PRD) is a new water saving strategy that could also be suited to apple production (LOVEYS et al. 2000). PRD 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 signalling that reduces stomatal conductance (g_s) (GOWING et al. 1990) and transpiration (DRY and LOVEYS 1999). Other benefits of PRD include the maintenance of plant water potential (ψ) (LOVEYS et al. 2000), reduced shoot growth (DRY and LOVEYS 1999), and decreased soil evaporation (KANG et al. 2003). To date, PRD studies of perennial fruit crops have focused on grape (DRY and LOVEYS 1999; LOVEYS et al. 2000; STOLL et al. 2000), pear (KANG et al. 2002), and pot-grown apple (GOWING et al. 1990). CASPARI et al. (2002), LOMBARDINI et al. (2002), and EINHORN and CASPARI (2003) have published abstracts based on their PRD research in apple. Information on the suitability of PRD as a water saving strategy for field-grown apple is therefore scant. The aim of this research was to compare commercial irrigation with PRD and with no irrigation for their effects on irrigation use efficiency, water relations, growth, yield, and fruit quality of field-grown 'Pacific Rose'™ apple.

Materials and Methods

The experiment was conducted during the 2002–2003 growing season at the Fruit Crops Unit, Massey University, Palmerston North (lat. 40.2 ºS, long. 175.4 ºE), New Zealand. The climate of the region is temperate and humid with an average annual rainfall of 960 mm. The Manawatu fine sandy loam was the predominant soil type. This soil has an upper profile of 500 mm of fine sandy loam, underlain by 400 mm of fine sand, with gravely coarse sand below 900 mm. Seven-year-old 'Pacific Rose'™ apple trees 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 metres on each side of the row) were installed under the trees two months before full bloom, which occurred on 14 October 2002.

Volumetric soil water content (θ) 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. 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 º 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).

Leaf water potential (ψ) was assessed on two mature exposed leaves per tree (1 per side) within the following intervals: 04:30–05:30 hours (predawn), 12:00–13:00 hours (midday), and 17:00–18:00 hours (dusk). All measurements were conducted using a Scholander pressure chamber (Soilmoisture Equipment Corp. Santa Barbara, California, USA) within 30 seconds of leaf removal. Four measurements of stomatal conductance (g_s, mol m^{-2} s^{-1}) and photosynthetic rate (µmol m^{-2} s^{-1}) were taken over the growing season using a Li-Cor system (LI-6200, Li-Cor Inc., Nebraska, USA). Measurements were taken on sunny days between 1200–1400 hours on two well-lit leaves per tree.

Ten fully exposed leaves per tree (5 per side) were sampled on 135 DAFB and 165 DAFB for the measurement of discrimination against $^{13}CO_2$. Leaf samples were oven dried and ground to a fine powder (<200 µm). Carbon isotope analysis was carried out at the Waikato Stable Isotope Unit, University of Waikato, New Zealand. Isotopic abundance analysis was measured using a Europa Scientific 20/20 isotope analyser. Gases were separated by gas chromatography and analysed by mass spectrometry. Organic matter is often depleted in ^{13}C relative to the standard against which it is compared. Values (Table 1) are, therefore, negative as $\delta^{13}C = ((R_{sample}/R_{standard}) - 1) \times 1000$, where R is the ratio of ^{13}C:^{12}C. $R_{standard}$ is for Pee Dee belemnite (FARQUHAR et al. 1982). A less negative figure represents less discrimination against $^{13}CO_2$ during photosynthesis.

Table 1. Carbon isotope discrimination of 'Pacific Rose'™ apple leaves grown under commercial irrigation (CI), partial rootzone drying (PRD), and no irrigation (NI). Means within columns sharing the same letter are not significantly different at P≤0.05 using the LSD test.

Treatment	A $\delta^{13}C$ at 135 DAFB (‰)	B $\delta^{13}C$ at 165 DAFB (‰)	B – A Gain of $\delta^{13}C$ (‰)
CI	–27.40a	–27.45a	–0.05a
PRD	–27.34a	–27.17a	0.17a
NI	–27.63a	–27.36a	0.27b

To measure shoot growth, four uniform shoots per tree were tagged and measured at weekly intervals commencing on 14 DAFB. On 60 DAFB, crop load was adjusted in all treatments to 6 fruit per cm^2 of trunk cross sectional area. Four fruit per tree of uniform size (2 per side) were tagged and their diameter was measured across the widest point at weekly intervals using digital callipers (model CD-6, Mitutoyo Corporation, Japan).

The first harvest commenced on 183 DAFB followed by two more at weekly intervals. Fruit 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 between 220–250 grams) per tree were randomly selected for quality assessment. Fruit colour intensity was measured using a portable Tristimulus Chromameter (CR-200, Minolta,Osaka, Japan) after calibration with a standard green plate (CR-A47 G). Measurements of fruit colour intensity were taken from opposing sides of each fruit. 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). To determine fruit dry matter concentration, 50 grams of flesh tissue were oven dried at 71 °C. Dried samples were weighed and converted to units of milligrams of dry mass per gram of fresh mass. 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.

Data for $\delta^{13}C$, shoot growth, starch pattern index, and colouration of fruit were square root transformed and are reported after back transforming. Statistical analysis was performed using the GLM procedure of SAS software (Version 8.2, SAS institute, Cary, NC, USA). Treatment means were separated by the LSD test at $P \leq 0.05$.

Results

The irrigated PRD side (Side 1) had the same θ as CI throughout the growing season (Fig. 1). From 62 DAFB, θ of NI and the un-irrigated PRD side (Side 2) were significantly lower than CI and Side 1. No significant differences in predawn ψ were detected between the treatments from 67 to 95 DAFB, although ψ of PRD and NI were always more negative than CI during this period (Fig. 2A). From 137 to 151 DAFB, predawn ψ of PRD was identical to CI despite having received 50 % less irrigation water. In contrast, predawn ψ of NI decreased from 95 DAFB and was significantly lower than CI and PRD at all measurements thereafter. Midday ψ throughout the season was always higher for CI than NI and differences were significant on 123 DAFB and 151 DAFB (Fig. 2B). The lowest midday leaf ψ recorded for NI was –1.5 MPa on 81 DAFB and on 123 DAFB. With the exception of an overcast day on 137 DAFB, values of midday ψ for PRD fell between that of CI and NI. Midday ψ of PRD was significantly lower than CI on 123 DAFB because ψ decreased at a similar rate to NI during the morning. However, on the same day, ψ of PRD recovered at a greater rate than NI and CI during the afternoon and was not significantly different to CI by dusk. Similar to predawn results, ψ at dusk was lower for NI than CI with significant differences occurring on 123, 137, and 151 DAFB (Fig. 2C). Values of ψ for PRD at dusk were generally closer to CI than to NI. The exception was on 151 DAFB when ψ of PRD was not significantly different to NI, primarily because ψ failed to recover at a similar rate to CI during the afternoon. In summary, despite periodical fluctuations, θ of CI and PRD (Side 1) were similar to each other but higher than those of

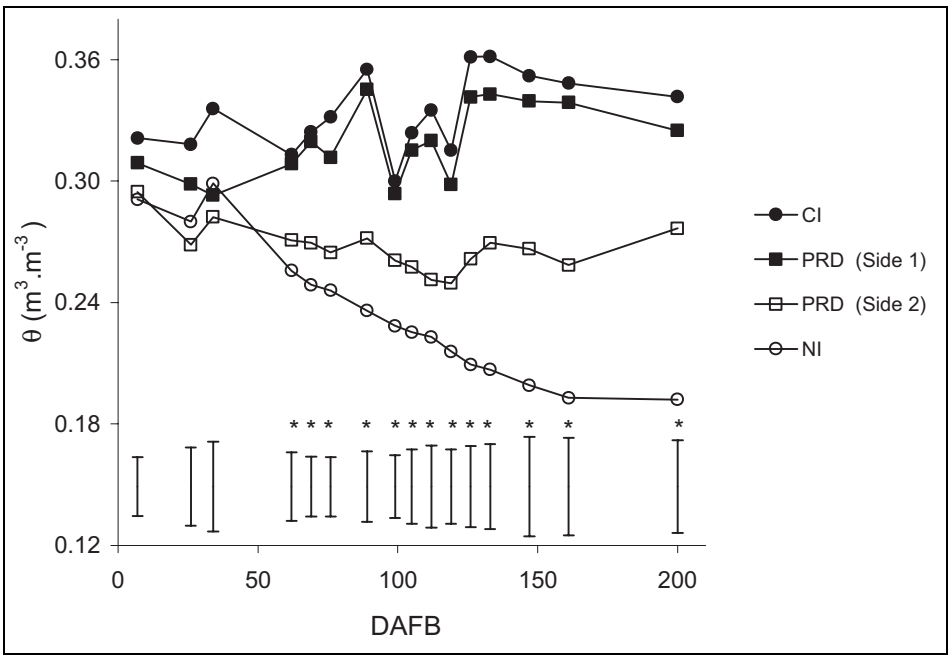


Fig. 1. Changes in volumetric soil water content (θ) over the growing season for 'Pacific Rose™' apple grown under commercial irrigation (CI), partial rootzone drying (PRD), and no irrigation (NI). (PRD Side 1 = irrigation, PRD Side 2 = no irrigation). Vertical bars represent the LSD at $P \leq 0.05$. Asterisks represent significant differences at $P \leq 0.05$.

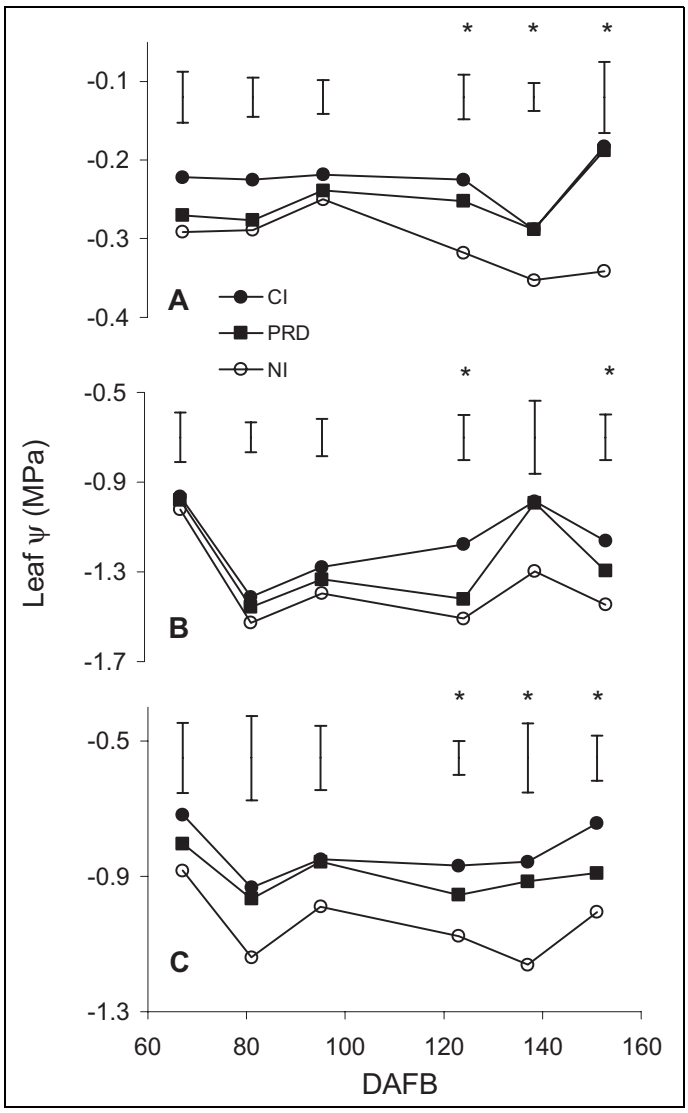


Fig. 2. Changes in seasonal leaf water potential (ψ) at predawn (A), midday (B), and dusk (C) for 'Pacific Rose'™ apple grown under commercial irrigation (CI), partial rootzone drying (PRD), and no irrigation (NI). Vertical bars represent the LSD. Asterisks represent significant differences at P≤0.05.

NI and the un-irrigated PRD side (Side 2). In the same way, ψ of PRD was generally similar to CI but higher than NI on most occasions throughout the season.

Four measurements of photosynthesis and g_s were conducted between 143 and 163 DAFB and there were no significant differences among the treatments. For example, the photosynthetic rates (μmol/m^{-2} s^{-1}) for CI, PRD, and NI on 151 DAFB were 15.8, 15.0, and 15.2, respectively. The corresponding values of g_s (μmol m^{-2} s^{-1}) were 0.29, 0.28, and 0.28.

Leaf discrimination against $^{13}CO_2$ was not significantly different among the treatments at individual sampling dates on 135 and 165 DAFB (Table 1). However, there was a significant increase in $\delta^{13}C$ for NI leaves between 135 and 165 DAFB that was not recorded for CI and PRD.

Mean shoot length at the cessation of growth (84 DAFB) did not differ (P≤0.05) despite the cumulative growth rate of NI slowing after 42 DAFB (data not shown). The mean values of final shoot length (mm) were 300, 280, and 269 for CI, PRD, and NI respectively. PRD and NI also did not affect cumulative fruit growth throughout the season (data not shown). This resulted in an identical fruit size among the treatments at harvest in terms of mean fruit mass (Table 2). Mean fruit numbers per tree were also similar at harvest because crop load was adjusted to 6 fruit per trunk cross sectional area on 60 DAFB. A similar mean fruit mass among the treatments resulted in no differences in gross yield at harvest. However, PRD improved irrigation use efficiency by 44 % relative to CI, primarily because 50 % less irrigation water was applied in the former treatment. In contrast, withholding irrigation water from NI throughout the season saved 100 % irrigation water compared to CI and did not reduce fruit size or gross yield. 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.

At harvest, no significant differences were found in fruit quality (Table 3). There were, however, consistent trends for some quality parameters. At each harvest fruit firmness and total soluble solids were always highest for NI fruit, whereas values for PRD fruit were always intermediate between that of NI and CI. CI had lower fruit dry matter concentration and higher fruit

Table 2. Fruit number (FN) per tree, mean fruit mass (MFM), gross yield, and irrigation use efficiency (IUE) of 'Pacific Rose'™ apple trees grown under commercial irrigation (CI), partial rootzone drying (PRD), and no irrigation (NI). IUE is defined as the gross yield per tree divided by the total volume of irrigation water applied per tree. Means within columns sharing the same letter are not significantly different at P≤0.05 using the LSD test.

Treatment	FN	MFM (g/fruit)	Gross yield (kg/tree)	IUE/tree (g/L H_20)
CI	297a	220a	65.5a	47a
PRD	290a	220a	63.7a	91b
NI	259a	220a	57.1a	NA

Table 3. Effects of commercial irrigation (CI), partial rootzone drying (PRD), and no irrigation (NI) on colouration of fruit (CF %), fruit colour intensity (FCI), total soluble solids (TSS), flesh firmness (FF), starch pattern index (SPI), fruit dry matter concentration (FDC), and fruit water content (FWC) of 'Pacific Rose'™ apple at harvest. CF % is defined as the number of red coloured fruit per tree divided by total number of fruit per tree. Means within columns sharing the same letter are not significantly different at P≤0.05 using the LSD test.

Treatment	CF (%)	FCI (Hue)	TSS (% Brix)	FF (Newtons)	SPI	FDC (mg g^{-1})	FWC (%)
CI	85.7a	30.0a	11.5a	81.6a	2.9a	129.7a	87.0a
PRD	84.5a	28.6a	11.8a	81.5a	2.9a	135.1a	86.5a
NI	76.5a	31.3a	12.0a	82.4a	2.7a	140.3a	86.0a

water content than NI at P<0.06. Although not statistically significant, NI fruit tended to have a lower fruit colour intensity over the skin surface that resulted in 8–9 % less coloured fruit than CI and PRD treatments.

Discussion

Unlike for NI, θ in the un-irrigated side of PRD tended to stabilise rather than continue to decrease from 120 DAFB (Fig. 1). This stabilisation may have involved one or more processes. Firstly, a degree of lateral soil water movement from Side 1 to Side 2 of the rootzone could have occurred. However, this was unlikely to be the major reason because this soil type is relatively free draining, therefore a great deal of lateral water movement would not be expected. STOLL et al. (2000) reported that wet roots subjected to PRD could redistribute water to roots located within the dry soil during the night. ZEGBE-DOMINGUEZ (2003) also found that tomato roots in the irrigated part of the rootzone could act as a source of water to those in the un-irrigated part of the rootzone. In our experiment, the stabilisation of θ in Side 2 may have involved redistribution of water from the wet roots of Side 1 to the dry roots of Side 2. A lowering gradient of water potential between the roots and the soil of Side 2 may have then facilitated water movement out of the roots and into the soil. It is also possible that the water requirement of PRD trees was met by absorption from Side 1, obviating the more difficult absorption from Side 2 after a low level of θ was reached.

Despite a significantly lower θ for NI from 62 DAFB, predawn values of ψ were not significantly different from CI until 123 DAFB (Fig. 2). CLOTHIER et al. (1990) 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 ψ between NI and CI up until 95 DAFB was a probable result of NI roots utilising water from deeper in the soil profile beyond our TDR probes. Unlike for NI, predawn ψ in PRD did not significantly change throughout the season and values were identical to CI from 137 to 151 DAFB. This coincided with a time of the season when the lowest values of ψ were expected because fruit would become competitive for leaf water due to increasing sugar levels that lower fruit ψ (MILLS et al. 1996). Similar values of predawn ψ for CI and PRD indicate that PRD did not affect ψ recovery during the night. ψ of PRD also recovered at a greater rate than CI and NI during the afternoon on 123 DAFB. Recovery of ψ for PRD during these times could have been aided by improved root extraction and transfer of soil water. For example, apple trees responded to partial wetting of rootzone by increasing water uptake in the wet part of the rootzone by approximately two fold (GREEN and CLOTHIER 1999). Furthermore, water transfer from localised areas of irrigation occurred at much higher rates than when the entire rootzone was irrigated (GREEN et al. 1997). On 123 and 151 DAFB, ψ of PRD was significantly lower than CI at midday and dusk, respectively. These results do not fully support short-term studies in which PRD maintained ψ compared to fully watered controls for both grape (LOVEYS et al. 2000; STOLL et al. 2000) and potted apple (GOWING et al. 1990). ψ of field-grown apple over an entire growing season was likely to be affected by normal fluctuations of soil water that occurs in between irrigation events, combined with changing metrological conditions affecting evaporative demand (HSIAO 1990). However, generally ψ of PRD appeared to be similar to CI throughout most of the season.

Photosynthesis of apple trees can decrease when ψ approaches a critical range of –1.8 to –2.5 MPa (MILLS et al. 1996; MPELASOKA et al. 2001b). Photosynthesis was not affected in this experiment because NI only reached a ψ of –1.5 MPa. For PRD, STOLL et al. (2000) reported that the leaves of grape reduced their g_s and maintained photosynthesis. This was not observed in our experiment because PRD did not significantly reduce g_s or photosynthesis compared to CI late in the season.

Effects of irrigation treatments on photosynthesis and g_s can be masked by environmental factors at the time of measurement (BEHBOUDIAN et al. 1994). In Palmerston North, this can include daily fluctuations in irradiance and VPD due to cloud cover. We measured isotope discrimination because it is an integrated measure of internal, physiological, and environmental parameters affecting photosynthesis throughout the season (EHLERINGER et al. 1993). It involves measuring the quantity of natural isotopes within leaf tissue. During photosynthesis, C_3 plants naturally discriminate against atmospheric $^{13}CO_2$ because of slower diffusion rates into the leaf, as well as slower rates of fixation by ribose bisphosphate carboxylase in comparison to the lighter isotope $^{12}CO_2$ (KRAMER and BOYER 1995). Leaf cells, therefore, accumulate less $^{13}CO_2$ than $^{12}CO_2$, and unused $^{13}CO_2$ diffuses out of the leaf according to stomatal aperture (KRAMER and BOYER 1995). Water stressed plants, however, show reduced discrimination against $^{13}CO_2$ because of less diffusion out of their leaves due to reduced g_s. Consequently, water stressed plants fix more $^{13}CO_2$ relative to non-stressed plants.

Our data showed that PRD leaves discriminated against $^{13}CO_2$ at a similar level to that of CI leaves between 135 to 165 DAFB (Table 1). Results of isotope discrimination could also indicate that PRD did not significantly reduce g_s because a reduction in g_s would have decreased $^{13}CO_2$ movement out of the leaf, thereby increasing the fixation of $^{13}CO_2$ relative to $^{12}CO_2$. Less discrimination against $^{13}CO_2$ for NI leaves could indicate a reduction in g_s, and therefore, improved water use efficiency as explained by KRAMER and BOYER (1995). The same conclusion could not be drawn for PRD because discrimination against $^{13}CO_2$ was not statistically different to that of CI during the same period.

The maintenance of g_s for PRD leaves could be related to factors including the aerial environment and the use of a fixed PRD irrigation protocol. For example, LOVEYS et al. (2000) reported that root ABA production and reduced g_s were transient when PRD was not alternated between sides of the rootzone in grape. Notably, their PRD treatment used for grape was similar to our PRD treatment applied to apple. DAVIES et al. (2002) also reported that the ability of root-derived chemical signals to reduce g_s might be dependent on the rate of transport to the leaf as influenced by evaporative demand. Under low evaporative demand, slower rates of signal transport may enable metabolic and sequestering processes to maintain signals at low concentrations within the leaf (DAVIES et al. 2002). Although speculative, this may explain why g_s was not affected by PRD in the humid climate of Palmerston North. Given the limitations of our data, further research is required to clarify whether PRD effects on g_s within the field are influenced by the use of a fixed PRD irrigation strategy and by site evaporative demand. Results of EINHORN and CASPARI (2003) suggest that PRD effects on g_s are also masked under conditions of high evaporative demand. They applied the following irrigation treatments to 'Gala' apple: well-watered control, deficit irrigation receiving 50 % of control volume, and three PRD treatments receiving 25 %, 50 %, and 75 % of control volume. g_s was low in all treatments and the authors attributed it to high vapour pressure deficit rather than to soil and plant water status. Plant water status in their experiment remained high for all treatments because of low g_s.

GOWING et al. (1990) reported that PRD promoted root to leaf chemical signalling that reduced vegetative growth of potted apple. In the field we found that PRD did not cause a significant reduction in fruit or shoot growth. There was, however, a strong trend that PRD and NI shoots were shorter when shoot growth had ceased. For DI, IRVING and DROST (1987) found that a midday ψ of –1.4 to –1.6 MPa coinciding with active growth was necessary to reduce shoot length. The importance of the timing of water stress during active growth was also reaffirmed in this experiment. For example, ψ of NI did not reach –1.5 MPa until 81 DAFB, or three days before cessation of shoot growth, indicating that shoot growth was not significantly influenced. NI also did not affect fruit growth because ψ was not significantly lower than that of CI until 123 DAFB. KILILI et al. (1996) found that a significant reduction of ψ developed late in the season did not decrease fruit size of 'Braeburn' apple at harvest.

Fruit quality at harvest was not improved by applying more irrigation water. Slightly lower values of total soluble solids for CI may have occurred due to sugar dilution because of a higher fruit water content (MILLS et al. 1997). Although not statistically significant, red colour development for NI fruit was reduced by approximately 8–9 % compared to CI and PRD. TUSTIN et al. (1999) also reported that red colour development of 'Pacific Rose'™ was delayed by water stress. This trend for 'Pacific Rose'™ does not agree with previous research in which NI enhanced red fruit colour of 'Braeburn' apple (KILILI et al. 1996). However, conflicting reports concerning fruit colour development under reduced irrigation do exist. For example, MPELASOKA et al. (2001a) found that deficit-irrigated fruit showed a similar red colour intensity at harvest to fully watered controls. The trend of reduced colour development for 'Pacific Rose'™ grown under NI may indicate that colour responses to water stress are different between cultivars. Further research on the effects of reduced irrigation is warranted considering the importance of fruit colour as a quality factor.

In summary, our results show that PRD is a suitable method of irrigation for apple production because it reduced water use by 50 %, yet did not adversely alter seasonal ψ, photosynthesis, fruit quality, and yield at harvest. PRD could be used in preference to CI to improve irrigation efficiency and to maintain fruit quality. Irrigation strategies should also utilise NI, especially under similar climatic conditions to ours, because it was 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.

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