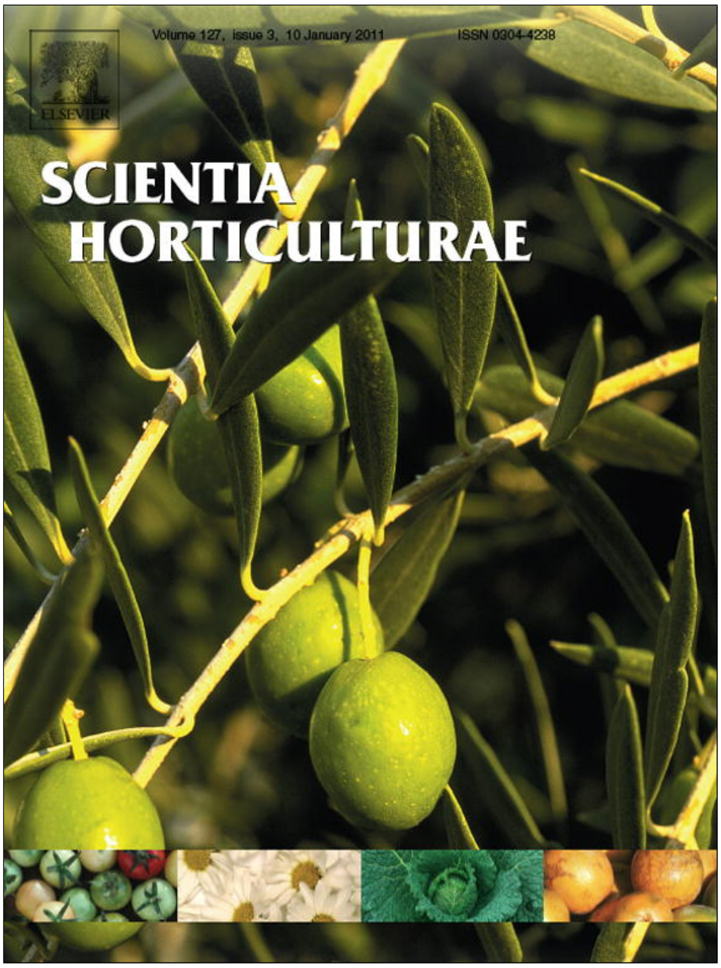
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Short communication

Partial rootzone drying maintains fruit quality of 'Golden Delicious' apples at harvest and postharvest

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ABSTRACT

Partial rootzone drying (PRD) has been evaluated at harvest, but its effects on apple fruit postharvest life is little known for apples grown in semi-arid regions. The objective of this study was to test the hypothesis that water savings via PRD may affect fruit quality at harvest and postharvest-life of 'Golden Delicious' apples grown in a semi-arid region. The experiment was conducted from 2005 to 2007. The irrigation treatments were commercial irrigation as control (CI) and PRD. After 3 years of evaluation, fruit quality at harvest, measured as fruit weight, flesh firmness, and total soluble solids concentration, was similar between CI fruit and PRD fruit. Dry matter concentration (DMC) was higher in PRD fruit than in CI fruit in 2005. The fruit quality after 18 days storage at room temperature (13–18 °C and 51–56% relative humidity) was similar between CI fruit and PRD fruit. The DMC was the highest in PRD fruit in the 2005 and 2007 growing seasons, and tended to be higher in PRD fruit than in CI fruit in 2006. Total soluble solids concentration was ≈8.7% higher in PRD fruit than in CI fruit in 2007. Fruit weight loss was similar between treatments. This study suggests that water deficit via PRD did not damage fruit quality at harvest or after storage at room temperature. Additionally, PRD irrigation saved about 3240 m^3 of water per hectare. Therefore, PRD can be recommended for commercial use in semi-arid regions and to those growers interested in either long-term storage or distant markets.

1. Introduction

As a temperate fruit crop, apple (*Malus domestica* Borkh) has the largest acreage after grape worldwide and is often grown in water-limited agro-ecosystems. In these production regions, water shortages for irrigation are jeopardizing agriculture outputs and therefore compromising social stability (Postel, 2003). Furthermore, inefficient use of groundwater has led to overexploitation of the 23% of the aquifers in other countries (Postel, 2003) and in the Central and Northern regions of Mexico (CNA, 2008). In these Mexican production areas, 98% of apple growers still use furrow irrigation. An important aspect of apple production research is the development and adoption of new irrigation technologies for improving both irrigation water-use efficiency and overall water-use efficiency without compromising yield and fruit quality.

Thus far, there are two irrigation alternatives to save water: regulated deficit irrigation (RDI) and partial rootzone drying (PRD). RDI supplies the entire rootzone with less water than the prevailing evapotranspiration (Behboudian and Mills, 1997; Mpelasoka et al., 2001a). In contrast, PRD involves wetting only part of the rootzone at each irrigation event, while the remainder is allowed to dry to a pre-determined level of soil water depletion (Zegbe et al., 2008). Normally, RDI reduces yield but increases fruit quality in fruit trees (Fernández et al., 2006; Grattan et al., 2006; O'Connell and Goodwin, 2007; Cui et al., 2009; Egea et al., 2009; Pérez-Pastor et al., 2009; Pérez-Pérez et al., 2010). In contrast, PRD attempts to save water by 50% while maintaining yield and fruit quality comparable to commercial irrigated fruit trees (Kang et al., 2002; Stoll et al., 2002; Goldhammer et al., 2002; van Hooijdonk et al., 2007; Leib et al., 2006; Zegbe and Behboudian, 2008). However, irrigation regimens affect quality and postharvest life of apples (Mpelasoka et al., 2001a,b). So far, except for one report (O'Connell and Goodwin, 2007), research on PRD in apple has resulted in water savings without negatively affecting either yield or fruit quality at harvest in several apple cultivars (van Hooijdonk et al., 2004; Lo Bianco et al., 2008; Talluto et al., 2008; Zegbe et al., 2007; Zegbe and Behboudian, 2008). However, studies of PRD on fruit postharvest life of apples grown under semi-arid conditions are scant (Leib

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et al., 2006) and may provide different results than studies from humid areas (van Hooijdonk et al., 2004; Zegbe et al., 2008). Therefore, the objective of this study was to test the hypothesis that water savings via PRD may affect fruit quality at harvest and postharvest-life of 'Golden Delicious' apples grown in a semi-arid region. Here, we report a more comprehensive study of PRD effects on apple fruit quality at harvest and after storage at room temperature. PRD effect on fruit weight loss is relevant for its implication regarding fruit storability potential, distant markets, and consumer acceptance.

2. Materials and methods

2.1. Experimental site and plant material

The experiment was conducted in the Campo Experimental Zacatecas, Calera de Víctor Rosales, Zacatecas, Mexico (location 22°54′N latitude, 102°39′W longitude, 2197 m altitude) for three consecutive growing seasons from 2005 to 2007. The experimental site has an annual mean temperature of 14.6 °C and receives 416 mm precipitation, of which 75% occurs between July and October. Average annual pan evaporation is 1609 mm. The orchard soil is classified as Kastanozem, with a sandy loam texture at pH 7.5 and 0.57% organic matter. The water used for irrigation had an electric conductivity of 0.47 dS cm^{-1} at pH 7.5. Thirty-two-year-old 'Golden Delicious'/'Malling7' (M7) apple trees were used as experimental entities. The trees were spaced at 5 m × 3.5 m and trained to the central leader form. There was a permanent native grass cover crop (*Chloris submutica*, *Botriochloa barbinodis*, and *Cynodon dactylon*) between the tree rows. Except for irrigation, all trees were treated according to standard cultural practices used for local commercial production. This included pruning on 9 February 2005, 24 January 2006, and 27 February 2007; application of chemical endodormancy releasers (2% tidiazuron and 4% mineral oil, with 6% biodegradable soap powder as an adherent) on 10 March 2005, 7 March 2006, and 13 March 2007; and thinning on 24 May 2005, 8 May 2006, and 1 May 2007 [39, 38, and 29 days after full bloom (DAFB) for 2005, 2006, and 2007, respectively]. Pest management practices were applied as needed.

2.2. Treatments, irrigation, and fertigation

Ten experimental units, comprised of four consecutive trees in a row, were selected and randomly allocated to two irrigation treatments (five experimental units per treatment). Two to four guard trees at each end surrounded the experimental plots. The irrigation treatments were: (1) commercial irrigation as a control (CI) and (2) PRD. The experiment was arranged in a completely randomized design. Irrigation was applied to both treatments through two parallel irrigation lines, one on each side of the row. Trees were drip-irrigated through 10 emitters (five on each side of the tree row) that emitted 40 L h^{-1} in total, placed 50 cm away from the tree trunk. For this type of soil, the field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) were established at 0.25 $cm^3\,cm^{-3}$ and 0.15 $cm^3\,cm^{-3}$, respectively. The CI treatment consisted of irrigating both sides of the tree row until θ_{FC} was reached. In PRD treatment plots, irrigation was applied to one side of the tree row until θ_{FC} was reached; the other side was left to dry until the following irrigation cycle. Volumetric soil water content (θ, mean ± standard deviation) of the dryer side of PRD plots was measured before each irrigation turn and was as low as 0.159 ± 0.026 $cm^3\,cm^{-3}$ and 0.161 ± 0.019 $cm^3\,cm^{-3}$ during the 2005 and 2006 growing seasons, respectively (Fig. 1). The experiment started applying the first irrigation at θ_{FC} before blossom. The θ was monitored in a single tree of each experimental unit using time domain reflectometry (TDR, Mini-Trase System-Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Two pairs of TDR probes were installed permanently at a soil depth of 40 cm (one on each side of the row for one tree in each of the ten experimental units) between the tree trunk and emitters.

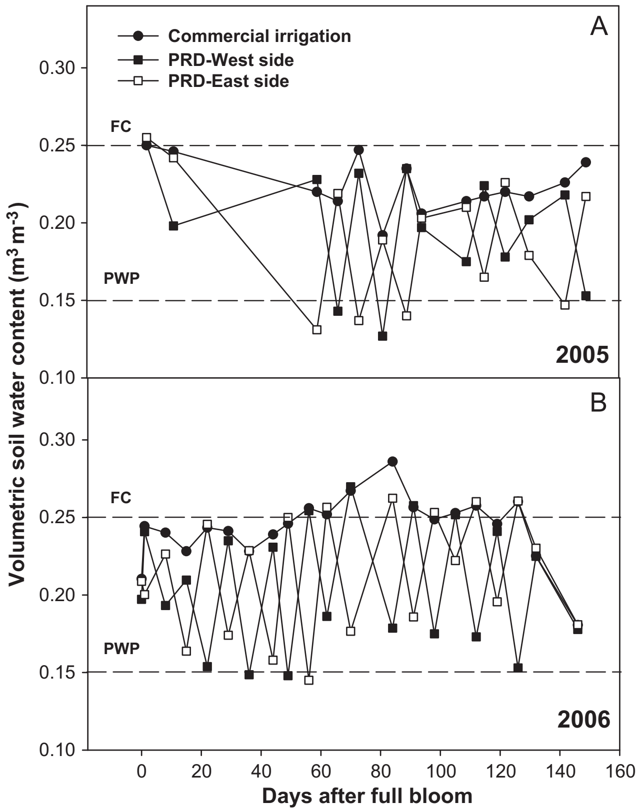

Fig. 1. Changes in the volumetric soil water content in response to commercial irrigation and partial rootzone drying (PRD) in both sides of the root system of 'Golden Delicious' apple trees for the 2005 (A) and 2006 (B) growing seasons. Dashed parallel lines indicate field capacity (FC) and permanent wilting point (PWP).

Reference evapotranspiration (ETo; mm) was estimated from a class A evaporation pan (Ev; mm) using the relationship ETo = Ev × Kp, where Kp is the pan coefficient (Atwell et al., 1999), which for the study site is 0.75. Meteorological data was collected from a weather station located near the experimental orchard.

In 2005 and 2006, applied water was estimated as the difference between θ at the start and at the end of each irrigation period at a soil depth of 40 cm. The water consumptive use (WCU) was estimated by a soil water balance (Brady and Weil, 2000), considering the θ readings and the effective rainfall (Zegbe-Domínguez et al., 2006). Due to malfunctioning of the TDR during the 2007 growing season, irrigation was applied by estimating the crop evapotranspiration (ETc) between irrigations. This was determined weekly using the equation ETc = ETo × Kc, where ETo was as defined above and Kc is the crop coefficient estimated for our local conditions, which varied from 0.4 in March to 1.0 in July. The ETo, applied water, and WCU for the three growing season are shown (Table 1). The water applied to the PRD treatment was about 44.5%, 46.6%, and 47.3% less than the control for the 2005, 2006, and 2007 growing seasons, respectively.

Trees were fertigated in the first four irrigation events with 75N–75P–75K kg per hectare. Half of the N (68 g) and all of the P (286 g) and K (219 g) per tree were applied in the first four irrigations. The remaining half of the N (143 g/tree) was supplied via fertigation 2 weeks after fruit harvest. The sources for N and K were urea (46%) and potassium chloride (60%), respectively. The P source was the monoammonium phosphates (MAP, 12N–46P–00K, Hydrosol MAP, Rhadio Fosfatados de México S.A. de C.V).

Table 1
Accumulated reference evapotranspiration (ETo), applied water, and water consumptive use (WCU) for the irrigation treatments applied to 'Golden Delicious' apple trees in three consecutive growing seasons.

Irrigation treatments	ETo (mm)	Applied water (mm)	WCU (mm)
2005			
Commercial irrigation	720.0	726.8	788.8
Partial rootzone drying	720.0	403.0	445.2
2006			
Commercial irrigation	837.6	740.8	881.7
Partial rootzone drying	837.6	395.8	507.5
2007			
Commercial irrigation	775.9	598.6	808.6
Partial rootzone drying	775.9	295.3	505.3

2.3. Determination of leaf xylem water potentials

The central two trees from each experimental unit were used for data collection. Diurnal changes in leaf xylem water potential (Ψ_{leaf}) were recorded using a Scholander pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) on four (two per tree) fully expanded and mature leaves from the middle of shoots located in the middle and outer part of the tree canopy. This was done at 06:00, 9:00, 12:00, 15:00 and 18:00 h on three sampling dates during each growing season: after fruit set, during fruit growth, and before harvesting.

2.4. Fruit assessment at harvest and after storage

At harvest, six fruits (three per tree) per plot (30 per treatment) were randomly chosen to assess fruit quality parameters. Twenty-four hours after harvest, fruits were individually weighed with a precision scale (Mettler PE11; Mettler Instruments, Greifensee-Zurich, Switzerland). Then, after removing the fruit skin, two flesh firmness determinations were done on opposite sides of the equator of each fruit using a press-mounted Effegi penetrometer (Model FT 327, Wagner Instruments, Greenwich, CT, USA) with an 11.1-mm tip. Total soluble solids concentration was determined by mixing several drops from each side of the fruit and using a digital refractometer with automatic temperature compensation (Model PR-32α, Atago Co., ltd., Tokyo, Japan). Dry matter concentration of fruit (expressed on a fresh weight basis) was determined using 25 g of a composite sample of fresh cortical tissue from three fruits, which was then oven-dried at 60 °C for 2 weeks. Another set of six fruits per plot (30 per treatment) was used to evaluate fruit quality after 18 days in storage at room temperature following the protocol described above. During storage, each fruit was individually weighed every other day and fruit weight loss was calculated as the percentage reduction from initial weight. Storage conditions at room temperate in 2005 were: 15 ± 1 °C and 53 ± 5% relative humidity (RH). In 2006, fruits were stored at 13 ± 1 °C and 56 ± 4% RH and in 2007, at 18 ± 2 °C and 51 ± 4% RH.

2.5. Data analysis

Data were analyzed in a completely randomized model using the GLM procedure of SAS software (Version 9.1; SAS Institute, Cary, NC, USA). The information was taken from the two central trees and the appropriate error term was calculated to exclude the sub-sample error term from the GLM analysis. Treatment means were grouped by Fisher's Least Significant Difference test at $P \leq 0.05$.

3. Results and discussion

3.1. Fruit quality at harvest

Fruit quality at harvest, in terms of mean fruit weight, flesh firmness, and total soluble solids concentration, was similar in both treatments. The dry matter concentration (DMC) was higher in PRD fruit than in CI fruit in 2005 only (Table 2). Improved fruit quality in apples has been associated with the application of regulated deficit irrigation (RDI; Behboudian and Mills, 1997). Under RDI, the Ψ_{leaf} must be much lower than −2.0 MPa, with corresponding benefits to fruit quality (Mpelasoka et al., 2001a,b). In this experiment, the latter situation did not occur at any phenological stage or at any particular hour during the daytime (Table 3), and consequently there were no differences in fruit quality between treatments. The CI trees had higher leaf xylem water potential (Ψ_{leaf}) than PRD trees on nine occasions out of 15 throughout the experiment. Although one study disagrees (Gowing et al., 1990), others reported lower Ψ_{leaf} in apple trees experiencing PRD (Zhao et al., 2006; Zegbe et al., 2007; Zegbe and Behboudian, 2008). Therefore, it is likely that that PRD trees cannot maintain the Ψ_{leaf} at the level of CI trees.

3.2. Fruit quality after storage

After 18 days of storage at room temperature, fruit quality attributes were similar between PRD and CI fruits in all three growing seasons (Table 2). An exception was DMC, which was significantly higher in PRD fruits in 2005 and 2007 and trended higher in 2006 than in CI fruit (Table 2). The DMC is associated with fruit

Table 2
Mean fruit weight (MFW), flesh firmness (FF), total soluble solids concentration (TSSC), and dry matter concentration (DMC) of fresh weight (FW) at harvest and after 18 days of storage at room temperature of 'Golden Delicious'/M7 apples under commercial irrigation (CI) and partial rootzone drying (PRD).

Irrigation treatments	Fruit quality attributes											
	2005				2006				2007			
	MFW (g)	FF (N)	TSSC (%)	DMC (mg/g FW)	MFW (g)	FF (N)	TSSC (%)	DMC (mg/g FW)	MFW (g)	FF (N)	TSSC (%)	DMC (mg/g FW)
At harvest												
CI	108.6a[a]	68.5a	16.9a	184.4b	127.4a	81.1a	15.9a	184.2a	124.1a	76.2a	13.7a	157.4a
PRD	107.5a	71.2a	17.6a	200.6a	115.5a	85.3a	15.3a	185.8a	106.6a	78.1a	13.6a	157.5a
$P > F$	0.77	0.49	0.10	0.00	0.084	0.132	0.29	0.82	0.10	0.27	0.86	0.99
CV (%)[b]	10.8	15.0	5.2	5.2	22.3	11.0	11.4	5.7	15.0	6.6	6.5	3.6
After storage												
CI	100.5a	54.5a	17.6a	180.0b	105.0a	67.4a	16.6a	178.8a	118.0a	67.3a	13.8b	169.7b
PRD	100.9a	53.4a	18.6a	196.5a	104.0a	72.7a	17.2a	180.2a	104.9a	70.3a	15.0a	177.4a
$P > F$	0.905	0.502	0.058	0.006	0.841	0.068	0.405	0.825	0.127	0.430	0.013	0.036
CV (%)[b]	10.7	22.0	6.1	2.9	17.9	17.2	10.5	6.6	13.9	11.9	7.58	4.2

[a] For each year, mean separations within a column and storage condition were by Fisher's LSD ($P \leq 0.05$). Mean values followed by the same lower-case letter are not significantly different.
[b] Coefficient of variation.

Table 3
Diurnal changes in leaf xylem water potential (MPa) of 32-year-old 'Golden Delicious'/M7 apple trees exposed to commercial irrigation (CI) or partial rootzone drying (PRD) irrigation treatments (IT) at three phenological stages: after fruit set (AFS), during fruit growth (DFG), and before harvesting (BH).

	Phenological stages														
	AFS					DFG					BH				
IT	0600[a]	0900[a]	1200[a]	1500[a]	1800[a]	0600[a]	0900[a]	1200[a]	1500[a]	1800[a]	0600[a]	0900[a]	1200[a]	1500[a]	1800[a]
CI	−0.5a[b]	−1.2a	−1.8a	−1.9a	−1.7a	−0.4a	−1.0a	−1.6a	−1.5a	−1.5a	−0.3a	−1.0a	−1.6a	−1.7a	−1.6a
PRD	−0.5a	−1.3b	−1.9b	−2.0b	−1.9b	−0.5b	−1.1a	−1.7b	−1.7b	−1.5a	−0.4b	−1.0a	−1.7a	−1.9b	−1.7a
$P > F$	0.14	0.05	0.03	0.00	0.02	0.00	0.77	0.01	0.01	0.24	0.02	0.99	0.13	0.01	0.53
CV (%)[c]	30.2	18.6	11.1	8.5	15.1	27.7	20.1	14.1	8.5	12.8	35.8	17.5	10.0	10.0	15.6

[a] Diurnal time (h).
[b] For each phenological stage, mean separations within an hour and column were by Fisher's LSD ($P \leq 0.05$). Mean values followed by the same lower-case letter are not significantly different.
[c] Coefficient of variation.

containing more densely packed cells (Mpelasoka et al., 2000), a result of increased cell number during the first stage of fruit growth. High DMC has also been observed in apples undergoing regulated deficit irrigation (Mpelasoka et al., 2000), but has not been reported before for apple trees undergoing PRD irrigation in a semi-arid zone. Total soluble solids concentration (TSSC) tended to be higher in PRD than in CI fruit in 2005 and 2006; this trend became significant in 2007. Rather than a direct PRD effect, TSSC enhancement in 2007 could be the result of a dilution process because the PRD mean fruit weight was 11.1% lower than in CI fruit (Table 2).

Fruit water loss (FWL) was similar between treatments over the three growing seasons (Fig. 2). Thus, PRD does not alter the epidermis to speed up or to delay FWL as was observed in apples under different irrigation treatments (Mpelasoka et al., 2000). Our results support recent reports arguing no PRD effect on FWL (van Hooijdonk et al., 2007). However, there is another report showing either a reduction or no change in FWL (Zegbe et al., 2008). The latter discrepancy, perhaps, is associated with the way PRD is applied. For instance, when part of the root system is not irrigated during whole growing season, FWL is reduced (van Hooijdonk et al., 2007; Zegbe et al., 2008). In this study, the irrigation in PRD trees alternated sides of the tree row, keeping the volumetric soil water content between field capacity and permanent wilting point. Therefore, PRD irrigation as applied here avoided water deficit events during fruit growth, leaving no measurable effects on FWL.

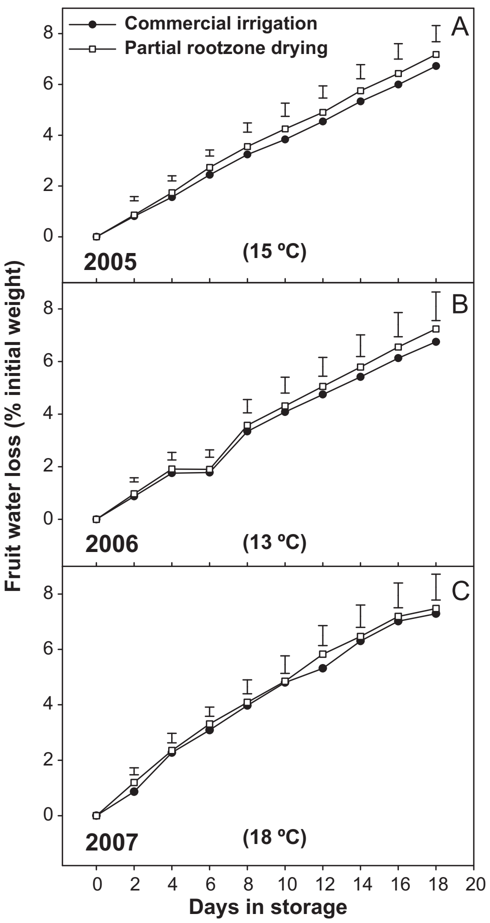

Fig. 2. Cumulative water loss of 'Golden Delicious'/M7 apple fruit from trees undergoing commercial irrigation or partial rootzone drying during storage at various room temperatures and relative humidities for 18 days. For each sampling date, vertical bars represent LSD values by Fisher's test at $P \leq 0.05$.

The PRD used ≈47% less water, on 3-year average, than commercial irrigation. PRD is thus an effective water-saving irrigation technology for apple trees that does not reduce fruit quality at harvest or after storage. Therefore, PRD can be recommended for commercial use in semi-arid regions. In addition, since postharvest performance of PRD fruit was similar to CI fruit, this irrigation technology can be used by apple growers interested in long-term storage or distant markets.

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