Nutrient status of apple leaves not affected by three years of irrigation using partial rootzone drying

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Abstract

Partial rootzone drying (PRD) is a water-saving irrigation technology that may affect apple (*Malus domestica* Borkh cv. Golden Delicious/Malling7)-tree nutrition if applied for an extended period. The objective of this study was to test the hypothesis that long-term application of PRD causes seasonal changes in macro- and micronutrients of apple leaves. The irrigation treatments were: (1) commercial irrigation as control (CI) and (2) PRD. After 3 years of evaluation, PRD irrigation had saved about 3240 m^3 of water per hectare. Leaf xylem water potential was slightly lower in the PRD treatment than in CI. The seasonal concentration of macro- and micronutrients was comparable between treatments, although significant differences were found at times. The macronutrient concentrations were within the normal range in PRD apple leaves. All micronutrient concentrations were slightly above the normal range except for Zn, which was slightly below the normal range. No physiological disorders associated with plant nutrition were observed on leaves or fruits. Therefore, data suggest that PRD did not alter apple-tree nutrition during the 3-year trial. Thus, PRD may be feasible for apple production in Central Mexico. However, further studies need to be conducted in those regions where groundwater is the main water source for irrigation and rain is negligible, particularly during the growing season.

Key words: water saving / leaf xylem water potential / *Malus domestica* Borkh

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1 Introduction

Worldwide, water resources for agriculture have been reduced dramatically in the last two decades due to overexploitation of groundwater and increasing nonagricultural demand for fresh water (*Postel*, 2003). This is particularly true in the arid and semiarid regions of Central and North-Central Mexico, where 85% of extracted groundwater are used for agriculture, of which 57% are lost annually due to inadequate hydraulic infrastructure (*CNA*, 2008). The challenge of producing more food with less water could be met using localized irrigation technologies (*i.e.,* drip irrigation and microsprinkling systems) combined with water-saving irrigation strategies such as regulated deficit irrigation (RDI) and partial rootzone drying (PRD). The RDI supplies the entire rootzone with less water than the prevailing evapotranspiration (*Behboudian* and *Mills*, 1997). In contrast, PRD involves wetting only part of the rootzone at each irrigation event, while the remainder is allowed to dry to a predetermined level of soil-water depletion (*Zegbe* et al., 2008). The PRD has been successfully applied to herbaceous (*Gençoğlan* et al., 2006; *Shahnazari* et al., 2008; *Du* et al., 2008) and perennial crops (*Kang* et al., 2002; *Stoll* et al., 2002; *Goldhamer* et al., 2002; *van Hooijdonk* et al., 2004; *Leib* et al., 2006; *Zegbe* and *Behboudian*, 2008).

Plants undergoing PRD are exposed to heterogeneous soil water content in the rootzone during the growing season, which may affect long-term plant nutrition (*Zhao* et al., 2006). Reports from some short-term studies indicate that PRD did not decrease nitrogen absorption and accumulation in herbaceous plants (*Hu* et al., 2006, 2009; *Shahnazari* et al., 2008) or apple trees (*Nakajima* et al., 2004), but effects of long-term PRD irrigation in apple (*Malus domestica* Borkh)-tree nutrition have not been reported. The objective of this study was to test the hypothesis that long-term application of PRD causes seasonal changes in macro- and micronutrients of apple leaves.

2 Material and methods

2.1 Experimental site and plant material

The experiment was conducted in the Campo Experimental Zacatecas, Calera de Víctor Rosales, Zacatecas, México (22°54′ N, 102°39′ W, elevation 2,197 m) during 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 with 75% occurring between July and October. Average annual pan evaporation is 1609 mm. The orchard soil is classified as Kastanozem (*Michéli* et al., 2006) with a sandy-loam texture at pH 7.5 and 0.57% organic matter. Soil-fertility analysis indicated a total concentration (in mg kg^{-1}) of 10.4 N, 5.44 P, 212 K, 2630 Ca, 774 Mg, 7.25 Fe, 0.71 Zn, 28 Mn, and 1.81 Cu (*Jones*, 2001). Thirty-two-year-

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old apple trees (*Malus domestica* Borkh cv. Golden Delicious/ Malling7) 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 received standard cultural practices used for local commercial production. These included pruning, application of chemical endodormancy releasers (2% Tidiazuron, 4% mineral oil, with 6% biodegradable soap powder as adherent) on March 10, 2005, March 7, 2006, and March 13, 2007, and manual thinning to two fruits per spur ≈ 35 d after full bloom. Pest-management practices were applied as needed.

2.2 Treatments and irrigation

Ten experimental units, each comprising 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 control (CI) and (2) partial rootzone drying (PRD). The experiment was arranged in a completely randomized design.

Irrigation was applied in both treatments through two parallel irrigation lines (one to each side of the row). Trees were drip-irrigated through ten emitters (five on each side of the tree row) that emitted a combined total of 40 L h^{-1}, 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 0.25 $cm^3\,cm^{-3}$ and 0.15 $cm^3\,cm^{-3}$, respectively. The CI treatment involved irrigating both sides of the tree row to return to θ_{FC}. In the PRD-treatment plots, irrigation 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. 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. The first irrigation was given at θ_{FC} in both treatments. The θ was monitored on a single tree per 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 plots) at a distance halfway between the tree trunk and the emitters.

Reference evapotranspiration (ETo; in mm) was estimated from a class A evaporation pan (Ev; in mm) using the relationship ETo = Ev × *Kp*, where *Kp* is the pan coefficient, which for the study site is 0.75 (*Allen* et al., 2006). Meteorological data were 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 using a soil water balance (*Allen* et al., 2006) considering the θ readings and the effective rainfall (*Zegbe-Domínguez* et al., 2006).

Due to malfunctioning of the TDR during the 2007 growing season, the WCU between irrigations was determined by the relationship ETc = ETo × *Kc*; where ETc is WCU, ETo was defined already, and *Kc* is the crop coefficient estimated for our local conditions, which varied from 0.4 in March to 1.0 in July. The applied water was estimated weekly as the difference between ETc and the effective rainfall (*Zegbe-Domínguez* et al., 2006).

2.3 Fertigation program

Trees were fertigated with 75N-75P-75K kg ha^{-1}. The sources for N and K were urea and potassium chloride, respectively. The P source was monoammonium phosphate (MAP, 12N-46P-00K 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) was supplied *via* fertigation to both treatments 2 weeks after fruit harvest following the protocol described above.

2.4 Determinations of leaf xylem water potentials

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, California, USA) on four (two per tree) fully expanded and mature leaves from the middle of shoots located in the middle and outer parts of the trees. This was done 2 d after irrigation at 06:00 a.m., 12:00 noon, and 06:00 p.m. at three phenological stages: after fruit set, during fruit growth, and before harvest.

2.5 Leaf sampling and nutrient analysis

For leaf-mineral analysis, one leaf was collected midway along the axis of each of 30 outer canopy fruiting shoots that were approximately equally distributed around each tree. A composite sample of 60 leaves per replication (30 per tree) was prepared. Leaves were sampled on the same three dates as the Ψ_{leaf} determinations, and a fourth sampling was collected 43, 41, and 40 d after harvest in 2005, 2006, and 2007, respectively. Each sample was washed with distilled water, dried at 65°C for 48 h, and ground. Leaf tissue was wet-digested using a micro–Kjeldahl apparatus to determine N concentration. For determination of the concentrations of other nutrients, samples were wet-digested and analyzed with an inductively coupled plasma–emission spectrometer (Fisons Instruments, Dearborn, MI).

2.6 Nitrogen-status determination

Leaf color, as a leaf-nitrogen-status indicator, was measured in the field using a portable Ch meter SPAD 502 (Minolta Camera, Osaka, Japan) on four leaves in the vicinity of those used for Ψ_{leaf} determinations on the same sampling dates used for leaf-nutrient analysis.

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2.7 Data analysis

Data were analyzed by a completely randomized model using the general linear model (GLM) procedure of SAS (Version 9.1; SAS Institute, Cary, NC, USA). Treatment means were compared using Fisher's least-significant-difference (LSD) test at ≤ 5%.

3 Results and discussion

According to the applied water values, on average PRD irrigation saved about 47% (3240 m^3 ha^{-1}) of the water applied to the control (Tab. 1). The ETc, in terms of water consumptive use, was also enhanced around 41% by PRD irrigation. Compared to commercial irrigation practices, PRD irrigation enhanced water-use efficiency (WUE) by 51%. Irrigation water-use efficiency (IWUE) was improved by 81%, because the yields of CI and PRD trees were similar. The 3-year-average yields were 34.1 and 31.4 kg $tree^{-1}$ (LSD = 8.2 kg $tree^{-1}$) for CI and PRD, respectively. The corresponding values for IWUE were 30.7 and 55.5 kg ha^{-1} mm^{-1} (LSD = 10.6 kg ha^{-1} mm^{-1}), respectively, and the WUE values were 23.9 and 36.1 kg ha^{-1} mm^{-1} (LSD = 7.4 kg ha^{-1} mm^{-1}), respectively. The improvement in IWUE partially agreed with that reported for apple trees cv. Fuji growing in a semiarid climate with PRD (*Leib* et al., 2006). The discrepancy in IWUE between that study and ours was due to the high volume of water applied to the PRD treatment during the second growing season of the reported study, which lowered IWUE values compared to ours. The low average yields reported for both treatments was in part due to the apple cultivar–rootstock combination used here compared with the same cultivar grafted onto other rootstocks (*Westwood*, 1993). The low winter chill accumulation in the first two seasons may also have contributed to low yields. An attempt was made to alleviate this problem by applying endo-dormancy releasers (Tidiazuron plus mineral oil). However, the applications did not enhance bud break, and this was reflected in the low yields. The opposite occurred when chill accumulation was constant or higher than that observed during the winter 2006–2007 (north latitude). The chill accumulated during the winters 2004–2005, 2005–2006, and 2006–2007 was 243, 254, and 494 chill units (as defined by *Anderson* et al., 1986), respectively. Variation in chill accumulation, and therefore low yields, is becoming a problem for the cultivation of temperate fruit trees in this region as reported for other production areas (*Luedeling* et al., 2009). This implies that in the near future, low-chill apple varieties will be grown to stabilize yields.

Table 1: Accumulated reference evapotranspiration (ETo), applied water, and water consumptive use (WCU) for two irrigation treatments applied in three consecutive growing seasons to apple trees (cv. Golden Delicious/M.7).

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

Table 2: Diurnal changes in leaf xylem water potential of 32-year-old apple trees (cv. Golden Delicious/M.7) exposed to commercial irrigation (CI) or partial-rootzone-drying (PRD) irrigation at specific times of day over the growing season. For each hour, mean separations within a row, a year (Y), and the days after full bloom (DAFB) were by Fisher's LSD ($p \le 5\%$). Mean values followed by the same lowercase letter are not significantly different. The readings were collected 2 d after irrigation.

	Diurnal time / h					
	0600		1200		1800	
Y/DAFB	CI	PRD	CI	PRD	CI	PRD
2005						
54	–0.59a	–0.59a	–1.92a	–2.00a	–2.10a	–2.20a
69	–0.51a	–0.55a	–1.36a	–1.50b	–1.27a	–1.43b
131	–0.46a	–0.45a	–1.65a	–1.77a	–1.73a	–1.82a
2006						
85	–0.31a	–0.34a	–1.56a	–1.67a	–1.62a	–1.78a
112	–0.28a	–0.39b	–1.47a	–1.66a	–1.57a	–1.68a
126	–0.26a	–0.42b	–1.50a	–1.66a	–1.35a	–1.44a
2007						
65	–0.52a	–0.65b	–1.85a	–1.99b	–1.54a	–1.83b
93	–0.32a	–0.43b	–1.87a	–1.89a	–1.54a	–1.54a
122	–0.24a	–0.25a	–1.63a	–1.58a	–1.81a	–1.77a

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Table 3: Effect of commercial irrigation (CI) and partial rootzone drying (PRD) on macronutrient concentrations of apple leaves (cv. Golden delicious/M.7). Mean separations within a row, a year, and the days after full bloom (DAFB) were by Fisher's LSD ($p \leq 5\%$). Mean values followed by the same lowercase letters are not significantly different.

	Macronutrient concentrations / %									
	N		P		K		Ca		Mg	
Year/DAFB	CI	PRD	CI	PRD	CI	PRD	CI	PRD	CI	PRD
2005										
54	1.91a	2.00a	0.19a	0.20a	1.71a	1.68a	0.99a	1.02a	0.29a	0.29a
69	1.99a	1.86a	0.23a	0.22a	1.49a	1.56a	1.34a	1.01b	0.35a	0.26a
131	1.57b	1.83a	0.19a	0.19a	1.25a	1.16a	1.34a	1.23a	0.29a	0.27a
174	1.58a	1.64a	0.17a	0.17a	1.05a	1.00a	1.77a	1.60a	0.36a	0.31a
2006										
85	2.23a	2.08a	0.19a	0.17a	1.64a	1.39b	1.08a	1.16a	0.34a	0.35a
112	2.09a	2.05a	0.16a	0.15a	1.42a	1.21a	1.42a	1.44a	0.40a	0.36a
126	2.11b	2.15a	0.17a	0.15a	1.30a	1.00a	1.20b	1.61a	0.32a	0.37a
167	1.86a	1.83a	0.14a	0.11a	1.16a	0.92b	1.77b	2.01a	0.41a	0.42a
2007										
65	2.51a	2.50a	0.21a	0.18a	1.75a	1.58a	0.89a	0.92a	0.30a	0.30a
93	2.28a	2.38a	0.18a	0.18a	1.27a	1.19a	1.12a	1.15a	0.33a	0.29a
122	2.20b	2.34a	0.15a	0.14a	1.08a	0.81b	1.26b	1.43a	0.32a	0.34a
162	2.05a	2.01a	0.13a	0.13a	0.90a	0.87a	1.62a	1.66a	0.37a	0.38a

Table 4: Effect of commercial irrigation (CI) and partial rootzone drying (PRD) on micronutrient concentrations of apple leaves (cv. Golden Delicious/M.7). Mean separations within a row, a year, and the days after full bloom (DAFB) were by Fisher's LSD ($p \leq 5\%$). Mean values followed by the same lowercase letters are not significantly different.

	Micronutrient concentrations / $mg\,kg^{-1}$									
	B		Fe		Zn		Cu		Mn	
Year/DAFB	CI	PRD	CI	PRD	CI	PRD	CI	PRD	CI	PRD
2005										
54	54.6a	54.7a	136.6a	151.0a	10.3a	10.3a	7.1a	7.4a	32.0a	31.1a
69	53.5a	35.0b	154.0a	112.0b	13.1a	09.3b	8.2a	7.7a	39.1a	26.6b
131	36.9a	35.5a	150.0a	148.6a	09.2a	09.6a	6.7a	7.2a	38.0a	36.1a
174	32.3a	34.8a	123.6a	125.4a	10.0a	09.5a	6.8a	6.6a	49.2a	45.4a
2006										
85	80.1a	78.0a	129.0b	150.4a	09.5a	12.9a	4.3a	4.6a	34.7a	37.6a
112	47.8a	47.4a	127.2a	127.4a	20.8a	11.7b	5.9a	6.5a	49.6a	46.0a
126	46.6a	44.0a	105.0b	142.6a	13.6a	07.2a	5.0b	6.0a	39.3a	46.7a
167	38.9a	42.6a	147.4a	141.8a	11.4a	06.6a	4.8a	4.6a	58.4a	73.1a
2007										
65	53.0a	47.7a	123.7a	145.2a	10.4a	8.9a	4.1a	3.8a	33.3a	33.8a
93	40.8a	43.8a	115.4b	147.6a	09.6a	9.8a	2.9b	5.0a	36.5a	33.9a
122	39.9a	36.9a	127.4a	128.6a	09.4a	9.5a	7.3a	7.5a	40.2a	47.0a
162	36.3a	36.9a	106.2a	118.2a	10.6a	9.2a	4.7a	7.0a	52.2a	51.9a

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The CI trees had higher leaf xylem water potential (Ψ_{leaf}) than PRD trees on 8 occasions out of 27 throughout the experiment. In general, Ψ_{leaf} tended to be lower in PRD trees than in CI trees (Tab. 2). The latter Ψ_{leaf} pattern is consistent not only with previous PRD apple experiments conducted in a humid area (*Zegbe* et al., 2007; *Zegbe* and *Behboudian*, 2008), but also with olive (*Fernández* et al., 2006) and peach (*Goldhammer* et al., 2002) grown in semiarid climates. Although one study disagrees (*Gowing* et al., 1990), another reported lower Ψ_{leaf} in cv. Gala apple trees experiencing PRD in a split-root experiment (*Zhao* et al., 2006). Therefore, it is likely that that PRD trees cannot maintain the same Ψ_{leaf} of CI trees. Nevertheless, while Ψ_{leaf} was not low enough to reduce yield, data suggest that apple trees are sensitive to small changes in Ψ_{leaf} because fruit size, final shoot growth, and pruning weights were consistently, though not significantly, lower in PRD trees. Final average fruit diameters were 6.58 cm and 6.13 cm for CI and PRD fruit, respectively (3-year average, LSD = 1.22 cm). The corresponding values for final shoot growth were 19.1 cm and 15.6 cm (LSD = 6.2 cm), respectively, and for pruning weights per tree 5.2 kg and 3.4 kg (LSD = 2.0 kg), respectively.

Despite the relatively lower Ψ_{leaf} in PRD trees than in CI trees, macro- and micronutrient concentrations were generally unaffected by irrigation type during the 3-year experimental period. While significant differences were detected occasionally between treatments (Tab. 3 and 4), their concentrations and seasonal patterns agreed with those reported previously (*Fallahi* et al., 1984; *Westwood*, 1993; *Cheng* and *Raba*, 2009).

Leaf color, as a leaf-nitrogen (N)-status indicator, followed a seasonal pattern for both treatments similar to that found by direct measurement (data not shown). However, only a weak relationship was found between leaf color (SPAD units) and the percentage N in both treatments (Fig.1). The data indicate that the leaf N concentration was not modified by the irrigation treatments. Therefore, PRD was not a limiting factor for apple-tree nutrition, as is sometimes observed in RDI (*Irving* and *Drost*, 1987; *Mills* et al., 1994). This finding may be due to the way the fertilizers were applied here, which was similar to that used successfully in a split-root experiment with maize (*Hu* et al., 2009). It is also possible that lateral water movement from the wetted roots to the drying part of the root system (*Stoll* et al., 2000; *Smart* et al., 2005) may have contributed to nutrient acquisition, and therefore nutrient concentrations became similar between treatments. Additionally, rainfall in the last third of the growing season (late June and August) may have contributed also to nutrient uptake in both sides of the root system. Nevertheless, the leaf K and Zn values suggest that deficiencies of these two nutrients are possible, and therefore their uptake may need further study under our conditions and in climates where groundwater is the main water source for irrigation and rainfall is negligible or occurs outside the growing season.

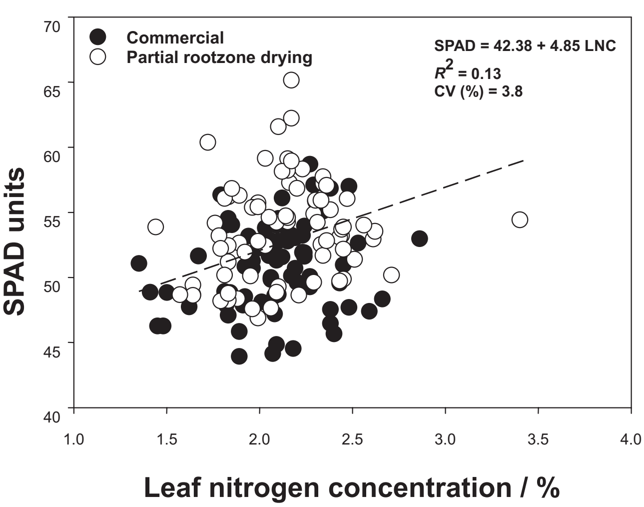

Figure 1: Relationship between leaf color (SPAD units) and leaf nitrogen concentration (LNC) of field-grown apple trees (cv. Golden Delicious/M.7) undergoing commercial irrigation or partial rootzone drying during three consecutive growing seasons (2005–2007). The coefficient of variation and coefficient of determination are CV and R^2, respectively.

4 Conclusions

During a 3-year field trial on a sandy-loam soil with pH 7.5 and 0.57% organic matter, data suggest that PRD irrigation did not affect apple-tree nutrition in a semiarid agro-ecosystem. Nevertheless, this result must be confirmed in other semiarid regions where the rainfall is negligible or occurs outside the growing season.

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