IRRIGATION AND DRAINAGE
Irrig. and Drain. **61**: 251–259 (2012)
Published online 24 June 2011 in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ird.635

PARTIAL ROOTZONE DRYING TO SAVE WATER WHILE GROWING APPLES IN A SEMI-ARID REGION†

JORGE A. ZEGBE* AND ALFONSO SERNA-PÉREZ

Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Zacatecas, Zacatecas, México

ABSTRACT

Water availability represents the main environmental limitation in arid and semi-arid agro-ecosystems. In these regions, irrigation water is a scarce and expensive resource for apple and other horticultural production systems. The north-central part of Mexico, where 70% (≈ 44 thousand hectares) of apples are grown, is such a semi-arid system. The objective of this research was to determine the impact of partial rootzone drying (PRD) on tree physiology, yield, water use efficiency (WUE), and irrigation water use efficiency of 'Golden Delicious' apple trees growing in a semi-arid region. Treatments were commercial irrigation (CI, as control) and PRD (50% of the irrigation water supplied to CI). The PRD trees had slightly reduced leaf xylem water potential, stomatal conductance, and transpiration rate. Yield, fruit size and quality, vegetative growth, and pruning weight were not modified by the irrigation treatments. Over three years, average WUE increased by 51% under PRD irrigation and water savings were ≈ 3, 240 m^3 water per hectare. Therefore, PRD is a potential irrigation technique to make apple production sustainable not only in the semi-arid regions of Mexico, but also in other regions where water resources are becoming insufficient. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: *Malus domestica* Borkh; plant water relationships; yield; water use efficiency; irrigation water use efficiency

Received 6 July 2010; Revised 23 February 2011; Accepted 27 February 2011

RÉSUMÉ

La disponibilité en eau représente la principale limitation de l'environnement pour les plantes dans les ago-écosystèmes des zones arides et semi-arides. C'est le cas pour le Centre-Nord du Mexique où 70% (≈ 44 000 hectares) des pommes sont cultivées. L'objectif de cette recherche était de déterminer l'impact de l'assèchement partiel de la zone racinaire (PRD) sur certains paramètres physiologiques des arbres, le rendement, l'efficacité d'utilisation de l'eau (WUE), et l'efficacité de l'utilisation de l'eau d'irrigation (IWUE) de pommiers 'Golden Delicious' cultivés en région semi-aride. Les traitements ont été l'irrigation commerciale (contrôle, CI) et le PRD (50% de l'eau d'irrigation fournie au CI). De légères diminutions du potentiel hydrique du xylème foliaire, de la conductance stomatique et du taux de transpiration ont été constatées. Le rendement, la taille des fruits et leur qualité, la croissance végétative, et le poids des branches élaguées n'ont pas été modifiés par les traitements d'irrigation. 'Une évaluation sur trois ans a montré que, en moyenne, le WUE a été considérablement augmenté de 51% dans l'irrigation PRD et que l'économie d'eau a été d'environ ≈ 3, 240 m^3 par hectare. Par conséquent, le PRD est une technique d'irrigation qui peut rendre durable les systèmes actuels de production de pommes, non seulement dans les régions semi-arides du Mexique, mais aussi dans d'autres régions où les ressources en eau deviennent insuffisantes. Copyright © 2011 John Wiley & Sons, Ltd.

MOTS CLÉS: *Malus domestica* Borkh; relations hydriques de la plante; rendement; efficacité de l'utilisation de l'eau; efficacité de l'irrigation

INTRODUCTION

Mexico faces a constant population growth combined with a dramatic decrease in fresh water available for human, industrial, and agricultural consumption. According to the National Water Commission of Mexico (Comisión Nacional del Agua (CNA, 2008), 85% of groundwater is used for agricultural purposes, but 57% of this water is lost due to

* Correspondence to: Dr Jorge A. Zegbe, Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo Experimental Zacatecas, Apartado Postal No. 18, Calera de Víctor Rosales, Zacatecas, Código Postal 98500, México. E-mail: jzegbe@zacatecas.inifap.gob.mx
†Assèchement partiel de la zone racinaire pour économiser l'eau de pommiers cultivés en région semi-aride.

inadequate hydraulic infrastructure. This inefficient use of groundwater has led to overexploitation of 23% of the aquifers in central and northern Mexico. Therefore, there is an urgent need to identify and adopt efficient irrigation management strategies to develop sustainable agricultural systems. A relatively minor reduction in irrigation water could substantially increase the water available for human and industrial purposes (Postel, 2003). This is particularly true for apple production (*Malus domestica* Borkh) in northern Mexico, where ≈ 44,000 hectares of this fruit crop are cultivated, and the goal is to increase agricultural water productivity by improving crop water use efficiency through drip irrigation combined with reduced irrigation techniques.

Regulated deficit irrigation (RDI) has been used to save water not only for apple production (Behboudian and Mills, 1997), but also in other fruit crops (Moriana *et al.*, 2003); (Romero *et al.*, 2005). The RDI normally reduces fruit size and yield but enhances fruit quality by concentrating soluble solids, dry matter, and flesh firmness (Mpelasoka *et al.*, 2001a; 2001b); (Leib *et al.*, 2006).

Partial rootzone drying (PRD) is another water-saving irrigation strategy developed in Australia for grapevines (Loveys *et al.*, 1997). This method involves wetting only half of the root system during each irrigation turn, while the other half is left to dry to a pre-determined level of soil water depletion (Zegbe *et al.*, 2008). The PRD can save water by up to 50% while maintaining yield in some grape cultivars (Loveys *et al.*, 1997). The PRD uses the plant's root-to-shoot chemical signalling mechanisms, inducing partial stomatal closure when part of the rootzone is experiencing water deficit (Davies *et al.*, 2002). As a result, transpiration (but not photosynthesis) is limited, leaf water potential is maintained, and as a result, water use efficiency improves (Gowing *et al.*, 1990); (Davies *et al.*, 2002); (Dodd *et al.*, 2006). However, there are reports of fruit trees that do not support root-to-shoot signalling induced by PRD (Tan and Buttery, 1982); (Goldhammer *et al.*, 2002); (Fernández *et al.*, 2006); (Zegbe and Behboudian, 2008). Therefore, it is important to clarify whether PRD is effective for semi-arid-grown apples. To date, PRD has been tested in pears (Kang *et al.*, 2002), red raspberries (Stoll *et al.*, 2002), peaches (Goldhammer *et al.*, 2002), olives (Fernández *et al.*, 2006), and apples (Caspari *et al.*, 2004); (van Hooijdonk *et al.*, 2004); (Leib *et al.*, 2006); (Zegbe and Behboudian, 2008). The PRD has improved water use efficiency and maintained both yield and fruit quality of 'Pacific Rose™' apples grown in a humid area (van Hooijdonk *et al.*, 2007); (Zegbe *et al.*, 2008). The PRD also tended to increase yield and fruit quality in 'Braeburn' (Caspari *et al.*, 2004) and 'Fuji' (Leib *et al.*, 2006) apples grown under semi-arid conditions. This suggests that PRD performance may be specific to the cultivar and climatic conditions, calling for further study of different cultivars and climatic conditions to elucidate this relationship. Additionally, there is limited information on the performance of apples growing in a semi-arid environment (Leib *et al.*, 2006); (Talluto *et al.*, 2008).

The objective of this research was to determine the impact of PRD on tree physiology, yield, water use efficiency, and irrigation water use efficiency of 'Golden Delicious' apples grown in a semi-arid region. We postulated that PRD might induce adverse effects on apple tree performance due to high evaporative demand and because of the lack of rain during bloom and the first two thirds of fruit growth.

MATERIALS AND METHODS

Experimental site and plant material

The experiment was conducted in the Campo Experimental Zacatecas, Calera de Víctor Rosales, Zacatecas, Mexico (lat. 22° 54' N, long. 102° 39' W, elevation 2,197 m) 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 1,609 mm. The orchard soil is classified as Kastanozem with a sandy loam texture and 0.57% organic matter at pH 7.5. Thirty-two-year-old 'Golden Delicious'/'Malling7' (M.7) apple trees were used as experimental entities. The trees were spaced at 5 x 3.5 m and trained to the central leader form. There was a permanent native grass (*Chloris submutica, Botriochloa barbinodis*, and *Cynodon dactylon*) cover crop 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 end dormancy releasers (2% tidiazuron and 4% mineral oil, with 6% of biodegradable soap powder as 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), respectively). Pest management practices were applied as needed.

Treatments and irrigation

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) partial rootzone drying (PRD). The experiment was arranged in a completely randomized design (Figure 1).

In both treatments, irrigation was applied through two parallel irrigation lines, one on each side of the row. Trees were drip-irrigated through 10 emitters (five on each side of

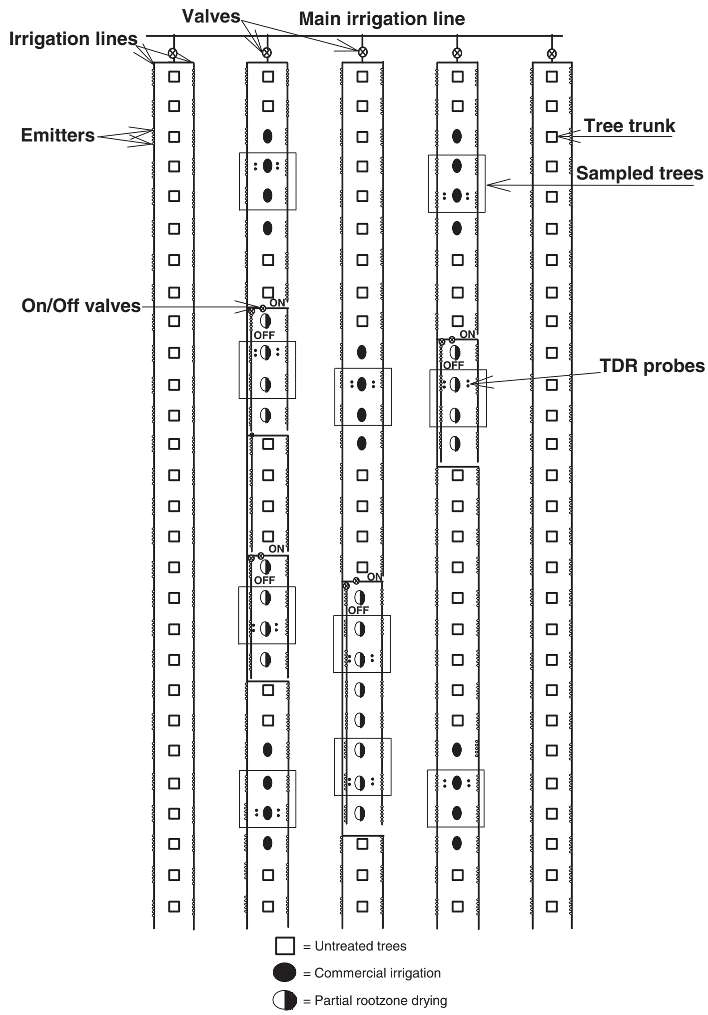

Figure 1. View of the experimental orchard, showing the layout of experimental plot distribution, irrigation lines, time-domain reflectometry (TDR) probes, and other experimental details

the tree row), placed 50 cm from tree trunk that emitted a combined 40 L h^{-1}. 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 was irrigated on both sides of the tree row to return the soil to θ_{FC}. Irrigation in the PRD treatment was applied to one side of the tree row to return it to θ_{FC}; the other side was left unirrigated until the following irrigation cycle. The θ in the drying side of PRD at the end of every irrigation cycle was as low as 0.159 ± 0.026 cm^3 cm^{-3} and 0.161 ± 0.019 cm^3 cm^{-3} for 2005 and 2006 growing seasons, respectively. Volumetric soil water content was monitored before (θ_{bi}) and 24 h after each irrigation (θ_{ai}) 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 400 mm (one on each side of the row per tree per plot per treatment) at a distance of 25 cm and 25 cm from the tree trunk and the emitters, respectively.

Reference evapotranspiration (ETo; mm) was estimated from a class A evaporation pan (Ev; mm) using the relationship ETo = Ev x Kp, where Kp is the pan coefficient, which for the study site is 0.75.

In the growing seasons of 2005 and 2006, irrigation water depth (IWD) was estimated weekly using the soil water content at field capacity (θ_{FC}), soil water content before irrigation (θ_{bi}), and a soil depth of 400 mm according to the Equation (1):

$$IWD = ((\theta_{FC} - \theta_{bi}) \times 400\ mm) \qquad (1)$$

Crop evapotranspiration per treatment (ETc for CI or PRD in mm) was estimated between irrigation events using Equation (2):

$$ETc_{CI\ \mathrm{or\ PRD}} = SWD_i + ER + IWD - SWD_{i+1} \qquad (2)$$

where SWD_i and SWD_{i+1} (mm) are the soil water depth at the start and at the end of the period, respectively, ($SWD = \theta_{bi} \times 400\ mm$), and ER (mm) is the effective rainfall (rainfall ≥ 10 mm for local weather conditions), estimated from accumulated rainfall in mm (AR) according to (Zegbe-Domínguez *et al.*, 2006), with the Equation (3):

$$ER = (AR - 10) \times 0.8 \tag{3}$$

The ETc for CI was calculated directly using Equation (2). In PRD plots, a water balance was used to estimate ET for each side of the tree row. It is important to note that the IWD for the drying side was not considered because it was not previously irrigated. Since we estimated two independent water balances, we then calculated the average of each water balance and used the sum of both averages to estimate the actual ETc for PRD.

In the growing season of 2007, due to malfunctioning of the TDR, IWD, ETo, and ETc were estimated daily from Ev and solar radiation. The meteorological data for IWD, ETo, and ETc calculations were collected from a weather station located near the experimental orchard. The ETc between irrigations was determined weekly using the Equation (4):

$$ETc = Kc \times ETo \tag{4}$$

where ETc and ETo were defined above and Kc is the crop coefficient estimated for our local conditions. In this semi-arid region, there are no inputs from the groundwater table. Therefore IWD was calculated as the difference between ETc and ER.

Fertigation

Trees were fertigated with 75 N-75P-75 K kg ha^{-1}. The sources for N and K were urea (46%) and potassium chloride (60%), respectively. The P source was monoammonium phosphate (MAP, 12 N-46P-00 K with solubility of 225 g L^{-1}, Hydrosol MAP, RhadioFosfatados de México S.A. de C.V). Half of the N (68 g urea), all of the P (286 g MAP), and all of the K (219 g potassium chloride) for each tree were applied in the first four irrigations. For PRD trees, a quarter of the total fertilizer was applied at the first irrigation to the wet side of PRD trees. For the next irrigation turn, the second quarter was applied on the opposite side and so on, so that the same amount of fertilizer was applied to both treatments. The remaining half of the N (143 g of urea per $tree^{-1}$) was supplied via fertigation to both treatments two weeks after fruit harvest following the protocol described above.

Leaf xylem water potential determinations

The middle 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 trees. This was done 2 days after irrigation at 06:00, 09:00, 12:00, 15:00, and 18:00 hours at three sampling dates: after fruit set, during fruit growth, and before harvesting for each growing season.

Stomatal conductance and transpiration rate

On the same sampling dates, stomatal conductance and transpiration rate were measured between 10:00 and 11:00 hr local time with a portable steady state porometer (LI-1600, Li-Cor Inc., Lincoln, NE, USA) on four leaves close to those used for Ψ_{leaf} determinations.

Fruit and shoot growth

The diameters of five selected and tagged fruits from the outer and middle part of each tree canopy were measured at weekly intervals until growth ceased with a digital caliper (Digimatic, model 50–321, Mitutoyo, Co., Kanagawa, Japan). Shoot growth was measured by selecting and tagging five similar-sized current-season shoots from the outer and middle part of the tree canopy. The final shoot length was measured at the end of the experiment. Tree trunk perimeter was measured at 20 cm above the graft before and at the end of the experiment. Tree trunk diameter was expressed as trunk cross-sectional area (TCSA).

Yield and yield components, irrigated and water use efficiency

Fruit number, fruit yield per tree, and mean fruit weights were measured at harvest (140, 134, and 128 DAFB in 2005, 2006, and 2007, respectively). Yield efficiency was calculated by dividing the fruit yield per tree by the corresponding TCSA. Irrigation water use efficiency (IWUE) was expressed as kg fresh fruit per ha per mm water applied. Water use efficiency (WUE) was expressed as kg fresh fruit per ha per mm water consumed. Both parameters were calculated by dividing the gross yield (kg ha^{-1}) by the corresponding cumulative volumes of water.

Data analysis

Data were analyzed as a completely randomized model using the GLM procedure of SAS software (Version 9.1; SAS Institute, Cary, NC, USA). Treatment means were compared and separated using Fisher's least significant difference test at $P \leq 0.05$.

RESULTS AND DISCUSSION

Evapotranspiration, water applied, and water consumptive use

The accumulated water use expressed as the reference evapotranspiration, applied water, and water consumptive use (WCU) is shown in Table I. The PRD reduced the applied water by 44.6%, 46.6%, and 50.7% in 2005, 2006, and 2007, respectively. Over three years, the average amount of water saved by using PRD rather than conventional irrigation was 3,240 m^3 per hectare. The corresponding WCU percentages were 43.6%, 42.4%, and 37.5%, respectively.

Volumetric soil water content

Volumetric soil water content (θ) was nearly to field capacity (FC) in CI trees and on the irrigated sides of PRD trees (Figure 2). The θ in PRD trees fluctuated as the irrigation shifted from the wetted side to the drying side in PRD trees. On some occasions, the θ of the drying side dropped below the permanent wilting point in 2005 (Figure 2A), but this did not significantly affect tree growth or fruit production (Tables II and III; Figures 3 and 4). This θ pattern suggests the possibility that the root system may take up water from the deeper soil profile. In contrast, θ variation between field capacity and permanent wilting point on both sides of PRD trees was better controlled in 2006 (Figure 2B). For our weather conditions, the application of PRD was relevant only for the first two-thirds of the growing season (between 0 and 94 days after full bloom). After this time, natural rainfall might have overridden the effect of irrigation in PRD trees. We lacked θ information for 2007 due to malfunctioning TDR equipment.

Leaf xylem water potential, stomatal conductance, and transpiration rate

The pattern of plant water status, characterized by diurnal changes in leaf xylem water potential (Ψ_{leaf}), was consistent throughout the three growing seasons evaluated (Figure 3). Except for 93 and 122 DAFB in 2007 (Figure 3H and I, respectively), the Ψ_{leaf} of PRD trees tended to be slightly

Table I. Accumulated reference evapotranspiration (ETo), applied water, and water consumptive use (WCU) for the irrigation treatments applied to 'Golden Delicious'/M.7 apple trees in three consecutive growing seasons

Irrigation treatments	ETo (mm)	Applied water (mm)	WCU (mm)
2005			
Commercial irrigation	720	727	789
Partial rootzone drying	720	403	445
2006			
Commercial irrigation	838	741	882
Partial rootzone drying	838	396	508
2007			
Commercial irrigation	776	599	809
Partial rootzone drying	776	295	505

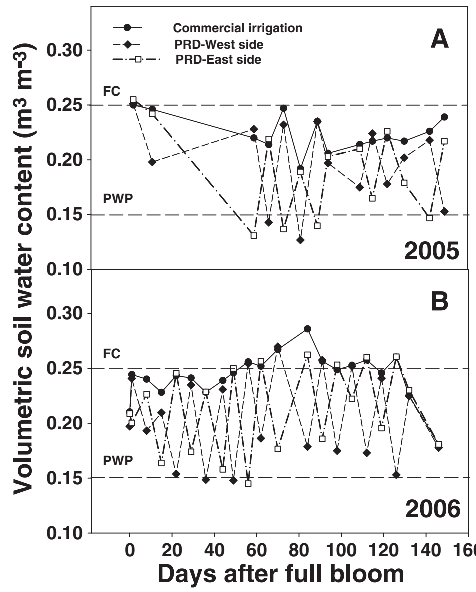

Figure 2. Changes in volumetric soil water content in response to commercial irrigation and partial rootzone drying (PRD) on both sides of the root system of 'Golden Delicious'/M.7 apple trees in the 2005 (A) and 2006 (B) growing seasons. Field capacity and permanent wilting point are FC and PWP, respectively

below the Ψ_{leaf} of control trees in a randomly significant fashion. This was accompanied by a non-significant reduction in stomatal conductance (g_s) and transpiration rate (*E*). The *E* was reduced, on average, by 5.9% and 9.7% in 2006 and 2007, respectively (Table II). Therefore, rather than being regulated by signals from the roots, our data suggest that even in plants exposed to PRD, g_s is controlled by the Ψ_{leaf} (Tan and Buttery, 1982); (Zhao *et al.*, 2006) in a similar fashion as in plants exposed to water deficit (Steudle, 2001). This is consistent with previous PRD apple experiments conducted in humid areas of New Zealand, where air vapour pressure deficit is much lower than in a semi-arid region (Zegbe *et al.*, 2007); (Zegbe and Behboudian, 2008). Furthermore, reports in olive (Fernández *et al.*, 2006) and in peaches (Goldhammer *et al.*, 2002), both crops grown under semi-arid climate conditions, also support the findings presented here. The Ψ_{leaf} on 93 and 122 DAFB was the same in PRD and CI trees (Figure 3H and I, respectively). Rainfall in the days prior to collecting the data could have overridden the influence of PRD irrigation on Ψ_{leaf}. The accumulated rainfall recorded before Ψ_{leaf} observations was 25.6 mm and 34.2 mm for 93 and 122 DAFB, respectively, in 2007.

Yield and yield components

Previous results emphasize that PRD maintains basic plant physiological processes in a similar fashion as those observed

Table II. Effect of irrigation treatments on stomatal conductance (g_s, cm s^{-1}) and transpiration (E, μg cm^{-2} s^{-1}) of 'Golden Delicious'/M.7 apple leaves. The g_s and E were not measured in 2005. The PPF means photosynthetic photon flux

	Physiological variables			
	2006		2007	
Irrigation treatments	g_s	*E*	g_s	*E*
Commercial irrigation	0.5a[a]	6.8a	0.7a	7.3a
Partial rootzone drying	0.5a	6.4a	0.6a	6.6a
Relative humidity (% ± SD)	23 ± 5		18 ± 8	
PPF (μmol m^{-2} s^{-1} ± SD)	1,142 ± 763		1,489 ± 157	

[a]For each year, mean separations within a column were by Fisher's LSD ($P \leq 0.05$). Mean values followed by the same lower-case letters were not significantly different.

Table III. Effect of commercial irrigation (CI) and partial rootzone drying (PRD) on plant efficiency and water productivity of 'Golden Delicious'/M.7 apple trees

	Irrigation treatments								
	2005			2006			2007		
Response variables	CI	PRD	P > F	CI	PRD	P > F	CI	PRD	P > F
Number of fruits	241a[a]	200a	0.6	247a	246a	0.9	1,011a	936a	0.5
Gross yield (kg $tree^{-1}$)	16.5a	13.5a	0.7	15.7a	15.9a	0.8	70.2a	64.8a	0.5
Trunk cross-sectional area (TCSA, cm^2)	360a	341a	0.7	366a	341a	0.6	385a	355a	0.7
Yield efficiency (kg TCSA cm^{-2})	0.04a	0.04a	0.8	0.04a	0.05a	0.9	0.18a	0.18a	0.5
Final shoot length (cm)	21.0a	20.8a	0.8	14.9a	11.6a	0.3	21.6a	14.8a	0.1
Pruning weight (kg $tree^{-1}$)	5.9a	3.9a	0.1	5.2a	4.7a	0.7	3.9a	2.5a	0.1
Water use efficiency (kg·ha^{-1} mm^{-1})	12.0a	17.3a	0.1	10.1b	17.8a	0.01	49.6b	73.2a	0.01
Irrigation water use efficiency (kg·ha^{-1} mm^{-1})	13.0a	19.1a	0.1	12.1b	22.1a	0.01	67.0b	125.3a	0.01

[a]For each year and response variable, mean separations within a row between CI and PRD were by Fisher's LSD ($P \leq 0.05$). Mean values followed by the same lower-case letters were not significantly different.

in plants adequately irrigated (Stoll *et al.*, 2000); (Davies *et al.*, 2002). Therefore, yields are expected to be similar between PRD and CI plants, but WUE is significantly improved by PRD (Davies *et al.*, 2002). Although a slight reduction in Ψ_{leaf} (randomly significant throughout the study) and non-significant reduction of g_s and *E* were observed, yield and yield components were consistently similar between PRD and CI trees among the three seasons evaluated (Table III; Figure 4). However, even though fruit growth was statistically similar between CI and PRD over the growing seasons evaluated, there was a strong trend toward reduced yield in PRD trees in 2007. The PRD fruit growth was reduced in two occasions out of 14 (Figure 4C). This suggests that the slight reduction in Ψ_{leaf} observed in PRD trees was not enough to limit gas exchange; thus, there were no negative effects on yield, yield components, or fruit growth. In contrast, there are reports arguing that PRD increases yield in apples (Caspari *et al.*, 2004); (Leib *et al.*, 2006) and in pears (Kang *et al.*, 2002). Previous experiments do not support such effect in terms of number of fruit, yield, and yield efficiency (van Hooijdonk *et al.*, 2004); (Zegbe and Behboudian, 2008); (Talluto *et al.*, 2008), Table III). However, after fruit set, fruit trees undergoing water deficit episodes may experience a small second bloom that may be reflected as 'yield increases' (Kang *et al.*, 2002); (Caspari *et al.*, 2004); (Leib *et al.*, 2006). Yields in 2005 and in 2006 were lower than in 2007. This lower yield, in part, is the result of low winter chill accumulation in the first two seasons, which is typical of temperate fruit crops cultivated in subtropical areas (Aslamarz *et al.*, 2009). We tried to alleviate this problem in the first two winters by applying endodormancy releasers (tidiazuron plus mineral oil). However, the applications were insufficient to enhance bud breaking and this was reflected in the low yields. The opposite occurred when chill accumulation was constant and high, as during the winter 2006–2007 (north latitude). The chill accumulated for the winters 2004–2005, 2005–2006, and 2006–2007 was 243, 254, and 494 chill units, respectively as

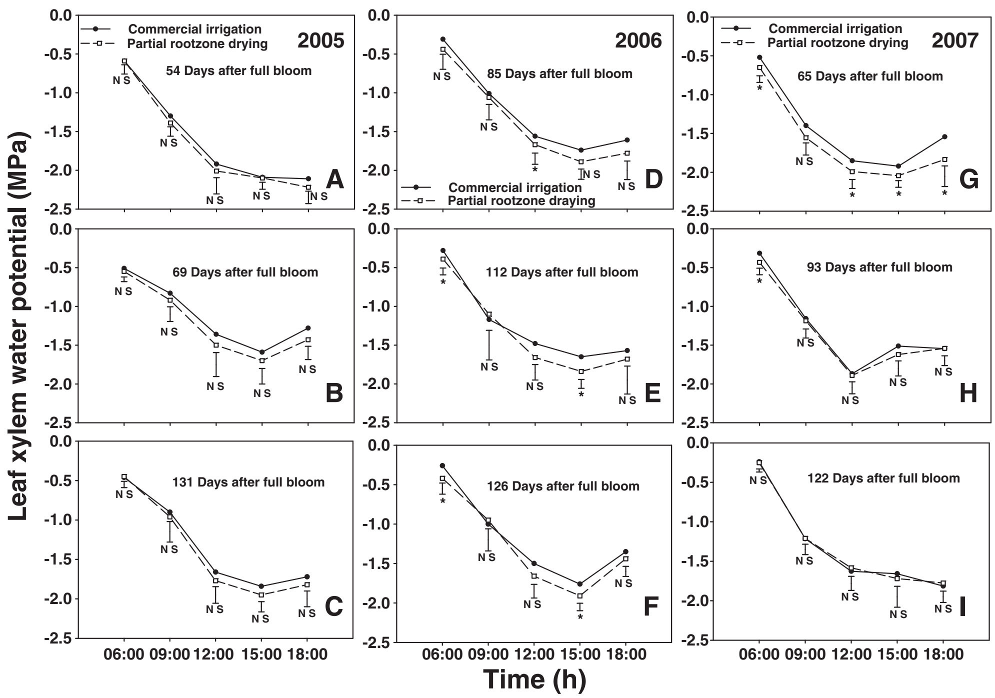

Figure 3. Diurnal changes in leaf xylem water potential of 'Golden Delicious'/M.7 apple trees exposed to commercial irrigation and partial rootzone drying. For each sampling date, vertical bars represent LSD values and asterisks or NS indicate significant or non-significant differences, respectively, by Fisher's test at $P \leq 0.05$

defined (Anderson *et al.*, 1986). Indeed, as in other production areas (Luedeling *et al.*, 2009), low annual winter chill accumulation is becoming a problem for the cultivation of deciduous fruit trees in this region. In addition, the apple cultivar-rootstock combination used here produces lower yields than when the same cultivar is grafted on other rootstocks (Westwood, 1993).

The data suggest that apple trees are sensitive to small changes in Ψ_{leaf} because final shoot growth and pruning weights were consistently (albeit non-significantly) lower in PRD trees than in CI trees (Table III). The reductions in final shoot growth were 1%, 22%, and 31% for 2005, 2006, and 2007, respectively. The corresponding reductions in pruning weight were 34%, 22%, and 29%, respectively. This may have implications for pruning costs, but deserves further evaluation.

Water use efficiency and irrigation water use efficiency

Irrigation water use efficiency (IWUE), in terms of $kg \cdot ha^{-1}$ mm^{-1} water applied, was improved in PRD trees over CI trees by 46.9%, 82.6%, and 87.0% for 2005, 2006, and 2007, respectively. Water use efficiency (WUE), in terms of $kg \cdot ha^{-1}$ mm^{-1} of water consumed, was also consistently improved in PRD trees (Table III). Compared to CI trees, the improvement of WUE in PRD trees was 44.2%, 76.2%, and 47.6% for 2005, 2006, and 2007, respectively. The IWUE and WUE results reported here are consistent with those found in apples grown in humid regions (van Hooijdonk *et al.*, 2007); (Zegbe *et al.*, 2007) and in semi-arid zones (Leib *et al.*, 2006). Therefore, we can confirm that PRD is a feasible irrigation technique that can save enormous amounts of water every growing season.

CONCLUSIONS

Although partial rootzone drying slightly reduces Ψ_{leaf}, stomatal conductance, and transpiration rate, it could maintain yields similar to those trees using standard irrigation practices. Both irrigation water use efficiency and water use efficiency were improved by partial rootzone drying. Thus, partial rootzone drying could potentially save enormous amounts of water in central and north-central Mexico and in other semi-arid agro-ecosystems where the 'blue gold' is now scarce.

ACKNOWLEDGEMENTS

We are grateful to M Sc. Katherine Jarvis-Shean, Dr. Richards Evans, and Dr. Mary Lou Mendum, all from the University of California, for their comments on the manuscript. We thank Manuel González-Solís, Juan Bernal-Galván, and Jorge Omar Zegbe for their technical support. This research was funded in part by The Fundación Produce

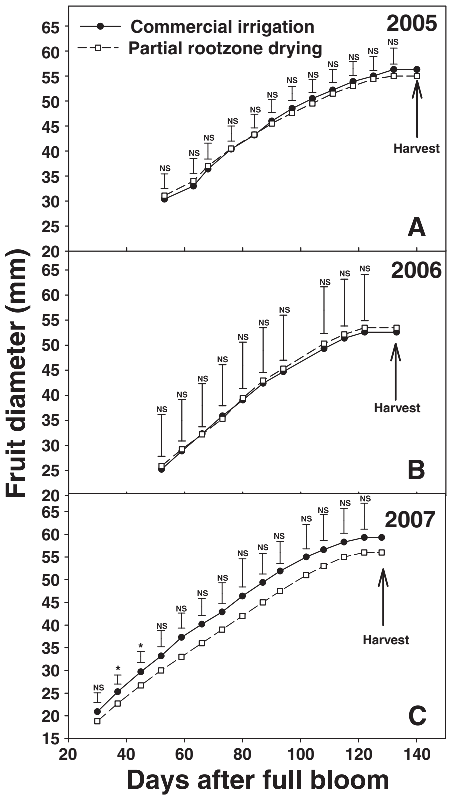

Figure 4. Cumulative fruit growth of 'Golden Delicious'/M.7 apple trees undergoing commercial irrigation and partial rootzone drying. For each sampling date, vertical bars represent LSD values and NS indicates non-significant differences by Fisher's test at $P \leq 0.05$

Zacatecas A.C. (No. Ref.: 1036186A), The CONACYT (No. Ref.: SNI_52538-Z), and The International Foundation for Science (Stockholm, Sweden). The Sabbatical Leave for the first author at the University of California at Davis was funded by the CONACYT (No. Ref.: 94173), the INIFAP México, and the Universidad Autónoma de Zacatecas.

REFERENCES

Anderson JL, Richardson EA, Kesner CD. 1986. Validation of chill unit and flower bud phenology models for 'Montmorecy' sour cherry. *Acta Horticulturae* **184**: 71–78.

Aslamarz AA, Vahdati K, Rahemi M, Hassani D. 2009. Estimation of chilling and heat requirements of some Persian walnut cultivars and genotypes. *Hortscience* **44**: 697–701.

Behboudian MH, Mills TM. 1997. Deficit irrigation in deciduous orchards. *Horticultural Reviews* **21**: 105–131.

Caspari HW, Neal S, Alspach P. 2004. Partial rootzone drying-A new deficit irrigation strategy for apple? *Acta Horticulturae* **646**: 93–100.

Comisión Nacional del Agua (CNA). 2008. *Estadísticas del Agua en México 2008*. Secretaría del Medio Ambiente y Recursos Naturales. México, D.F. 233 pp.

Davies WJ, Wilkinson S, Loveys B. 2002. Stomatal control by chemical signalling and the exploitation of the mechanism to increase water use efficiency in agriculture. *The New Phytologist* **153**: 449–460.

Dodd IC, Theobald JC, Bacon MA, Davies WJ. 2006. Alternation of wet and dry sides during partial rootzone drying irrigation alters root-to-shoot signaling of abscisic acid. *Functional Plant Biology* **33**: 1081–1089.

Fernández JE, Díaz-Espejo A, Infante JM, Duran P, Palomo MJ, Chamorro V, Girón IF, Villagarcía L. 2006. Water relations and gas exchange in olive trees under regulated deficit irrigation and partial rootzone drying. *Plant and Soil* **284**: 273–291.

Goldhammer DA, Salinas M, Crisosto C, Day KR, Soler M, Moriana A. 2002. Effects of regulated deficit irrigation and partial root zone drying on late harvest peach tree performance. *Acta Horticulturae* **592**: 343–350.

Gowing DJG, Davies WJ, Jones HG. 1990. A positive root-sourced as an indicator of soil drying in apple, *Malus x domestica* Borkh. *Journal of Experimental Botany* **41**: 1535–1540.

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

Leib BG, Caspari HW, Redulla CA, Andrews PK, Jabro JJ. 2006. Partial rootzone drying and deficit irrigation of 'Fuji' apples in a semi-arid climate. *Irrigation Science* **24**: 85–99.

Loveys BR, Grant WJR, Dry PR, McCarthy MR. 1997. Progress in the development of partial rootzone drying. *The Australian Grapegrower & Winemaker* **404**: 18–20.

Luedeling E, Zhang M, Girvetz EH. 2009. Climatic changes lead to declining winter chill for fruit and nut trees in California during 1950–2099. *PLoS ONE* **4**(7), e6166. doi:10.1371/journal.pone.0006166.

Moriana A, Orgaz F, Pastor M, Fereres E. 2003. Yield response of a mature olive orchard to water deficit. *Journal of the American Society for Horticultural Science* **128**: 425–431.

Mpelasoka BS, Behboudian MH, Green SR. 2001a. Water use, yield and fruit quality of lysimeter-grown apple trees: response to deficit irrigation and to crop load. *Irrigation Science* **20**: 107–113.

Mpelasoka BS, Behboudian MH, Ganesh S. 2001b. Fruit quality attributes and their interrelationships of 'Braeburn' apple in response to deficit irrigation and to crop load. *Gartenbauwissenschaft* **66**: 247–253.

Postel SL. 2003. Securing water for people, crops, and ecosystems: new mindset and new priorities. *Natural Resources Forum* **27**: 89–98.

Romero P, Garcia J, Botia P. 2005. Cost-benefit analysis of a regulated deficit-irrigated almond orchard under subsurface drip irrigation conditions in southeastern Spain. *Irrigation Science* **24**: 175–184.

Steudle E. 2001. The cohesion-tension mechanism and the acquisition of water by plant roots. *Annual Review of Plant Physiology and Plant Molecular Biology* **52**: 847–875.

Stoll M, Loveys B, Dry P. 2000. Hormonal changes induced by partial rootzone drying of irrigated grapevine. *Journal of Experimental Botany* **51**: 1627–1634.

Stoll M, Jones HG, Infante JM. 2002. Leaf gas exchange and growth in red raspberries is reduced when part of the root system is dried. *Acta Horticulturae* **585**: 671–676.

Talluto G, Farina V, Volpe G, Lo Bianco R. 2008. Effects of partial rootzone drying and rootstock vigour on growth and fruit quality of 'Pink Lady' apple trees in Mediterranean environments. *Australian Journal of Agricultural Research* **59**: 785–794.

Tan CS, Buttery BR. 1982. The effect of soil moisture stress to various fractions of the root system on transpiration, photosynthesis, and internal water relations of peach seedlings. *Journal of the American Society for Horticultural Science* **107**: 845–849.

van Hooijdonk BM, Dorji K, Behboudian MH. 2004. Responses of 'Pacific Rose^{TM}' apple to partial rootzone drying and deficit irrigation. *European Journal of Horticultural Science* **69**: 104–110.

van Hooijdonk BM, Dorji K, Behboudian MH. 2007. Fruit quality of 'Pacific Rose^{TM}' apple grown under partial rootzone drying and deficit irrigation. *Journal of Food, Agriculture and Environment* **5**: 173–178.

Westwood MN. 1993. *Temperate-zone pomology*. Timber Press. Portland, Oregon. 523.

Zegbe JA, Behboudian MH. 2008. Plant water status, CO_2 assimilation, yield, and fruit quality of 'Pacific Rose™' apple under partial rootzone drying. *Advances in Horticultural Science* **22**: 27–32.

Zegbe JA, Behboudian MH, Lang A, Clothier BE. 2007. Respuesta del manzano cv. 'Pacific Rose^{TM}' al riego parcial de la raíz. *Revista Chapingo serie Horticultura* **13**: 43–48.

Zegbe JA, Behboudian MH, Clothier BE, Lang A. 2008. Postharvest performance of cv. 'Pacific Rose^{TM}' apple grown under partial rootzone drying. *HortScience* **43**: 952–954.

Zegbe-Domínguez JA, Serna-Pérez A, Bravo-Lozano, AG. 2006. Riego parcial de la raíz en manzano 'Golden Delicious' en un ambiente semi-árido. *Revista Fitotecnia Mexicana* **29**: 69–73.

Zhao JY, Wang LJ, Fan PG, Dai ZW, Li SH. 2006. Effect of half and whole root drying on photosynthesis, nitrate concentration, and nitrate reductase activity in roots and leaves of micropropagated apple plants. *Journal of the American Society for Horticultural Science* **131**: 709–715.

