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PERFORMANCE OF 'GOLDEN DELICIOUS' APPLES GROWN IN A SEMI-ARID REGION UNDER PARTIAL ROOTZONE DRYING

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SUMMARY - Plant-water availability represents the main environmental limitation for arid and semi-arid agro-ecosystems where water for irrigating is scarce and expensive resource for apple production. This is the case for the North part of Mexico where 70% (≈ 44 thousand hectares) of apples are grown. The objective of this research work was to determine the impact of partial rootzone drying (PRD) on the pre- and post-harvest performance of 'Golden Delicious' apple grown in a semi-arid region. Treatments were: full irrigation (FI, as control) and PRD. The 100 % and 50 % of the irrigation water depth (IWD) was supplied to FI and PRD, respectively. In the latter treatment, irrigation was given alternatively from the wetted side to the drying side of the root system every 8 days or when soil water content reached a threshold of soil water depletion. In general, leaf water potential appeared unaffected by treatments. Yield was the same between treatments, but water use efficiency was higher in PRD trees by 70 %. A soil water balance pointed out that PRD saved water by *ca* 44 %. Mean weight, flesh firmness, total soluble solids concentration of fruit were the same between treatments. Concentration of dry matter of fruit was higher in PRI trees than in FI trees. Fruit quality parameters were consistent after storage for 18 days (15 ºC and 53 % of relative humidity). Fruit weight loss was similar between treatments. There was a strong tendency to enhance fruit quality by PRD which deserves to be further studied in other apple cultivars for their implications for fresh-marketing and long-term storage.

Key words: *Malus pumila* Mill, plant water potential, yield, fruit quality, post harvest.

PERFORMANCE DE LA POMME 'GOLDEN DELICIOUS' DANS UNE REGION SEMI-ARIDE SOUMISE A L´IRRIGATION PARTIELLE

RESUME *– La disponibilité de l'eau pour les plantes, représente une limite environnementale dans les écosystèmes agricoles des régions semi-arides où l'eau pour l'irrigation et la production des pommes est rare et coûteuse. Ceci est le cas du nord du Mexique où l´on trouve le 70% de la surface nationale des pommes (plus ou moins 44,000 hectares). L'objectif de ce travail d'investigation est de déterminer l'impact de l´irrigation partial (en anglais PRD) et son effet sur la pré et post récolte de la pomme 'Golden Délicieux' dans une région semi-aride. Les traitements choisies ont été: irrigation totale comme témoin (en anglais FI), et irrigation partielle (PRD). La quantité d´eau a été apporte en un 100% pour le témoin (FI) et en un 50% pour le PRD. Pour ce dernier traitement, on a irrigue alternativement chaque 8 jours: du côté humide au côté sec des racines ou quand le contenu de l'eau du sol arrivait au seuil prédétermine. En général, le potentiel hydrique de la feuille, ne fut pas affecté pour les traitements. Le rendement a été le même entre traitements, mais l'efficacité de l'eau a été un 70% meilleure sur les arbres partiellement irrigués. Le bilan hydrique du sol a montre que les arbres partiellement irrigués, économisaient 44% de l'eau. Le poids moyen, la fermeté du fruit, la concentration totale des solides solubles ont été identiques entre traitements. La concentration en matière sèche du fruit a été plus élevée pour les arbres partiellement irrigués. Les paramètres de la qualité du fruit ont été consistants après 18 jours de stockage (15°C et 53% d´humidité relative). La perte du poids du fruit a été similaire entre traitements. Il a eu, une tendance très forte à améliorer la qualité du fruit sur les arbres partiellement irrigués, tendance qui mérite d'être étudie plus profondément sur différents cultivars de pomme, dû à son implication dans le marché «en frais » et dans le stockage à long terme.*

Mots-clés: Malus pumila *Mill, potentiel hydrique des plantes, rendement, qualité du fruit, post récolte.*

INTRODUCTION

After grapes, apple is the most cultivated fruit crop worldwide (FAOSTAT, 2006). Irrigation is important for achieving both high yield and fruit quality, but water is scarce and expensive in many regions where apples are grown (Lötter *et al*., 1985). This is particularly true in arid and semi-arid agro-ecosystems. This is the case for apple production in the North part of Mexico where approximately 44 thousand hectares are cultivated with this fruit crop. Here, the goal is to increase agricultural water productivity by improving irrigation water use efficiency (WUE_I) of apple crop. Therefore, new irrigation strategies need to be developed.

Regulated deficit irrigation (RDI) has been a strategy to save water not only for apple production (Behboudian and Mills, 1997), but other fruit crops (Moriana *et al*., 2003; Romero *et al*., 2005). However, application of RDI normally correlates negatively with lower fruit size and yield, but enhances fruit quality in terms of concentration of soluble solids, dry matter, flesh firmness, and lesser fruit water loss of fruit under storage (Kilili *et al*., 1996a; 1996b; Mpelasoka *et al*., 2000; 2001a; 2001b; Leib *et al*., 2006).

Partial rootzone drying (PRD) is another water-saving irrigation strategy which has been developed and tested for grapevines in Australia since ten-year ago (Loveys *et al*., 1997). This technology consists that at each irrigation turn; only a part of the root system is wetted, with the complement left to dry to a pre-determined level of soil water depletion (Zegbe, 2003). PRD attempts to save water by up to 50% and yet to maintain yield as shown for some grape cultivars (Loveys *et al*., 2000). Nowadays, PRD technology has been tested in pear (Kang *et al*., 2002), red raspberries (*et al*., 2002), peach (Goldhamer *et al*., 2002), olive trees (Fernández *et al*., 2004), and apples (Zegbe, 2003; van Hooijdonk *et al*., 2004; Caspari *et al*., 2004; Leib *et al*., 2006). PRD has improved WUE_I and maintained both, yield and fruit quality of 'Pacific Rose^{TM}' apples grown in a humid area of New Zealand (Zegbe, 2003; van Hooijdonk *et al*., 2004). In contrast, PRD has trended to increase yield and fruit quality in 'Braeburn' (Caspari *et al*., 2004) and in 'Fuji' apples grown under semi-arid conditions (Leib *et al*., 2006). This suggests that PRD could perform according to the cultivar and climatic conditions. Irrigation regimes affect quality and storage life of fruit as was demonstrated in peaches (Crisosto *et al*., 1994), but the influence of PRD under storage conditions has been little (Lieb *et al*., 2006) or not studied (van Hooijdonk *et al*., 2004). Therefore, the objective of this research work was to determine the impact of partial rootzone drying (PRD) on the pre- and post-harvest performance of 'Golden Delicious' apple grown in a semi-arid region. We postulated that PRD could induce adverse effects on yield, fruit quality and fruit post harvest life due to high evaportranspirative demand and lack of rain during blooming time and during the first fruit growth stage.

MATERIALS AND METHODS

Experimental site, plant material, and treatments

The experiment was conducted at the Campo Experimental Zacatecas in Calera de V.R., Zacatecas, Mexico (latitude 22° 54' N, longitude 102° 39' W) during the growing season of 2005. The research site has a dry-temperate climate and it is located at 2, 197 m over the sea level with mean annual temperature of 14.6 º. Average chilling accumulation from November to February is ≈ 600 chill units. Average annual rainfall is about 416 mm, which 75 % occurs between July and October; while average pan evaporation is 1609 mm. The largest differences between rainfall and evaporation are found from March to June. The orchard soil is sandy clay loam, poor in organic matter (0.57 %) and pH of 7.5. Thirty five-year-old 'Golden Delicious' apple trees growing on M7 were used in this trial. The trees were spaced at 5 m between rows and 3.5 m within the row and trained as a central leader.

Ten experimental units, each comprising four trees, were selected and then randomly allocated to two irrigation treatments (five experimental units per treatment). The two middle trees of every experimental unit were used for data collection. The Irrigation treatments were: 1) Fully irrigated control (FI); and 2) Partial rootzone drying (PRD). The last treatment received 50% of water given in FI trees.

Irrigation in both treatments was applied by installing two parallel irrigation lines (one to each tree row) and placed 50 cm away from the tree trunk. Trees were drip irrigated by using ten drippers (five on each side of the tree row) that emitted ≈ 40 L h^{-1}. Irrigation in PRD trees was applied to one side of the tree row and the other side was left to dry until volumetric soil water content (θ) dropped close to permanent wilting point (θ_{PWP} = 0.15 cm^3 cm^{-3}) and it was irrigated to bring it back close to field capacity (θ_{FC} = 26 cm^3 cm^{-3}). Estimation of irrigation water depth applied is explained below.

Trees received standard cultural practices for local commercial fruit production including: pruning (between 9 and 16 February), application of chemical endodormancy releasers (10 March) thinning (39 days after full bloom, DAFB), fertilisation, pest and disease control, and weed control.

Measurements of volumetric soil water content

Since the beginning of the experiment and from then on, volumetric soil water content was monitored before (θ_{bi}) and 24 h after each irrigation (θ_{ai}) with time domain reflectometry technique (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 pair each side of the row) at a distance of 25 and 50 cm away from the drippers and tree trunk, respectively. However, because of malfunctioning of the equipment, most of the soil moisture monitoring was done with the gravimetric method, at the same soil depth.

Estimation of the irrigation water depth, evapotranspiration of the crop, and potential evapotranspiration

Irrigation water depth (*IWD*) was estimated beginning with data of soil water content at field capacity (θ_{FC}), soil water content before irrigation (θ_{bi}), and a soil depth of 40 cm according to the following: $IWD = \left(\left(\theta_{FC} - \theta_{bi}\right) \times 400mm\right)$. Because of a drip irrigation system was used the IWD was corrected by the application system efficiency, therefore the total IWD (TIWD) applied was: TIWD = IWD/0.9. Evapotranspiration of the crop per treatment (ETc for FI or PRD in millimetres) was estimated (for periods between irrigation events) by using the following water budget procedure (Brady and Weil, 2000):

$$ETc_{FI\ or\ PRD} = SWD_i + ER + IWD - SWD_{i+1}; \tag{1}$$

In which ER (Quiñones, 1997) is estimated from:

$$ER = (AR - 10) \times 0.8 \tag{2}$$

where: SWD$_i$ and SWD$_{i+1}$ (mm) are the soil water depth at the beginning and end of the period respectively ($SWD = \theta_{bi} \times 400\,mm$), ER (mm) is the portion of the rainfall that is infiltrated into the soil profile, and AR (mm) is the accumulated rainfall in the period. For PRD treatment, a water budget was independently estimated to each side of the tree row to get the ETc. It is important to note that in the case of the drying side the IWD was not considered. Daily Potential Evapotranspiration (PET in mm) and daily rainfall (R) were recorded in an automatic weather station located at the Campo Experimental Zacatecas. Finally, R, ETc (for FI and PRD) and PET were weekly accumulated during the growing season.

Measurements of leaf water potential

Diurnal changes in leaf water potential (Ψ_{leaf}) were recorded using a Scholander pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, California, USA) on mature and exposed leaves of shoots placed in the middle and outer part of the trees. This was done at 06:00, 09:00, 12:00, 15:00, and 18:00 hours on 54, 69, and 131 DAFB.

Fruit Growth, shoot length, and tree trunk

Fruit growth was recorded at weekly intervals, in terms of fruit diameter, on ten fruit randomly sampled at the outer and middle part of each tree canopy with a digital hand-calliper (Digimatic, model 50-321, Mitutoyo, Co., Japan) until growth ceased. Shoot growth in apple was measured by selecting and tagging similar sized current-season shoots at 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 before and at the end of the experiment at 20 cm above the graft level. Tree trunk diameter was expressed in terms of trunk cross-sectional area (TCSA).

Yield, fruit quality, and water use efficiency

At harvest, which occurred on 140 DAFB, fruit from each tree were counted and weighed and the yield was recorded as the sum of individual weight of fruit from each tree (gross yield). Mean fresh weight of fruit (MFMF) was calculated by dividing the gross yield by number of fruit per tree. Yield efficiency was calculated by dividing the yield per tree by the corresponding TCSA. Water use efficiency (WUE) for treatment was obtained as the ratio of the gross yield (kg ha^{-1}) to the corresponding cumulative ETc value and then expressed as kg ha^{-1} mm^{-1}.

At harvest, six-fruit per plot per treatment were randomly selected to assess fruit quality parameters. After removing fruit skin, two flesh firmness (FF) determinations were done on two opposite sides in the equatorial part of each fruit using a press-mounted Effegi penetrometer (Model FT 327, Wagner Instruments, Greenwich, CT, USA) with an 11.1-mm head. Total soluble solids concentration (TSSC) was measured mixing some drops from each side of the fruit with a digital refractometer (Model PR-32α, Atago, Co. ltd., Tokyo, Japón) with automatic temperature compensation. Dry matter concentration of fruit (DMCF, expressed on a fresh weight basis) was determined from a 25-g fresh cortical tissue, oven-dried at 60° C during 15 d. Another set of six-fruit per plot per treatment was used to evaluate fruit quality, in terms of FF, TSSC, and DMCF after 18 days in storage at 15 ± 1 ºC and 53 ± 5 % of relative humidity. During storage, each fruit was individually weighted every other day and fruit weight loss was calculated as the percent reduction from initial weight.

Statistical analysis

Data were analysed by completely randomised model using GLM procedure of SAS software (SAS Institute ver. 9.1, 2002-2003). Treatment means were compared and separated by Scheffé's test at $P \leq 0.05$.

Results and Discussion

The PET is presented as reference to the ETc under FI and PRD (Fig. 1A). ETP was higher than the ETc of FI between 0 and 114 days after full bloom (DAFB). Thereafter, ETc of FI was higher than ETP which was, in part, due to the low precipitation rain (174 mm), a higher water demand by the tree crop, and the tree phenological stage (fruit elongation mainly, Fig. 3.). In contrast, ETc of PRD was approximately lower by 35 and 44 % in relation to PET and ETc of FI, respectively. Consequently, PRD treatment saved water by 44 % compared with FI treatment. Cumulated values for PET, ETc of FI, and ETc of PRD were: 720, 789, and 445 mm, respectively.

Volumetric soil water content (θ) was maintained near the field capacity (FC) in FI trees, while it was alternatively increasing and decreasing during the growing season as the irrigation was shifted from the wetted side to the drying side in PRD trees (Fig. 1B). In some occasions, θ dropped to the permanent wilting point level or below, but this situation did not affected negatively on the response variables evaluated (*Table 1*); such behaviour suggests that water uptake by roots system was taken place in deeper soil depths. Variation of θ in both sides of PRD treatment was greater between 0 and 94 DAFB; afterwards, θ variation was lesser between both sides of PRD trees. This was concomitant with the precipitation, which may have overridden an eventual water deficit effect on PRD trees in favour of yield maintenance between PRD and FI trees (as show latter). Information suggests that PRD irrigation protocol had relevance only during the first half of the growing season; thereafter the presence of rain may also contribute to save water in PRD treatment.

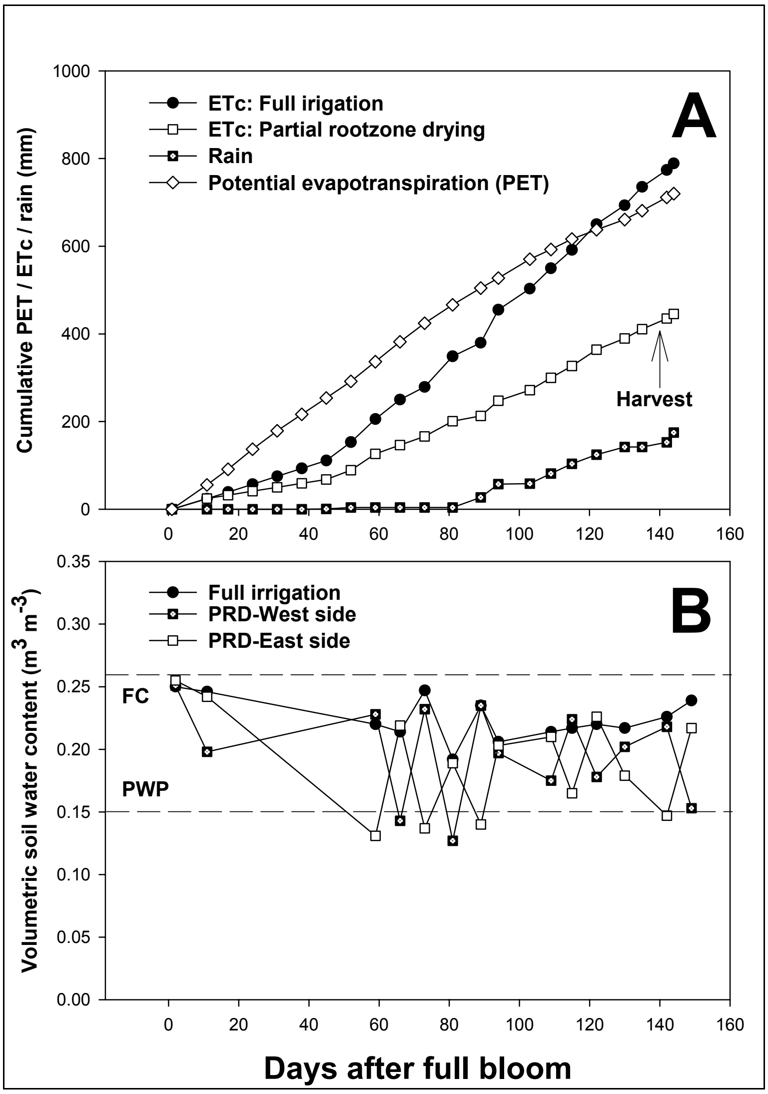

Fig. 1. Accumulated reference of potential evapotranspiration, crop evapotranspiration (ETc) for full irrigation (FI) and partial rootzone drying (PRD) of 'Golden Delicious' apple trees (A). Changes in the volumetric soil water content in response to FI and PRD in both sides of the root system (B). Field capacity (FC); permanent wilting point (PWP).

Theoretically, it is expected that plants experiencing PRD promote positive signals inducing partial closure of stomata. Transpiration will therefore decrease maintaining leaf water potential (Ψ_{leaf}) similar to those well watered and so water use efficiency can improved (Gowing *et al.*, 1990; Dry and Loveys, 1998; Davies *et al.*, 2002). This could be the case for this trial, because drying one side of the PRD tree row resulted in non significant reduction in Ψ_{leaf} during diurnal cycle for three sampling dates (Fig. 2). Therefore, maintenance of Ψ_{leaf} in PRD trees may be explained by the increase in the rate of water absorption by roots in the wetted soil as observed in apple roots by Green *et al.* (1997). Green and Clothier (1995) observed that water absorption was enhanced upon re-watering in the roots of kiwifruit vines that had been previously water deprived. Both mechanisms could take place in apple roots resulting in similar values of Ψ_{leaf} between PRD and FI trees. However, we observed that Ψ_{leaf} in PRD trees was slightly lower compared with FI trees, maybe because of the vapour pressure deficit at field conditions is higher than in controlled conditions as demonstrated in a split-root apple experiment by Gowing *et al.* (1990) and reiterated by Dry and Loveys (1998) and Davies *et al.* (2002). Our Ψ_{leaf} behaviour agrees with that in apple (Zegbe, 2003) and in olive trees (Fernández *et al.*, 2006) both exposed to PRD under field conditions.

In theory, PRD maintains the basic plant physiological processes (e.g. Ψ_{leaf}) similar to those of well watered plants (Gowing *et al.*, 1990; Croker *et al.*, 1998; Dry y Loveys, 1998; Stoll *et al.*, 2000; Davies *et al.*, 2002); therefore, yield and yield components would not be adversely affected, but water use efficiency would have been significantly improved compared with FI (Davies *et al.*, 2002). Ours findings agree with those of Davies *et al.* (2002), because in this experiment, number of fruit per tree, yield, trunk cross-sectional area, yield efficiency, final shoot growth, and fruit growth were the same between treatments ($P \leq 0.05$), but the water use efficiency improved significantly ($P \leq 0.05$) in PRD trees relative to FI trees (*Table 1* and Fig. 3). An increase on fruit number and yield by applying PRD has been reported in pear (Kang *et al.*, 2002) and in apple (Caspari *et al.* 2004; Leib *et al.*, 2006). This was not observed in our experiment or others reports with apples (Zegbe, 2003; van Hooijdonk *et al.*, 2004) or peaches (Goldhamer *et al.*, 2002). Therefore, results in the former reports suggest that the crop load was not adjusted at the start of their experiment. We found *ca* 70 % rise in water use efficiency in the PRD trees compared with FI trees as result of yield maintenance in PRD trees. Values quoted from the literature are: 20% for peach (Goldhamer *et al.*, 2002), 27 % for pear (Kang *et al.*, 2002), 89-100 % for grape (du Toit *et al.*, 2003; dos Santos *et al.*, 2003), and 93-120 % for apple (Zegbe, 2003; van Hooijdonk *et al.*, 2004). Water saved by PRD was *ca* 44 % similar to that reported by Leib *et al.* (2006) for 'Fuji' apple grown in a semi-arid environment. Another benefit of PRD is the reduction of pruning cost by reducing shoot growth as shown for field-grown grapevine (Dry *et al.*, 2000; du Toit *et al.*, 2004). In contrast, because of not measurable changes in (Ψ_{leaf}), not differences in apple shoot length between PRD and FI treatments were observed (*Table 1*).Then, PRD does not offer advantages in controlling apple tree growth, and therefore, in reducing pruning cost.

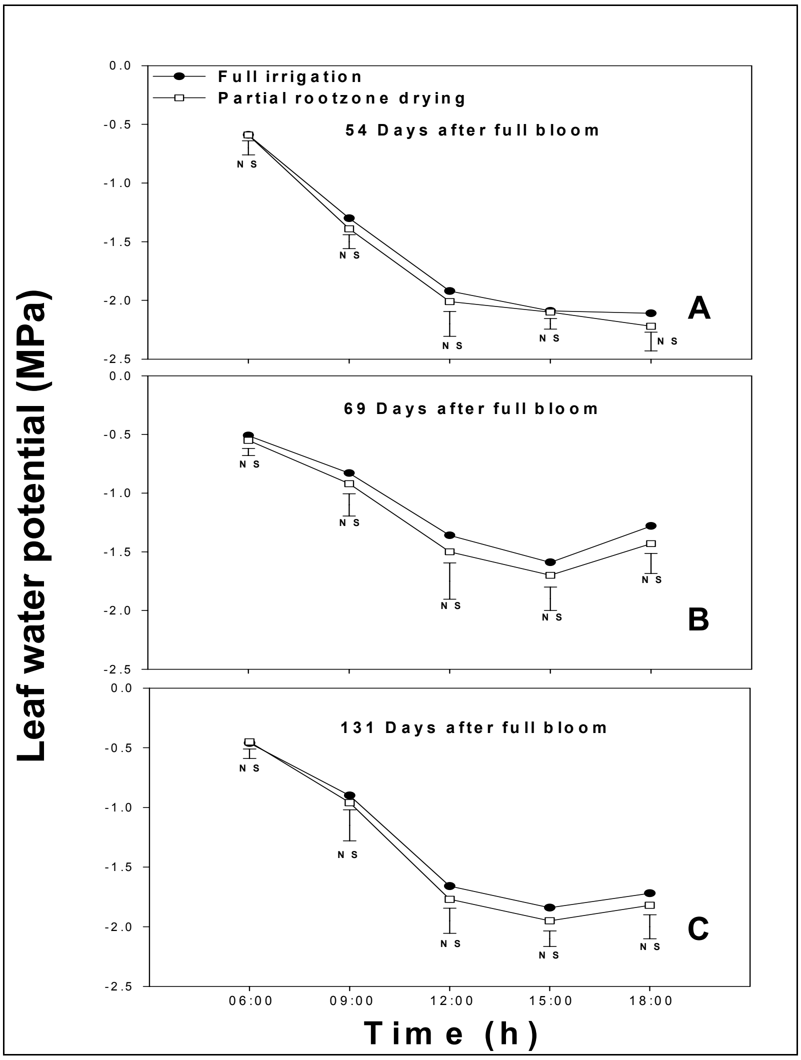

Fig. 2. Diurnal changes of leaf water potential for three occasions of 'Golden Delicious' apple trees under full irrigation and partial rootzone drying trees. Vertical bars represent the Scheffé's critical value and NS indicate non significant differences both at $P \leq 0.05$.

Table 1. Yield and yield components of 'Golden Delicious' apples at harvest under full irrigation (FI) and partial rootzone drying (PRD). Means within rows followed by the same letter are not significantly different by the critical value of Scheffé's test at $P \leq 0.05$.

Response variables	Irrigation treatments		Significance P > F
	FI	PRD	
Number of fruit per tree	241a¶	200a	0.653
Yield (kg tree^{-1})	15.7a	13.1a	0.675
Trunk cross-sectional area (TCSA)	360a	341a	0.707
Yield efficiency (kg tree^{-1}/cm^2 TCSA)	0.04a	0.04a	0.816
Water use efficiency (kg·ha^{-1} mm^{-1})	02.3b	03.9a	0.0001
Final shoot length (cm)	21.0a	20.8a	0.853

Except for fruit dry matter concentration (DMC), which was higher in PRD than in FI fruit, the remaining fruit quality attributes did not differ ($P \leq 0.05$) between treatments (*Table 2*). Nevertheless, the lack of detectable differences between treatments, there was a strong trend to increase both flesh firmness (FF) and total soluble solids concentration (TSSC) in PRD fruit. However, this cannot be attributed to a dilution phenomenon, because fruit growth and mean fruit weight were the same between treatments (*Table 2* and Fig. 3). Fruit cells are more densely packed as a result of reduced irrigation (Mpelasoka *et al.*, 2000). This could have led to increase DMC of PRD fruit in favor of the trend to enhance FF and TSSC.

Table 2. Effect of full irrigation (FI) and partial rootzone drying (PRD) on some fruit quality attributes at harvest of 'Golden Delicious' apple trees. Means within rows followed by the same letter are not significantly different by the critical value of Scheffé's test at $P \leq 0.05$.

Response variables	Irrigation treatments		Significance
	FI	PRD	P > F
Mean fruit weight (g)	108.6a	107.5a	0.773
Flesh firmness (Newtons)	68.5a	71.2a	0.491
Total soluble solids concentration (%)	16.9a	17.6a	0.101
Dry weight concentration of fruit (mg g^{-1} fresh weight)	184.4b	200.6a	0.001

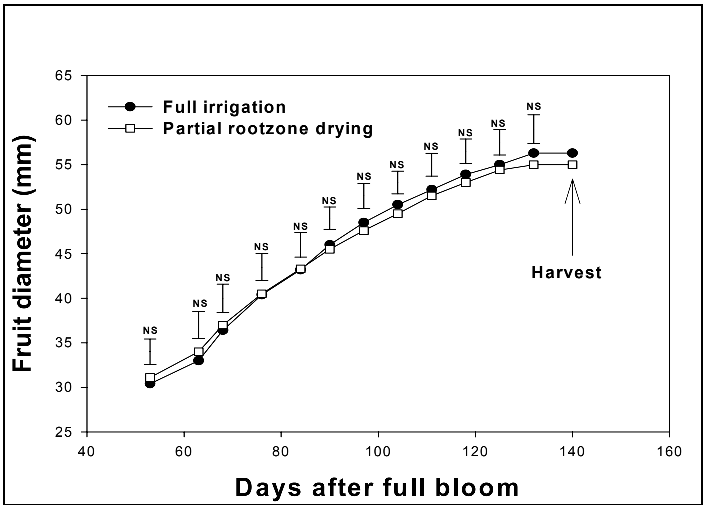

Fig. 3. Cumulative fruit growth of 'Golden Delicious' apple trees under full irrigation and partial root zone drying. Vertical bars represent the Scheffé's critical value and NS indicates non significant differences both at $P \leq 0.05$.

Fruit quality attributes were consistent after 18 days in storage (*Table 3*). Nevertheless fruit water lose was the same ($P \leq 0.05$) between treatments, there was a tendency for higher weight loss in PRD fruit than in FI fruit (Fig. 3). After harvest, fruit respiration and transpiration continues, resulting in weight loss (Wills et a., 1998). As PRD had more substrates, in terms of TSSC, to be respired, this could be a reason to increase fruit water loss.

Table 3. Effect of full irrigation (FI) and partial rootzone drying (PRD) on some fruit quality attributes of 'Golden Delicious' apple alter 18 days in storage at 15 ± 1 ºC and 53 ± 5 % of relative humidity. Means within rows followed by the same letter are not significantly different by the critical value of Scheffé's test at $P \leq 0.05$.

Response variables	Irrigation treatments		Significance
	FI	PRD	P > F
Mean fruit weight (g)	100.5a	100.9a	0.905
Flesh firmness (Newtons)	54.5a	53.4a	0.502
Total soluble solids concentration (%)	17.6a	18.6a	0.058
Dry weight concentration of fruit (mg g^{-1} fresh weight)	180.0b	196.5a	0.001

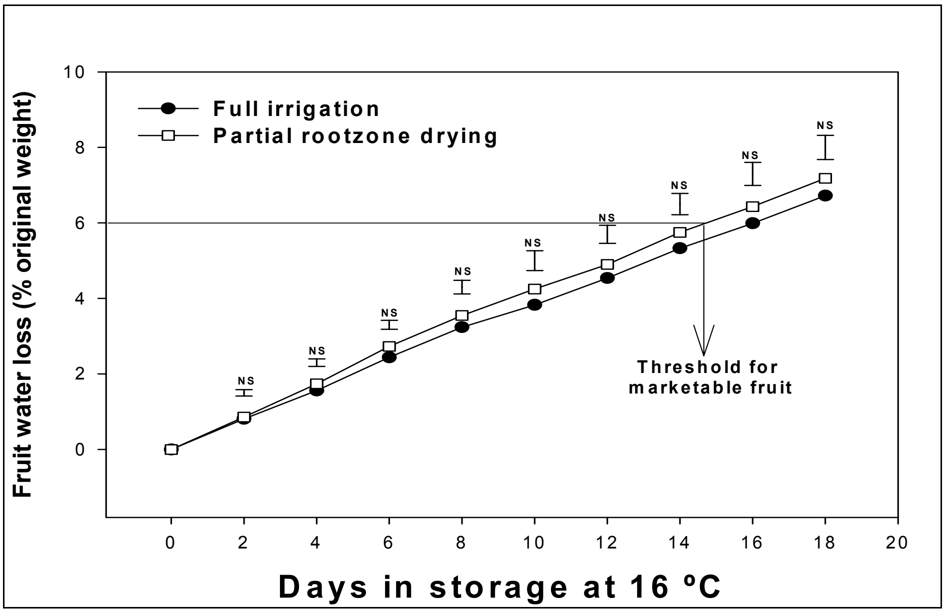

Fig. 4. Cumulative fruit water loss as percentage of original weight during storage at 15 ± 1ºC and 53 ± 5 % relative humidity for 18 day of 'Golden Delicious' apple trees under full irrigation and partial rootzone drying. Vertical bars represent the Scheffé's critical value and NS indicates non significant differences both at $P \leq 0.05$.

The study showed that drip-irrigated apple trees exposed to PRD did not experience significant changes in Ψ_{leaf}. Yield and yield components were the same between treatments. Water use efficiency, calculated as the yield per unit of water use, was improved by 70 % in PRD trees over CI trees, resulting in water saving by 44 % by applying PRD. Fruit growth and shoot length were the same between treatments. Except of dry matter concentration in PRD fruit, fruit quality, in general, was not enhanced by PRD, but there was a tendency to increase flesh firmness and total soluble solids concentration at harvest, which it was consistent after 18 days in storage. Fruit water loss was also the same between treatments, but PRD seemed to loss more fruit weight in relation to FI fruit, which deserve more research attention. Therefore PRD irrigation could be suggested as a water saving practice for semi-arid areas similar to our experimental conditions where water is scant and expensive for irrigation and the evapotranspiration demand is also higher in half of the growing season.

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