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Responses of 'Petopride' processing tomato to partial rootzone drying at different phenological stages

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Abstract Partial rootzone drying (PRD) is a water-saving irrigation practice which involves watering only part of the rhizosphere at each irrigation with the complement left to dry to a pre-determined level. The effect of PRD, applied at different phenological stages, on yield, fruit growth, and quality of the processing tomato cv. 'Petopride' was studied in this experiment. The treatments were: daily full irrigation (FI) on both sides of the root system considered as the control, and PRD treatments applied at three phenological stages. These were: during the vegetative stage until the first truss was observed ($PRD_{VS–FT}$), from the first truss to fruit set ($PRD_{FT–FS}$), and from fruit set to harvest ($PRD_{FS–H}$). In some occasions, leaf xylem water potential was lower in each PRD period than in FI. Number of fruits, total fresh and dry weight of fruit per plant, harvest index, and fruit growth were lower in $PRD_{FT–FS}$ and $PRD_{FS–H}$ plants than in FI and $PRD_{VS–FT}$ plants. However, irrigation water use efficiency, on a dry weight basis, was the same among the treatments. For $PRD_{FT–FS}$ and $PRD_{FS–H}$ treatments, mean fresh weight of fruit and fruit water content were reduced and dry matter concentration of cortex and total soluble solids concentration of fruit increased compared with FI and $PRD_{VS–FT}$ treatments. Incidence of blossom-end rot was the same among $PRD_{VS–FT}$, $PRD_{FS–FH}$, and FI fruit, but it was higher in $PRD_{FT–FS}$ fruit. Fruit skin colour was the same among treatments. Total dry weight of fruit per plant decreased by 23% for $PRD_{FT–FS}$ and by 20% for $PRD_{FS–H}$ relative to FI. Fruit quality improvement in $PRD_{FS–H}$ could compensate for the reduction in total dry weight of fruit where water is expensive for tomato production. But an economical analysis would be needed to substantiate this. PRD from the first truss to fruit set is not recommended because of the high incidence of blossom-end rot.

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Introduction

Water supplies are limited worldwide (Postel 1998) and there is an urgent need to identify and adopt efficient irrigation management strategies. As irrigation of agricultural lands accounts for over 85% of water usage worldwide (van Schilfgaarde 1994), even a relatively minor reduction in irrigation water could substantially increase the water available for other purposes. This is especially true for tomato (*Lycopersicon esculentum* Mill), which has the highest acreage of any vegetable crop in the world (Ho 1996). Partial rootzone drying (PRD) is a potential water-saving irrigation strategy where, at each irrigation, only part of the rhizosphere is wetted with the complement left to dry to a pre-determined level. PRD could save water by up to 50% and yet maintain yield as shown for some grape cultivars (Loveys et al. 2000). Plant water status is expected to equilibrate with the wettest part of the rhizosphere (Hsiao 1990) and therefore we expect PRD plants to maintain as high a leaf water potential as well-watered plants. Holbrook et al. (2002) showed that in a split-root experiment water potential was maintained for tomato. However, herbaceous plants might develop a lower leaf water potential than woody plants under PRD because in the former the root system is smaller and superficial, exploring a more limited soil volume (Davies and Zhang 1991; Kramer and Boyer 1995).

The phenological stages of tomato may react differently to PRD. These stages are affected by various non-hydraulic mechanisms (Mapelli et al. 1978; Ho 1984; Davies and Zhang 1991). Irrespective of plant water status, PRD is presumed to affect plants through a change in their hormonal balance (Loveys et al. 2000). We therefore applied PRD at different phenological stages to assess the effect on plant water status, yield, and fruit quality. We hypothesised that plant water status could be maintained, but at different phenological stages plant parameters including yield and fruit quality would respond differently to PRD.

Materials and methods

The experiment was conducted in a naturally lit glasshouse, with average maximum/minimum temperatures of 25/15°C, at the Plant Growth Unit, Massey University, Palmerston North (latitude 40°2′S, longitude 175°4′E), New Zealand. It was conducted from November 2002 to February 2003. Seeds of the processing tomato cv. 'Petopride' (Webling & Stewart Seeds, Onehunga, Auckland, New Zealand) were sown on 12 November 2002. Twenty-day-old individual and similar-sized plants were transplanted into 12 wooden boxes (2.53 m length × 0.65 m width × 0.20 m height), each housing four containers (0.60 m length × 0.60 m width × 0.20 m height), with one experimental plant per container (Fig. 1). One plant was transplanted into the centre of each container and roots colonised almost all the soil medium, but at the end of the experiment they were found more densely around the emitters. Before setting up the experiment and after some tests, lateral water movement was prevented in three ways. Firstly, a piece of wood (0.60 m length × 0.025 m width × 0.05 m height) was placed centrally on the base of each container. Secondly, each container was lined with black polyethylene with a thickness of 125 μm and laterally perforated at the bottom to allow drainage. Thirdly, observations indicated that water movement throughout the synthetic soil medium used was mainly vertical. Finally, location and distance of the emitters (Fig. 1) along with daily irrigation turns (described below) contributed to prevention of lateral water movement. Plants were grown in a bark:pumice:peat mixture ratio of 6:3:1 (by volume). They were fertilised (180 g/container) with a 1:2 (w:w) mixture of rapid- and slow-release fertilisers (Osmocote 15N–4.8P–10.8 K and Osmocote 16N–3.5P–10 K, respectively; Scotts Australia Pty. Ltd., Baulkam Hills, NSW, Australia). Both fertilisers and soil media were blended before filling the containers.

The first four trusses from the main stem of each plant were tagged as soon as they had developed. Pollination was assisted during anthesis with a truss vibrator to minimise flower abortion and to maximise the uniformity of fruit set among the treatments.

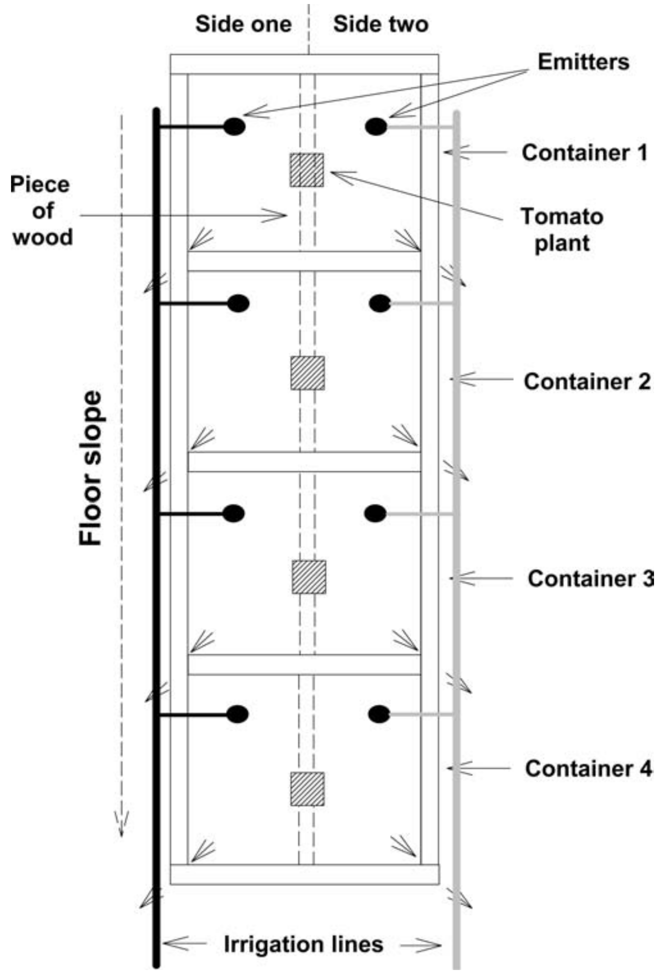

Fig. 1 Arrangement of the experimental wooden boxes. *Angled arrows* indicate drainage

Fourteen days after transplanting, four irrigation treatments were randomly applied to a total of 48 plants. The treatments were: daily full irrigation (FI) on both sides of the root system considered as the control, and three PRD treatments. The PRD treatments were applied at three phenological stages: during the vegetative stage until the first truss was observed (PRD_{VS-FT}), from the appearance of the first truss to fruit set (PRD_{FT-FS}), and from fruit set to harvest (PRD_{FS-H}). A completely randomised design was used with the four treatments replicated three times with four plants per plot. Each of the planting boxes, having four plant containers, was considered as a plot and the four plants in each box received the same treatment. Duration of each PRD treatment was determined by the length of the corresponding phenological stage. The durations were 12, 30, and 26 days for PRD_{VS-FT}, PRD_{FT-FS}, and PRD_{FS-H}, respectively. For the PRD treatments only one side of the rhizosphere was watered and the other side was left to dry for two consecutive days. The irrigation was then shifted to the dry side of the rhizosphere. This was accomplished by setting up two independent irrigation lines which operated separately (Fig. 1). Two emitters

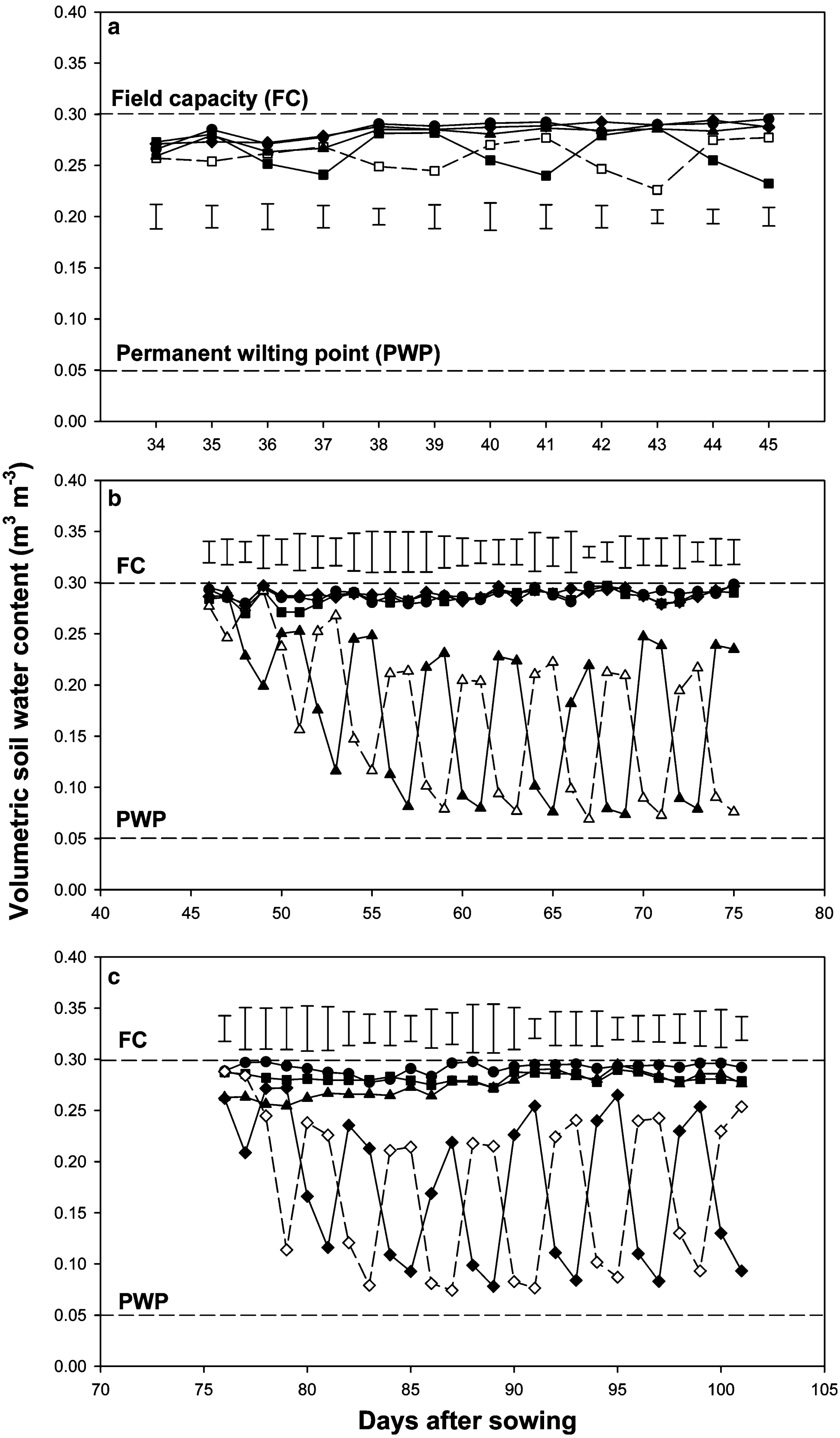

Fig. 2 Changes in volumetric soil water content (θ in the text) for fully irrigated (*FI*, *filled circle*) plants and partial rootzone drying (*PRD*) treatments in 'Petopride' processing tomato applied during the vegetative stage until the first truss (**a**, PRD_{VS-FT}), from the first truss to fruit set (**b**, PRD_{FT-FS}), and from fruit set to harvest (**c**, PRD_{FS-H}). *Empty symbols* represent the unirrigated side of each PRD treatment and their corresponding *full symbols* represent the irrigated side. The other *full symbols* in each **a**, **b**, and **c** either represent FI or the other two PRD treatments that were receiving full irrigation at the time. *Vertical bars* represent the minimum significant difference (*MSD*) by Tukey's Studentised range test at $P \leq 0.05$

(4 l h^{-1}) per plant, one on each line, were placed at 0.15 m away from the main stem (Fig. 1). At each irrigation PRD_{VS-FT}, PRD_{FT-FS}, PRD_{FS-H}, and FI were given an average of 4.3, 3.7, 3.5, and 4.5 l of water per plant, respectively. The average and total volume of water given in PRD treatments was influenced by the

duration of each phenological stage. This amount of water was applied daily at 0700, 1000, 1300, and 1600 hours by an automated drip irrigation system. Totals of 347, 300, 282, and 366 l of water (gross irrigation) per plant were applied to $PRD_{VS–FT}$, $PRD_{FT–FS}$, $PRD_{FS–H}$, and FI, respectively, from transplanting to harvest.

Volumetric soil water content (θ, $m^3\ m^{-3}$) was recorded daily on both sides of the row at 0.20 m depth and 0.05 m away from the emitters. This was done within 60 min after the last irrigation (1600 hours) by time domain reflectometry (TDR Trase System; Soil Moisture Equipment Corp., Santa Barbara, CA). Field capacity was reached at a θ of 30% and this was established according to Parchomchuk et al. (1997) before setting up the experiment. The amount of water supplied daily to bring soil water up to field capacity was calculated with a calibration curve previously obtained by using the relationship between TDR readings against known volumes of water. The water use increased in relation to crop development. Leaf xylem water potential was measured with a pressure chamber (Soil Moisture Equipment Corp.). At each measurement time, three plants per treatment were measured and two leaflets from each of these plants were sampled. Measurements were taken at 0500, 0900, 1200, 1500, and 1800 hours after 45, 65, and 85 days of sowing, corresponding to the three phenological stages, VS–FT, FT–FS, and FS–H, respectively.

Fruit from each plant was counted and weighed. They were then cut into halves and oven-dried at 85°C to a constant weight to determine total dry weight. The remaining parts of the plants, including the roots, were collected, weighed, and then oven-dried at 70°C to constant weight. Irrigation water use efficiency was calculated for each treatment by dividing total dry weight of fruit per plant by the litres of irrigation water applied to the plant. Harvest index was obtained by dividing total dry weight of fruit by total dry weight of plant. Fruit larger than 55 mm diameter were considered as marketable fruit (Obreza et al. 1996). Fruit size, in terms of mean fresh weight of fruit, was obtained by dividing fresh weight of all fruits by their number. Fruit growth was measured on the first two fruit from the second trusses. Fruit's equatorial diameter was measured once a week from 9 days after anthesis to harvest with a hand-held digital caliper (Mitutoyo Co., Kanagawa, Japan).

Eight fruit per plot from the first four trusses were randomly chosen and tagged at mature green stage and then later harvested at firm red stage to assess fruit quality. The fruit were assessed for the background skin colour in terms of hue angle. Measurements were taken on two opposite sides of the middle part of each fruit using a chromameter (CR-200; Minolta, Osaka, Japan). After measuring colour, fruit were cut into halves and a few drops from each half were used to measure total soluble solids concentration with a hand-held refractometer with automatic temperature compensation (ATC-1; Atago, Tokyo, Japan). After sampling for total soluble solids concentration, a fresh sample of approximately 25 g from the cortical tissue of each fruit was weighed and then oven-dried at 85°C to constant weight, and the dry matter concentration of fruit was expressed on a fresh weight basis. The remaining parts of each fruit were individually oven-dried at 85°C to a constant weight for measurement of fruit water content which was expressed on a fresh-weight basis.

Data were analysed by a completely randomised model using the GLM procedure of SAS software version 8.2 (SAS Institute, Cary, NC). To stabilise the variance, the variables expressed in percentage were arcsine-transformed and those expressed in discrete units were square-root transformed, respectively. Means are reported after back transforming. Treatment means were separated by Tukey's Studentised range test at $P \le 0.05$.

Results

Soil water content was maintained close to field capacity in all treatments when PRD was not applied (Fig. 2a–c). But θ for each side of plants undergoing PRD treatment depended on whether the side was irrigated or not (Fig. 2). The irrigated sides in $PRD_{VS–FT}$ had a θ close to field capacity, but θ for the irrigated sides of $PRD_{FT–FS}$ and $PRD_{FS–H}$ was lower than field capacity by 5–10% (Fig. 2b, c). Soil dried close to permanent wilting point in the last two phenological stages. Soil media composition had pumice (30% by volume). As one side was drying and the irrigation times were short, pumice rehydration was partial compared with FI where dehydration was avoided at all times. It is also likely that the irregularity in soil porosity might have reduced the irrigation efficiency so that additional amount of water would have been necessary to fill all of the soil pores. But drainage would also have increased introducing serious errors in the calculation of irrigation water use efficiency.

Leaf xylem water potential (ψ_x) followed a diurnal pattern on all the dates of measurement reaching a minimum value at midday and starting to recover early in the afternoon (Fig. 3). Plants undergoing $PRD_{VS–FT}$ had low ψ_x only at midday (Fig. 3a), but those under $PRD_{FT–FS}$ or $PRD_{FS–H}$ had lower ψ_x in four occasions out of five throughout the day compared to the FI plants (Fig. 3b, c).

Total fresh weight of fruit was significantly reduced in $PRD_{FT–FS}$ and $PRD_{FS–H}$ compared with FI and $PRD_{VS–FT}$ (Table 1). The same was true for the number of marketable fruit, total dry weight of fruit, and harvest index (Table 2). The reason for the lower harvest index for $PRD_{FT–FS}$ and $PRD_{FS–H}$ was that their total dry weight of fruit was lower than the other two treatments (Table 2) while the total dry weight of plant was the same among the treatments. The values for the latter (minimum significant difference, MSD = 138 g) were 927.7, 1050.6, 861.0, and 902.7 for FI, $PRD_{VS–FT}$, $PRD_{FT–FS}$, and $PRD_{FS–H}$, respectively.

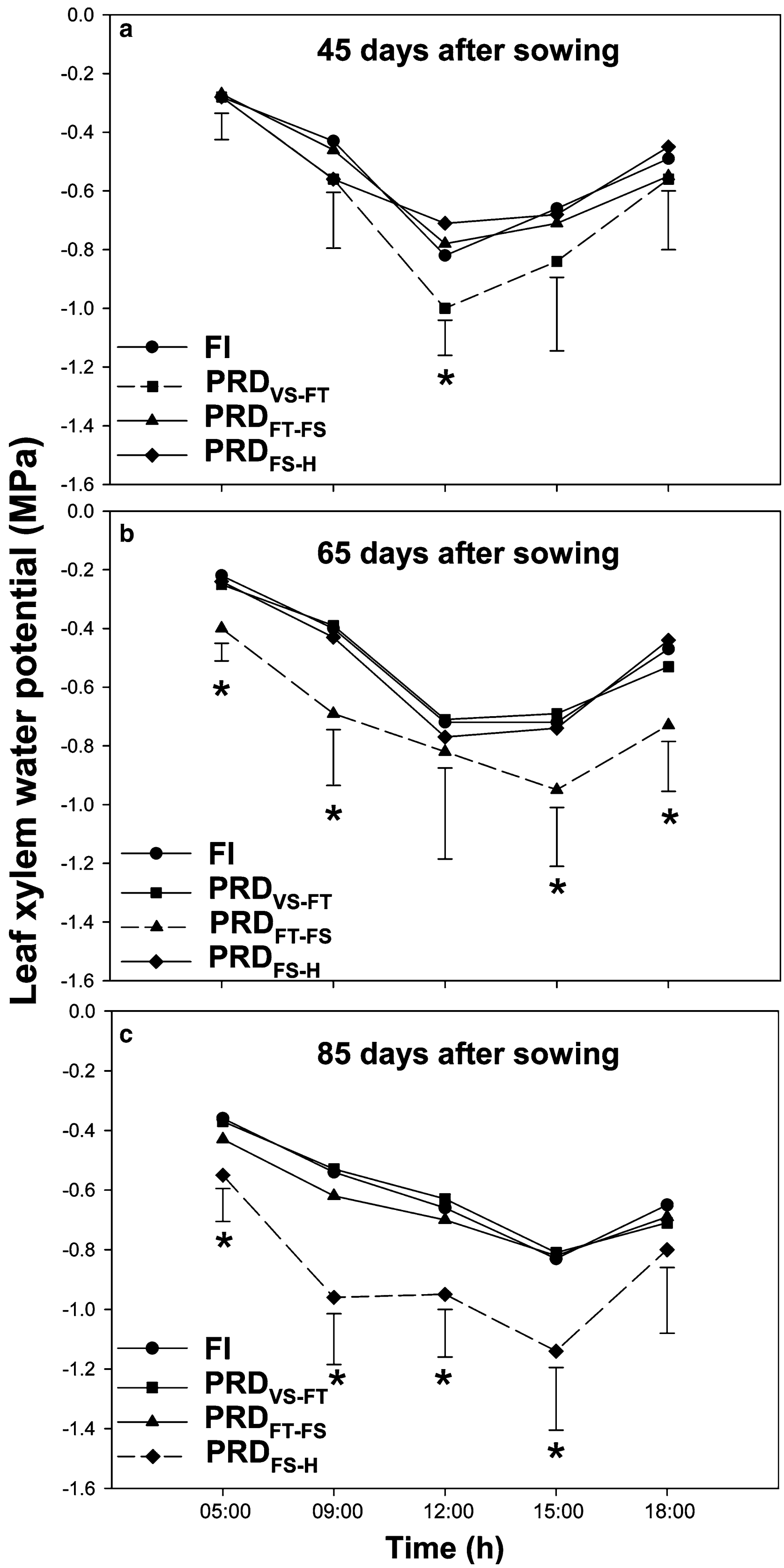

Fig. 3 Diurnal changes in leaf xylem water potential on three occasions in response to irrigation treatments: *FI* daily full irrigation, partial rootzone drying (*PRD*) during the vegetative stage until the first truss ($PRD_{VS–FT}$), from the first truss to fruit set ($PRD_{FT–FS}$), and from fruit set to harvest ($PRD_{FS–H}$). *Vertical bars* represent the MSD by Tukey's Studentised range test and the *asterisks* show significant differences at $P \leq 0.05$

Table 1 Number of marketable fruit (*NF*), total fresh weight of fruit (*TFWF*), total dry weight of fruit (*TDWF*), harvest index (*HI*), and irrigation water use efficiency expressed on a TDWF basis ($IWUE_{TDWF}$), all per plant, in response to irrigation treatments

Treatments	NF (per plant)	TFWF (kg/plant)	TDWF (g/plant)	HI	$IWUE_{TDWF}$ (g l^{-1} H_2O)
FI	52ab	5.3a	523ab	0.57a	1.4a
PRD_{VS-FT}	60a	5.9a	588a	0.56ab	1.7a
PRD_{FT-FS}	46bc	3.5b	404b	0.47bc	1.3a
PRD_{FS-H}	40c	3.4b	416b	0.46c	1.5a

FI daily full irrigation, partial rootzone drying (*PRD*) during the vegetative stage until the first truss (PRD_{VS-FT}), from the first truss to fruit set (PRD_{FT-FS}), and from fruit set to harvest (PRD_{FS-H}). *Different letters within columns* indicate significant differences by Tukey's Studentised range test at $P \leq 0.05$

Irrigation water use efficiency was the same among the treatments (Table 1). Fruit diameter was consistently lower in PRD $_{FT-FS}$ compared with FI from 76 DAS and these differences increased over time. Fruit diameter of PRD $_{FS-H}$ was lower compared with FI on 97 DAS. Fruit diameter tended to be less in PRD $_{VS-FT}$ compared with FI from 90 DAS (Fig. 4).

PRD_{FT-FS} and PRD_{FS-H} had lower mean fresh weight of fruit and fruit water content and higher dry matter concentration of cortex and higher total soluble solids concentration of fruit than FI and PRD_{VS-FT} (Table 2). However, PRD_{FT-FS} fruit had the highest blossom-end rot (BER) incidence (Table 2). Hue angle values were the same among the treatments. Nevertheless there was a trend for increased redness in skin colour of the PRD_{FS-H} fruit as hue angle values tended to be lower for this treatment (Table 2).

Discussion

Part of the rhizosphere too experiences a measure of drying with PRD and roots in the drying soil are expected to send chemical messages to the shoot. Although abscisic acid has been identified as a predominant chemical message, other chemicals might be involved (Sobeih et al. 2004). The non-hydraulic (chemical) signals can improve water use efficiency by inducing partial stomatal closure and therefore reducing transpiration without detectable changes in plant water status (Dry and Loveys 1999). We conducted this long-term experiment exposing processing tomato plants to PRD at different phenological stages. But ψ_x in PRD plants became lower than the FI plants. The PRD plants therefore experienced water deficit because the transpiration rate exceeded the absorption of water from the wetted part of the rhizosphere. The reduction of ψ_x was more noticeable in PRD_{FT-FS} and PRD_{FS-H} plants than the other two treatments. These phenological stages coincided with the summer months in the Southern Hemisphere with the expected higher evaporative demand of the atmosphere and the inability of the wetted part of the rhizosphere to meet this higher demand. Moreover, the amount of water given to the irrigated side and frequency of swapping the irrigation over from wet to dry sides may contribute to the reduced ψ_x as demonstrated by Zegbe et al. (2004, 2005). The root system was also confined to a relatively small container that might have limited the availability of water to the plants. It is expected that for field-grown tomato plants

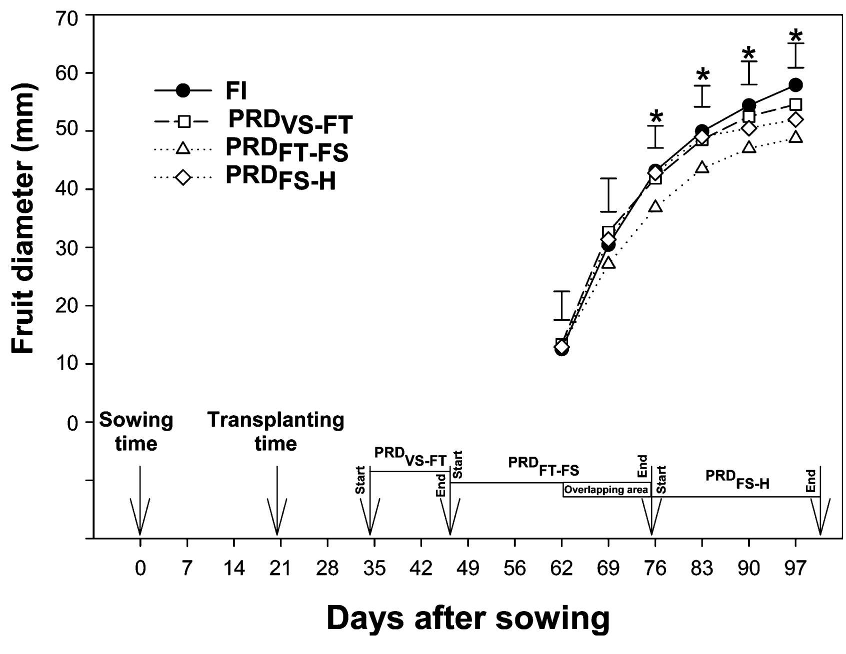

Fig. 4 Fruit diameter of 'Petopride' processing tomato in response to irrigation treatments: *FI* daily full irrigation, partial rootzone drying (*PRD*) during the vegetative stage until the first truss (PRD_{VS-FT}), from the first truss to fruit set (PRD_{FT-FS}), and from fruit set to harvest (PRD_{FS-H}). *Vertical bars* represent the MSD by Tukey's Studentised range test and the *asterisk* shows significant differences at $P \leq 0.05$

Table 2 Mean fresh weight of fruit (*MFWF*), dry matter concentration of fruit cortex (*DMCF*) on a fresh mass basis, fruit water content (*FWC*) on a fresh mass basis, fruit total soluble solids concentration (*TSSC*), blossom-end rot (*BER*), and fruit colour in terms of hue angle (*HA°*) at green and at firm red stages in response to irrigation treatments

Treatments	MFWF (g)	DMCF (mg g^{-1})	FWC (%)	TSSC (°Brix)	BER (%)	HA°	
						Green	Red
FI	99.0a	53.1b	95.0a	4.6b	4b	84a	84a
PRD_{VS-FT}	97.8a	55.0b	94.9a	4.8b	8b	84a	84a
PRD_{FT-FS}	73.8b	64.3a	94.2b	5.4a	48a	79a	79a
PRD_{FS-H}	83.3b	61.9a	94.2b	5.5a	8b	76a	76a

FI daily full irrigation, partial rootzone drying (*PRD*) during the vegetative stage until the first truss (PRD_{VS-FT}), from the first truss to fruit set (PRD_{FT-FS}), and from fruit set to harvest (PRD_{FS-H}). Different letters within columns indicate significant differences by Tukey's Studentised range test at $P \leq 0.05$

under the PRD regime, ψ_x will be maintained because the roots could take up sufficient water from a larger volume of soil while part of the root system would still be in drying soil.

The duration of PRD_{VS-FT} of just 11 days might not have been long enough to induce adverse effects on yield parameters and therefore all yield attributes were similar to FI. Compared to the other PRD treatments, PRD_{VS-FT} tended to have enhanced root growth in terms of dry weight, but when it was compared with FI the difference was significant. The root dry weights (MSD = 4.3 g) were 14.3, 20.3, 19.0, and 18.5 for FI, PRD_{VS-FT}, PRD_{FT-FS}, and PRD_{FS-H}, respectively. The higher root growth for the PRD treatments might have been stimulated by the frequent alternation of the irrigation from one side of the root system to the other and exposure of roots to water deficit which encourages their growth (Vartanian 1981; Steudle 2000). The roots were therefore stronger sinks than the fruit as reduction of fruit yield did occur for PRD_{FT-FS} and PRD_{FS-H} treatments (Table 2).

Yield reduction in tomato is attributed to floral abortion when water deficit is applied during flowering and fruit set (Helyes and Varga 1994; Pulupol et al. 1996). However, in this study, flower abortion and the number of undeveloped fruit were not responsible for the reduced yield in PRD_{FT-FS} and PRD_{FS-H} plants. The percentage of floral abortion (MSD = 3.9%) was 1.1, 1.1, 3.6, and 2.4 for FI, PRD_{VS-FT}, PRD_{FT-FS}, and PRD_{FS-H}, respectively. The corresponding percentage of undeveloped fruit (± standard error) was 44 ± 2.5, 46 ± 2.3, 44 ± 2.9, and 44 ± 2.8, respectively. However, the number of undersized fruit (fruit diameter less than 55 mm) per plant was higher in PRD_{FT-FS}, and PRD_{FS-H} compared with FI and PRD_{VS-FT} which would explain better the reduction in yield attributes in the former two treatments. The mean number of undersized fruit (MSD = 20) was 21, 15, 36, and 31 for FI, PRD_{VS-FT}, PRD_{FT-FS}, and PRD_{FS-H}, respectively.

The duration of each PRD treatment was not long enough to have an effect on irrigation water use efficiency that was similar among the treatments. Water lost in drainage might have introduced an error in the calculations of IWUE although the drainage was minimised by adjusting irrigation with the development of the crop. Nevertheless, compared with FI, water was saved by 6, 20, and 25% for PRD_{VS-FT}, PRD_{FT-FS}, and PRD_{FS-H}, respectively. Irrespective of undersized fruit, this is particularly useful if PRD_{FS-H} were applied in horticultural systems where water is a limiting factor for both processing tomato production and for the industry.

For the PRD_{FT-FS} treatment, lesser fruit growth, in terms of fruit diameter and therefore lower mean fresh weight of fruit, is indicative of fewer cell numbers and/or an irreversible reduction in cell size induced by a water deficit as reflected in the lower ψ_x. This conclusion can be corroborated by the lack of compensatory fruit growth after this treatment was re-watered (Fig. 4).

The following are some desirable quality attributes for the processing tomato: high total soluble solids concentration, enhanced dry matter concentration of the cortex, and low fruit water content because less energy would be needed to dry the fruit by the processing industry. Both PRD_{FT-FS} and PRD_{FS-H} had advantage in these attributes compared to FI and PRD_{VS-FT}. About 85% of water and photoassimilates are transported by the phloem during fruit growth of tomato (Ho 1999). Water transport into the fruit could have been reduced in PRD_{FT-FS} and PRD_{FS-H} plants. However, assimilate imports must have continued for these two treatments, although at a reduced rate, and this accounted for the increase in dry matter concentration of fruit cortex. Kitano et al. (1996) found that lower diurnal leaf water potential enhanced the assimilate flux into the tomato fruit in the late evening after re-watering. This may have occurred in PRD_{FT-FS} and PRD_{FS-H} treatments when ψ_x recovered. Higher total soluble solids concentration in tomato fruit under low ψ_x has been attributed to lower respiration rates and a lower dilution in the fruit resulting from reduced water level within the fruit (Young et al. 1993). Additionally, under water deficit there is a higher conversion of starch into sugars (Kramer 1983).

PRD_{FT-FS} was the most susceptible treatment to BER. BER is associated with local calcium deficiency in the distal fruit tissue (Ho 1999). This arises due to low levels of water transport through the plant and may also be associated with plant hormonal imbalance (Bangerth 1979; Ho 1999; Saure 2001). Lower water content in PRD_{FT-FS} fruit implies that water transport through the xylem to the fruit was reduced at the beginning of their growth (Davies et al. 2000) leading to a higher incidence of BER, possibly because of inadequate calcium concentration. Higher incidence of BER in PRD_{FT-FS} fruit could also be due to hormonal imbalance but we lack data to substantiate this. For PRD applied either before or after this phenological stage, BER incidence was similar to FI plants (Table 2).

Conclusions

This study showed that PRD_{VS-FT} plants could produce fruit similar in yield and quality to FI plants, but the water saving was only by 6%. Greater water savings were achieved in PRD_{FT-FS} and PRD_{FS-H}, but they produced significantly more undersized fruit and therefore reduced yield in terms of both fresh and dry weight. PRD_{FT-FS} and PRD_{FS-H} treatments showed increase in dry matter concentration of cortex and total soluble solids concentration of fruit with a corresponding reduction in fruit water content. PRD_{FT-FS} realised a water saving of 20%, but induced higher BER incidence and therefore cannot be recommended as a PRD option. Fruit quality improvement in PRD_{FS-H} plants, in terms of higher TSSC and fruit dry matter concentration, could compensate for the reduction in total fresh and dry weight of fruit where water is expensive for tomato production in view of 25% of water saved for this treatment compared to FI.

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References

Bangerth F (1979) Calcium-related physiological disorders of plants. Ann Rev Phytopathol 17:97–122

Davies WJ, Zhang J (1991) Root signals and the regulation of growth and development of plants in drying soil. Ann Rev Plant Physiol Plant Mol Biol 42:55–76

Davies WJ, Bacon MA, Thompson DS, Sobeih W, González-Rodríguez L (2000) Regulation of leaf and fruit growth in plants growing in drying soil: exploitation of the plants' chemical signalling system and hydraulic architecture to increase the efficiency of water use in agriculture. J Exp Bot 51:1617–1626

Dry PR, Loveys BR (1999) Grapevine shoot growth and stomatal conductance are reduced when part of the root system is dried. Vitis 38:151–156

Helyes L, Varga G (1994) Irrigation demand of tomato according to the results of three decades. Acta Hortic 376:323–328

Ho LC (1984) Partitioning of assimilates in fruiting tomato plants. Plant Growth Regul 2:277–285

Ho LC (1996) Tomato. In: Zemaski E, Schaffer AA (eds) Photoassimilate distribution in plants and crops: source–sink relationships. Marcel Dekker, New York, pp 709–728

Ho LC (1999) The physiological basis for improving tomato fruit quality. Acta Hortic 487:33–40

Holbrook NM, Shashidhar VR, James RA, Munns R (2002) Stomatal control in tomato with ABA-deficient roots: response of grafted plants to soil drying. J Exp Bot 53:1503–1514

Hsiao TC (1990) Plant–atmosphere interactions, evapotranspiration, and irrigation scheduling. Acta Hort 278:55–66

Kitano M, Yokomakura F, Eguchi H (1996) Interactive dynamics of fruit and stem growth in tomato plants as affected by root water condition. II. Relation with sucrose translocation. Biotronics 25:75–84

Kramer PJ (1983) Water relations of plants. Academic, London

Kramer PJ, Boyer JS (1995) Water relations of plants and soils. Academic, London

Loveys BR, Dry PR, Stoll M, McCarthy MG (2000) Using plant physiology to improve the water use efficiency of horticultural crops. Acta Hortic 537:187–197

Mapelli S, Frova C, Torti G, Sorcessi GP (1978) Relationship between set, development and activities of growth regulators in tomato fruit. Plant Cell Physiol 19:1281–1288

Obreza TA, Pitts DJ, McGovern RJ, Speen TH (1996) Deficit irrigation of micro-irrigated tomato affects yield, fruit quality, and disease severity. J Prod Agric 2:270–275

Parchomchuk P, Tan CS, Berard RG (1997) Practical use of time domain reflectometry for monitoring soil water content in microirrigated orchards. HortTechnology 7:17–22

Postel SL (1998) Water for food production: will there be enough in 2025? Bioscience 48:629–637

Pulupol LU, Behboudian MH, Fisher KJ (1996) Growth, yield and post harvest attributes of glasshouse tomatoes produced under deficit irrigation. HortScience 31:926–929

Saure MC (2001) Blossom-end rot of tomato (*Lycopersicon esculentum* Mill.)—a calcium—or a stress-related disorder? Sci Hortic 90:193–208

Sobeih WY, Dodd IC, Bacon MA, Grierson D, Davies WJ (2004) Long-distance signals regulating stomatal conductance and leaf growth in tomato (*Lycopersicon esculentum*) plants subjected to partial root-zone drying. J Exp Bot 55:2353–2363

Steudle E (2000) Water uptake by roots: effects of water deficit. J Exp Bot 51:1531–1542

van Schilfgaarde J (1994) Irrigation—a blessing or a curse. Agric Water Manage 25:203–219

Vartanian N (1981) Some aspects of structural and functional modifications induced by drought in root system. Plant Soil 63:83–92

Young TE, Juvik JA, Sullivan JG (1993) Accumulation of the components of total solids in ripening fruit of tomato. J Am Soc Hort Sci 118:286–292

Zegbe JA, Behboudian MH, Clothier BE (2004) Partial rootzone drying is a feasible option for irrigating processing tomatoes. Agric Water Manage 68:195–206

Zegbe JA, Behboudian MH, Clothier BE (2005) Yield and fruit quality in processing tomato under partial rootzone drying. Eur J Hort Sci (in press)