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Partial rootzone drying is a feasible option for irrigating processing tomatoes

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Abstract

World water supplies are limited and water-saving irrigation practices, such as partial rootzone drying (PRD), should be explored. We studied the effects of PRD, applied through furrow and drip irrigation, on plant water relations, yield, and the fruit quality of processing tomato (*Lycopersicon esculentum* Mill. cv. 'Petopride'). There were four treatments. The first two were: full irrigation by hand on both sides of the root system which mimicked furrow irrigation (FuI), and half of irrigation water in FuI given alternately only to one side of the root system with each irrigation (PRD_{FuI}). The next two treatments were: full drip irrigation (DrI) to both sides of the root system, and half of irrigation water in DrI given alternately only to one side of the root system with each irrigation (PRD_{DrI}). Leaf water potential was the same among the treatments except for the PRD_{FuI} plants, which had the lowest midday values only in one sampling out of four. Photosynthetic rate was the same among the treatments except for the drip-irrigated plants having the lowest value in one sampling out of four. Number of fruit, mean fruit mass of fruit, total fresh and dry mass of fruit, and harvest index were the same among treatments, but PRD plants had increased irrigation use efficiency compared to fully irrigated plants. There was no incidence of blossom-end rot in any of the treatments. PRD_{DrI} fruit had redder colour and higher total soluble solids concentration. Advancement in fruit maturity and enhancement of quality could be achieved without detrimental effect on fresh and dry mass of fruit by application of PRD. Independent of the irrigation method, PRD treatments improved irrigation use efficiency by ca. 70%. PRD has the potential for use in processing tomato especially in environments with limited water.

Keywords: Lycopersicon esculentum; Irrigation use efficiency; Water saving; Yield; Fruit quality; Fruit maturity advancement

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1. Introduction

Water supplies are limited worldwide (Postel, 1998) and there is an urgent need to identify and adopt effective irrigation management strategies. As irrigation of agricultural lands accounts for over 85% of water usage worldwide (van Schilfgaarde, 1994), even a 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, 1996a). Partial rootzone drying (PRD) is a potential water-saving irrigation strategy where, at each irrigation time, only a 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). Because plant water potential is expected to equilibrate with the wettest part of the soil (Hsiao, 1990), it is expected that plants under PRD will maintain as high a water potential as well-watered plants.

PRD is a variation of deficit irrigation (DI) and it has been observed that one of the negative outcomes of DI application on tomato is the development of blossom-end rot (BER) (Adams and Ho, 1992; Obreza et al., 1996). BER is a physiological disorder presumably caused by a lower calcium transport to the area of the fruit that eventually becomes affected. Irrigation method has also been implicated in the development of BER (Carrijo et al., 1983). We were interested in evaluating the effects of PRD on growth, yield, and fruit quality of tomato and were further interested in learning whether any outcome of PRD application would be affected by the method it is applied. Furrow and drip irrigation methods are widely used in tomato production (Phene, 1999). We applied PRD on the ‘Petopride’ processing tomato using these two methods. We hypothesised that the PRD outcome could be different for these two methods in view of the expected difference in root growth (Oliveira and Calado, 1996) and root responses such as signalling (Davies et al., 2000).

2. Materials and methods

2.1. Experimental conditions

The experiment was conducted in a naturally-lit glasshouse, with ventilation/heating set points of 25/15 °C, at the Plant Growth Unit, Massey University, Palmerston North (lat. 40°2′S, long. 175°4′E), New Zealand. It was conducted from March to August 2002. Seeds of the processing tomato cv. ‘Petopride’ were sown on 18 March 2002. Thirty eight days after seeding, uniform plants were transplanted into twelve wooden boxes (2.53 m length × 0.65 m width × 0.20 m height each) each housing four compartments (0.60 m length × 0.60 m width × 0.20 m height) with one experimental plant per compartment. To avoid lateral water movement and to mimic the central part of a furrow, a small piece of wood (0.60 m length × 0.025 m width × 0.05 m height) was placed centrally on the base of each compartment. The containers were lined with black polyethylene with a thickness of 125 μm and laterally perforated at the bottom to allow drainage. Plants were grown in a bark:pumice:peat mixture comprising 60:30:10 by volume. Media volume per compartment was 0.072 m^3. Plants were fertilised (180 g per container) with a 1:2 (w:w) mixture of rapidand slow-release fertilisers (Osmocote 15N-4.8P-10.8K and Osmocote 16N-3.5P-10K, respectively, Scotts, Australia, Pty. Ltd., Baulkam Hills, NSW, Australia).

2.2. Irrigation treatments

Eighteen days after transplanting four irrigation treatments were tested. The first two were: full irrigation by hand on both sides of the root system, which mimicked furrow irrigation (FuI), and half of irrigation water in FuI given alternately only to one side of the root system with each irrigation (PRD_{FuI}). The next two treatments were: full drip irrigation (DrI) to both sides of the root system, and half of irrigation water in DrI given alternately only to one side of the root system with each irrigation (PRD_{DrI}). The plants under PRD_{FuI} and FuI were irrigated once a day with 0.6 and 1.2 L, respectively. Irrigation in FuI treatment was given 0.10 m away from the main stem and on both sides of the row. Irrigation covered a total area and soil volume of 0. 24 m^2 and 0.048 m^3, respectively, but half of irrigated area and soil volume was wetted in PRD_{FuL} treatment at each irrigation. The same amount of water applied in PRD_{FuI} and FuI treatments was given to the plants under PRD_{DrI} and DrI, respectively, but half of it at 10:00 h and the other half at 16:00 h by an automated drip irrigation system. Two irrigation lines were set up and operated separately for the PRD_{DrI} treatment. Two emitters per plant (one on each line) each emitting 4 L/h were placed 0.15 m away from the main stem of each plant. Irrigation in DrI treatment covered a total area and soil volume of 0. 016 m^2 and 0.003 m^3, but half of irrigated area and soil volume was wetted in PRD_{DrI} treatment at each irrigation. A total of 65 and 130 L of water (gross irrigation) per plant was applied to PRD plants and to fully irrigated plants, respectively. There was some drainage in all treatments, but this was not measured. However, water losses by drainage were minimised by adjusting the amount of water as the crop developed. So, values of the irrigation use efficiency presented here might have been under-estimated considering the water losses by drainage.

2.3. Experimental design and data analysis

A complete randomised design was used with the four treatments replicated three times with four plants per replication. Data were analysed by a complete randomised model using the GLM procedure of SAS software version 8.2 (SAS Institute, Cary, NC, USA). 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 $P \leq 0.05$.

2.4. Measurements of soil water content and plant water status

Volumetric soil water content (m^3 m^{-3}) was recorded daily on both sides of the row at 0.20 m medium depth and 0.05 m away from the emitters. This was done within 60 min after the last irrigation (16:00 h) by time domain reflectometry (TDR, Trase System-Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Field capacity was reached at a volumetric soil water content of 0.25 m^3 m^{-3} for the medium and this was established according to

Parchomchuk et al. (1997) before setting up the experiment. Diurnal leaf water potential was measured on two leaves per plant using a pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Measurements were taken at 6:00, 09:00, 12:00, 15:00, and 18:00 h and on 73, 117, 141, and 161 days after seeding (DAS).

2.5. Measurements of photosynthetic rate and stomatal conductance

Photosynthetic rate, stomatal conductance, and photosynthetic photon flux were obtained with a portable photosynthesis system (LI-6200, LICOR Inc., Nebraska, USA) between 13:30 and 14:30 h on two expanded and exposed mature leaves per plant. These were taken on the same sampling days for leaf water potential.

2.6. Growth and yield component measurements

Fruits from each plant were counted and weighed. They were then cut into halves and oven-dried at 85 °C to a constant mass to determine total dry mass. The remaining parts of the plants, excluding the roots, were collected, weighed, and oven-dried at 70 °C to a constant mass. Irrigation-use efficiency was calculated for each treatment by dividing total dry mass of fruit per plant by the litres of irrigation water applied to the plant. Harvest index was obtained by dividing total dry mass of fruit by total dry mass of plant. Fruit larger than 55 mm diameter were included as marketable fruit (Obreza et al., 1996). Fruit size, in terms of mean fresh mass per fruit, was obtained by dividing fresh mass of all fruit by their number. To remove the effect due to fruit number variation detected among plants, total fresh and dry mass of fruit were adjusted by the number of fruit as covariate.

2.7. Advancement in fruit maturity

The reddest fruit from each plant were visually selected to evaluate the advancement in fruit maturity by collecting 18 fruits per treatment (six per replication). This was done on 152 and 163 days after seeding. Background skin colour, in terms of hue angle, was assessed on two opposite sides of the middle part of each fruit using a chromameter (CR-200 Minolta, Osaka, Japan). After sampling for colour, fruits were cut into halves and 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, 25 g of cortical tissue of each fruit were oven-dried at 85 °C to constant mass and the dry mass concentration of fruit was expressed on a fresh mass basis. Additionally, 18 fruits per treatment (six per replication) were collected on 145 days after seeding at green stage and colour development was followed for 16 days. Fruits used for colour and dry mass concentration measurements were included for measurement of total fresh and dry yields.

2.8. Fruit quality at harvest

Twelve fruits per treatment (four per replication), from the first trusses over two harvests, were randomly chosen at the firm red stage for quality measurements. Fruit quality was assessed in terms of hue angle, total soluble solids concentration, and fruit water content. All fruits were examined for presence of blossom-end rot.

3. Results

3.1. Volumetric soil water content

The volumetric soil water content (θ) in fully watered plants ranged between 0.2 and 0.28 $m^3\,m^{-3}$. But θ for each side of PRD treatments depended on whether the side was being irrigated or not (Fig. 1A and B). The missing data between 50 and 130 days after seeding were due to a malfunctioning of the equipment, which impeded data collection.

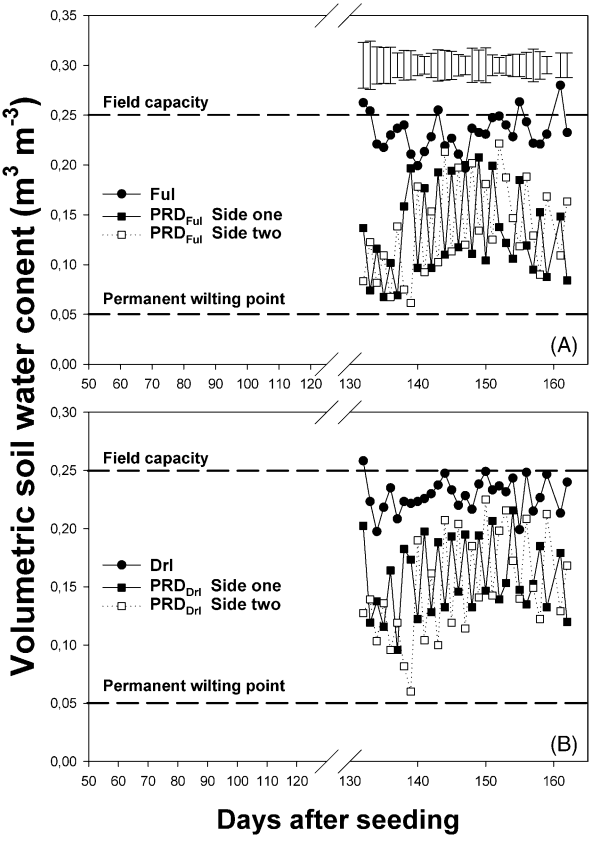

Fig. 1. Changes in soil water content (θ, m^3 m^{-3}) for furrow irrigation (A, FuI) and drip irrigation (B, DrI) treatments. Each side of partial rootzone drying (PRD) root system had either a high or a low θ depending on whether it was being irrigated or not. PRD_{FuI} = partial rootzone drying using furrow irrigation (A) and PRD_{DrI} = partial rootzone drying using drip irrigation (B). Vertical bars, which apply to A and B, represent the minimum significant difference (MSD) by Tukey's Studentised range test at $P \leq 0.05$.

3.2. Plant water status, photosynthesis, and stomatal conductance

Leaf water potential followed a diurnal pattern on all measurement dates reaching a minimum value at midday and starting to recover early in the afternoon (Fig. 2). On 73 DAS, leaf water potential was the same among treatments at all times of the day (Fig. 2A). On 117 DAS, FuI plants had the highest leaf water potential at 6:00 h (Fig. 2B). On 141 DAS, PRD plants had lower leaf water potential than fully watered plants at 09:00 h (Fig. 2C), but PRD_{FuI} plants showed the lowest leaf water potential at midday (Fig. 2C). A similar trend for PRD_{FuI} plants occurred on 161 DAS (Fig. 2D).

Photosynthetic rate was unaffected by the irrigation treatments for three of four measurements taken (Table 1). On 73 DAS, a reduction in photosynthetic rate in drip-irrigated plants relative to furrow irrigated plants was observed, but stomatal conductance remained unaffected by the treatments in all four measurement occasions (Table 1).

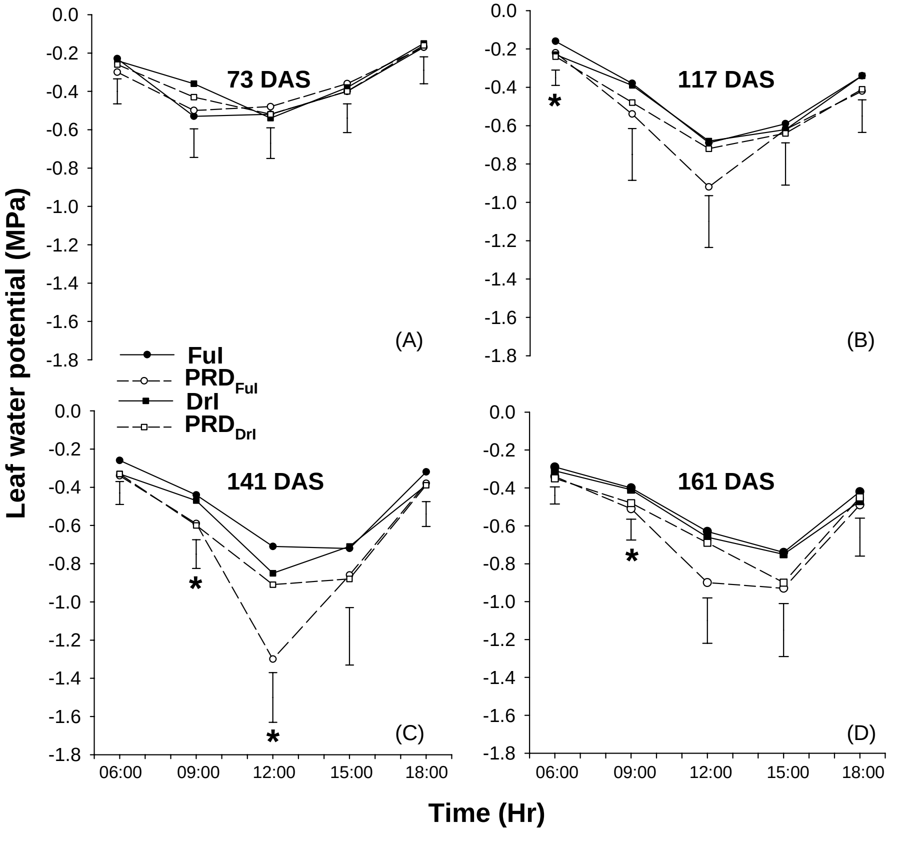

Fig. 2. Diurnal changes in leaf water potential at four occasions in response to irrigation treatments: FuI = daily full irrigation mimicking furrow irrigation, PRD_{FuI} = partial rootzone drying using furrow irrigation, DrI = daily full drip irrigation, and PRD_{DrI} = partial rootzone drying using drip irrigation. Vertical bars represent the MSD by Tukey's test and the asterisks show significant differences at $P \leq 0.05$.

Table 1
Photosynthetic rate and stomatal conductance[a] in response to irrigation treatments (ITs[b])

Parameter	ITs	Days after seeding			
		73	117	141	161
Photosynthesis (μmol m^{-2} s^{-1})	FuI	7.1 a	5.2 a	6.0 a	9.4 a
	PRD_{FuI}	7.6 a	5.6 a	4.5 a	7.0 a
	DrI	3.6 b	6.8 a	9.1 a	9.6 a
	PRD_{DrI}	4.7 b	7.2 a	6.8 a	8.3 a
Stomatal conductanace (mol m^{-2} s^{-1})	FuI	1.7 a	1.1 a	1.7 a	0.8 a
	PRD_{FuI}	1.3 a	1.2 a	1.3 a	0.8 a
	DrI	1.5 a	1.1 a	1.6 a	0.9 a
	PRD_{DrI}	1.5 a	1.0 a	1.5 a	0.9 a
PPF (μmol m^{-2} s^{-1} ± S.D.)		166 ± 66	461 ± 130	548 ± 213	778 ± 187

[a] Different letters within columns indicate significant differences by Tukey's Studentised range test at $P \leq 0.05$.
[b] FuI: daily full irrigation mimicking furrow irrigation, PRD_{FuI}: partial rootzone drying using furrow irrigation, DrI: daily full drip irrigation, and PRD_{DrI}: partial rootzone drying using drip irrigation. Photosynthetic photon flux (PPF) is given for each occasion.

3.3. Yield and yield components

Total fresh mass of plant was significantly reduced in PRD plants compared with fully watered plants (Table 2). However, number of fruit, mean fresh mass of fruit, total fresh mass of fruit, total dry mass of fruit, and harvest index were not affected by the treatments. Irrigation use efficiency was higher in PRD plants than in fully irrigated plants (Table 2).

3.4. Advancement in fruit maturity

Maturity advancement was evaluated in terms of dry mass concentration of fruit, total soluble solids concentration, and skin colour in terms of hue angle (Table 3). On 152 DAS,

Table 2
Total fresh mass of plant[a] (TFMP), number of fruit per plant (NF), mean fresh mass per fruit (MFMF), total fresh mass of fruit[b] (TFMF), total dry mass of fruit (TDMF), irrigation use efficiency (IUE_{TFMF}), and harvest index (HI), all per plant, in response to irrigation treatments (ITs[c])

ITs	TFMP (kg per plant)	NF	MFMF (g)	TFMF (kg per plant)	TDMF (g per plant)	IUE (g per L)	HI
FuI	4.5 a	30 a	87 a	2.7 a	161 a	1.2 b	0.48 a
PRD_{FuI}	3.6 b	29 a	84 a	2.5 a	165 a	2.3 a	0.53 a
DrI	4.7 a	33 a	88 a	2.7 a	157 a	1.4 b	0.53 a
PRD_{DrI}	3.8 b	30 a	86 a	2.6 a	159 a	2.3 a	0.53 a

[a] Different letters within columns in TFMP, NF, MFMF, and HI indicate significant differences by Tukey's Studentised range test at $P \leq 0.05$.
[b] TFMF and TDMF were adjusted by the number of fruit per plant as covariate and were ranked according to the least squares means at $P \leq 0.05$.
[c] FuI: daily full irrigation mimicking furrow irrigation, PRD_{FuI}: partial rootzone drying using furrow irrigation, DrI: daily full drip irrigation, and PRD_{DrI}: partial rootzone drying using drip irrigation.

Table 3
Dry mass concentration of fruit (DMCF) on a fresh mass (FM) basis, total soluble solids concentration (TSSC), and fruit colour in terms of hue angle[a] (HA°) at two harvest dates in response to irrigation treatments (ITs[b])

Harvest dates (days after seeding)	ITs	DMCF (mg g^{-1} FM)	TSSC	HA°
152	FuI	56.1 a	4.7 a	94.8 a
	PRD_{FuI}	56.0 a	4.9 a	88.3 a
	DrI	54.5 a	4.9 a	88.2 a
	PRD_{DrI}	54.3 a	5.1 a	63.8 b
163	FuI	55.6 b	4.5 c	80.4 a
	PRD_{FuI}	58.4 a	5.0 ab	79.4 ab
	DrI	53.9 b	4.7 bc	63.1 b
	PRD_{DrI}	57.7 a	5.2 a	50.2 c

[a] Different letters within columns indicate significant differences by Tukey's Studentised range test at $P \leq 0.05$.
[b] FuI: daily full irrigation mimicking furrow irrigation, PRD_{FuI}: partial rootzone drying using furrow irrigation, DrI: daily full drip irrigation, and PRD_{DrI}: partial rootzone drying using drip irrigation.

dry mass concentration of fruit and total soluble solids concentration were statistically the same among treatments. However, the lowest hue angle was observed in PRD_{DrI} fruit while the highest was in FuI fruit, thus the former fruit were redder than the latter. Lower values of hue angle represent redder fruit. On 163 DAS, PRD fruit had higher dry mass concentration of fruit and total soluble solids concentration relative to fully watered fruit, but drip-irrigated

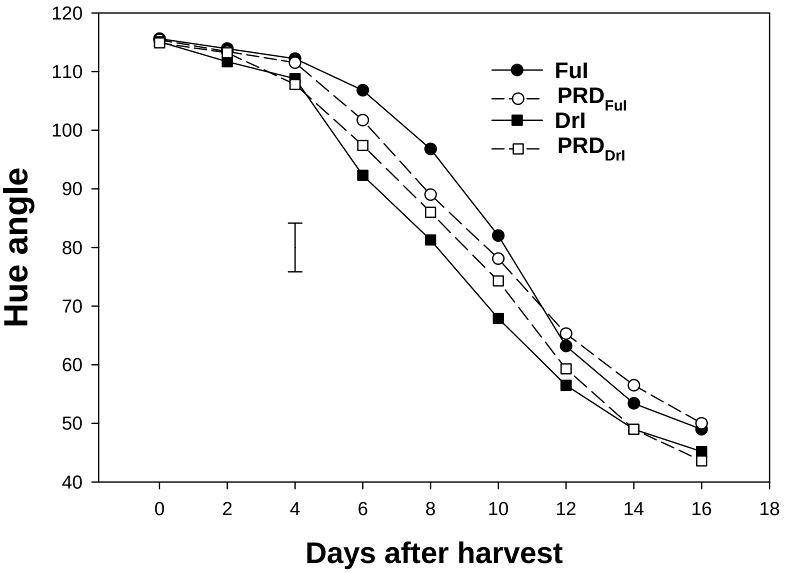

Fig. 3. Changes of skin colour of 'Petopride' processing tomato fruit in response to irrigation treatments (ITs): FuI = daily full irrigation mimicking furrow irrigation, PRD_{FuI} = partial rootzone drying using furrow irrigation, DrI = daily full drip irrigation, and PRD_{DrI} = partial rootzone drying using drip irrigation. Separate bar represents the MSD by Tukey's test at $P \leq 0.05$.

fruit were more advanced in redness of skin colour relative to furrow-irrigated fruit (Table 3). The last finding was confirmed by following the changes in fruit skin colour over 16 days (Fig. 3).

3.5. Fruit quality at harvest

The evaluation of fruit quality at firm red stage showed that PRD_{FuI} had the lowest fruit water content. The values (%, with minimum significant difference (MSD) = 0.37) were 93.9, 93.3, 94.0, and 93.9, for FuI, PRD_{FuI}, DrI, and PRD_{DrI}, respectively. Total soluble solids concentration was higher in PRD fruit than in fully irrigated fruit. The values (%, MSD = 0.48) were 4.5, 5.0, 4.7, and 5.0, for FuI, PRD_{FuI}, DrI, and PRD_{DrI}, respectively. Redness in skin colour tended to be higher in PRD_{DrI} fruit than the other treatments. The values for hue angle (± one standard error) were 45.4 ± 1.0, 44.0 ± 1.1, 45.1 ± 0.8, and 41.1 ± 0.8, for FuI, PRD_{FuI}, DrI, and PRD_{DrI}, respectively. No incidence of blossom-end rot was noticed in any of the treatments.

4. Discussion

The maintenance of leaf water potential in PRD plants depended on the irrigation method used. PRD_{FuI} plants tended to have lower leaf water potential than PRD_{DrI} plants (Fig. 2). Drip irrigation would therefore seem to be a better option in a PRD program, not only because of the maintenance of higher leaf water potential but also because of increased in irrigation use efficiency (Table 2). Other reasons are the precision and placement of the amount of water, and the minimisation of water losses by evaporation from the soil surface by drip irrigation over furrow irrigation.

In general, photosynthetic rate and stomatal conductance appeared unaffected by irrigation treatments (Table 1). However, photosynthetic rate was significantly reduced in both of the drip-irrigated treatments on 73 DAS, although stomatal conductance and leaf water potential were unaffected in all treatments (Table 1; Fig. 2). On this day, radiation was the lowest of the four occasions measured and it is possible that the measurements of stomatal conductance in drip-irrigated plants happened to be during the episodes of lowest radiation. Although lower leaf water potential values were observed in PRD_{FuI} plants on 141 DAS, no significant changes in stomatal conductance were noticed. In PRD_{FuI}, the stomatal conductance values might have been at their maximum when taken between 13:30 and 14:30 h. This might be expected under field conditions, because roots could explore and obtain water from deeper parts of the soil profile, to equilibrate leaf water potential, and therefore to keep the stomata open (Hsiao, 1990).

Total fresh mass of plant was higher in fully irrigated plants than in PRD plants, but number of fruit, mean fresh mass of fruit, and total fresh and dry masses of fruit were the same among treatments (Table 2). Tomato fruit, as the strongest sink for photoassimilates (Ho, 1996b), could compete for assimilates in the PRD_{FuI} and PRD_{DrI} plants. The vegetative dry mass was lower in PRD plants than in fully irrigated plants which shows higher sink strength of fruit than the rest of plant organs. The values for vegetative dry mass (g ± one standard error) were: 172 ± 11, 130 ± 4, 162 ± 7, and 135 ± 6 for FuI, PRD_{FuI}, DrI, and PRD_{DrI} plants, respectively. The maintenance of total dry mass of fruit in PRD_{FuI} and PRD_{DrI} plants was in agreement with those observed in a split-root experiment (Davies et al., 2000) and in a PRD experiment which was watered mimicking furrow irrigation (Zegbe-Domínguez et al., 2003). However, both groups of authors reported a significant reduction in total fresh mass of fruit, which did not occur in this experiment. The available information suggests that in the PRD plants the reduction of total fresh mass of fruit depends on the frequency by which the irrigation was shifted to the dry side. Here, the irrigation was reversed daily during the growing season. Zegbe-Domínguez et al. (2003) did the shifting when volumetric soil water content fell between 0.02 and 0.1 $m^3\ m^{-3}$. Davies et al. (2000) alternated the irrigation initially between 10 and 14 days and the alternating frequency was increased in accordance with the crop growth stage. Maintenance of total fresh mass of fruit in PRD treatments, relative to the fully watered treatments, resulted in an increase of 70% in the irrigation use efficiency. The harvest index therefore became similar among treatments (Table 2).

In processing tomatoes, two fruit quality attributes are important for the industry. Fruit colour is one, in particular lycopene concentration due to its human health benefits. Reduced fruit water content is the second because less energy would be needed to dry the fruit. Advancement in fruit maturity would reduce production cost and it is important in terms of early marketing (May and Gonzales, 1999). The fruits were strip-picked over two harvests on 152 and 163 days after seeding. Fruit maturity was more advanced, in terms of development of fruit skin colour, in PRD_{DrI} than any other treatment at the first harvest (Table 3; Fig. 3). This was also true for the second harvest (Table 3). As part of the root system was kept dry at each irrigation, possibly a root-to-shoot and shoot-to-fruit signalling mechanism could have started the ethylene biosynthesis in the fruit leading to the development of a redder colour (Giovannoni, 2001). Both PRD treatments also had higher dry mass concentration of fruit and total soluble solids concentration than their respective fully irrigated plants (Table 3). This could be presumably due to lower respiration rate and less dilution of total soluble solids concentration because of lower water content in the fruit (Young et al., 1993). The higher total soluble solids concentration could also be due to a higher conversion of starch to sugars under water deficit (Kramer, 1983, p. 364). Kitano et al. (1996) found that lower diurnal leaf water potential is associated with reduced assimilates flux rate into the tomato fruit during the day, in particular at midday when leaf water potential is lower, as observed here in PRD plants (Fig. 2C and D). They also observed that when leaf water potential started to recover early in the afternoon, the assimilate flux into the fruit not only recovered but was also enhanced. This would explain higher dry mass concentration and total soluble solids concentration in PRD fruit. We did not observe incidence of blossom-end rot, which means that PRD treatment did not promote this physiological disorder in tomato as observed in those under deficit irrigation (Obreza et al., 1996; Pulupol et al., 1996).

5. Conclusions

Partial rootzone drying could maintain the fresh and dry mass of fruit and save water by 50%, and therefore increase the irrigation use efficiency by 92% or 64%, by furrow and drip irrigation, respectively, in comparison with fully irrigated plants. Drip-irrigated PRD not only increased the irrigation use efficiency by 92% over fully furrow irrigated plants, but also kept the photosynthetic rate and leaf water potential similar to fully drip-irrigated plants. Fruit maturity was more advanced in drip-irrigated PRD in terms of redness of fruit with an increase in total soluble solids concentration and dry mass concentration of fruit compared with any other treatment. This is important for processing and for marketing. Either of the two PRD treatments has a great potential to be adopted as a water saving practice especially for environments with limited water. We conducted this trial in glasshouse conditions to avoid the interference of rain, but application of PRD to field-grown plants is expected to maintain these advantages because roots will have a higher volume of soil to explore.

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