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Yield and Fruit Quality in Processing Tomato under Partial Rootzone Drying

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Summary

Water resources are limited worldwide and there is a need to develop water-saving irrigation practices. Here we applied partial rootzone drying (PRD) to 'Petopride' processing tomato plants with the alternate sides of the root system (RS) being exposed to various extents of soil dryness. The treatments were: daily full irrigation (FI) in both sides of RS considered as the control; and irrigating only one side of the RS for two (PRD_2), four (PRD_4), and six (PRD_6) consecutive days before irrigation was shifted over to the dry side of the RS for the same periods. Leaf water potential, photosynthetic rate, total fresh mass of fruit and total dry mass of fruit significantly reduced in PRD treatments relative to FI. But irrigation water-use efficiency was improved in the PRD treatments. A lower percentage of dry mass was partitioned into the PRD fruit, which had lower fruit water content and higher total soluble solids concentration than the FI fruit. Fruit skin colour was the same for all the treatments. Blossom-end rot incidence was higher in PRD fruit than the FI fruit although their calcium concentration was the same. PRD saved irrigation water by 50 %, but total dry mass of fruit was reduced by 23 %. However, the considerable saving of water could make PRD feasible in areas where water is scarce and expensive.

Key words. *Lycopersicon esculentum* Mill. – plant water relations – Blossom-end rot – dry mass partitioning

Introduction

Water resources are increasingly becoming limited (Postel 1998), therefore there is a need to develop water saving irrigation practices. Irrigation of agricultural lands accounts for over 75 % of water usage worldwide (Wallace and Gregory 2002). Even a minor reduction in irrigation water will therefore lead to substantial saving of water for other purposes. This is especially true for tomato which has the highest acreage of any vegetable crop in the world (Ho 1996a) and it is grown in dry environments where irrigation is essential for high yields (Geisenberg and Stewart 1986).

Two water saving strategies could be considered: deficit irrigation (DI) where a percentage of evapotranspiration is applied to the entire rootzone, and partial rootzone drying (PRD) where at each irrigation only one portion of the rootzone is irrigated with the remaining portion left to dry to a predetermined level. Depending on its severity, DI can have a negative effect on yield with some benefits in terms of improvement in fruit quality (e.g. Pulupol et al. 1996). However, with PRD a portion of rootzone is always moist and plant water potential is expected to equilibrate with the wettest part of the rhizosphere (Hsiao 1990). At the same time roots in the drying soil can send chemical messages to the shoot, partially closing the stomata (Davies et al. 2002). Both transpiration and photosynthesis will therefore decrease with the latter decreasing to a lesser extent. Plant productivity could therefore be maintained under PRD, while water could be saved. There are reports in the literature indicative of yield maintenance and improvements of some aspects of fruit quality under PRD. Examples are for processing tomato (Zegbe-Domínguez et al. 2003; Zegbe et al. 2004), fresh-market tomato (Kirda et al. 2004), and hot pepper (Kang et al. 2001; Dorji et al. 2005). There are also reports of decreased yield under PRD as found in maize (Kang et al. 2000) and hot pepper (Kang et al. 2001). For the latter experiments only one, and the same part of the rootzone, was irrigated for the entire growing season with the other part left to dry. Roots exposed to dry soil for a long time lose their permeability due to suberization and lignification and therefore are unable to absorb water when re-watered (Cantore et al. 2000; Steudle 2000).

We were interested in knowing for how long a part of the rhizosphere could be kept un-watered in 'Petopride' tomato without deleterious effects on fruit yield and quality. We carried out an experiment where one side of the root system was left un-watered for three different durations. We measured the effect on plant and soil water status, photosynthesis, plant growth, yield, irrigation water-use efficiency, and fruit quality. We hypothesised that if plant water potential could be maintained under PRD treatments, the duration of soil dryness should not affect plant performance.

Materials and Methods

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 July to December 2001. Seeds of the processing tomato cv. 'Petopride' were sown on 31 July 2001. Forty days after seeding (DAS), uniform plants were transplanted into twelve wooden boxes (2.53 m length x 0.65 m width x 0.20 m height) each housing four compartments (0.60 m length x 0.60 m width x 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 x 0.025 m width x 0.05 m height) was placed centrally on the base of each compartment. The compartments 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 media of 60:30:10 by volume. Media volume per compartment was 0.072 m^3. Plants were fertilised (180 g $container^{-1}$) with a 1:2 (w:w) mixture of rapid- and slow-release fertilisers (Osmocote 15 N-4.8 P-10.8 K and Osmocote 16 N-3.5 P-10 K, respectively, Scotts Australia Pty. Ltd., Baulkam Hills, NSW, Australia).

The four irrigation treatments were applied 20 days after transplanting. They were: daily full irrigation (FI) in both sides of the root system (RS) considered as the control; and irrigating only one side of the RS for two (PRD_2), four (PRD_4), and six (PRD_6) consecutive days before irrigation was shifted over to the dry side of the RS for the same periods. The experiment was conducted in a completely randomised design with four treatments replicated three times. There were four plants per treatment for each replication.

The plants were irrigated four times daily (at 7:00, 10:00, 13:00, and 16:00 hours) and at each time for 12 minutes, on average, by an automated drip irrigation system with one or two drippers per plant each emitting 4 L per hour. Two emitters were placed 150 mm away from the main stem of FI treatment, while one emitter was used for PRD_2, PRD_4, and PRD_6 treatments. This emitter was manually shifted over when needed. On average, the PRD and FI plants were irrigated with 3.2 and 6.4 L per day, respectively. A total of 196 and 392 L of water per plant was applied during the experiment to PRD and FI plants, respectively. The volume of irrigation water applied daily was calculated with a calibration curve previously obtained by using the relation between time domain reflectometry (TDR, Trase System-Soil Moisture Equipment Corp., Santa Barbara, CA, USA) readings against known volumes of water. 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.

Volumetric soil water content (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, using the TDR, within 60 minutes after the last irrigation (16:00 hours). Field capacity was reached at a volumetric water content of 0.20 m^3 m^{-3} for the soil medium and this was established according to PARCHOMCHUK et al. (1997) before setting up the experiment.

Diurnal changes of leaf water potential (Ψ_{leaf}) were measured on two leaves per plant using a pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA). Measurements were taken at 06:00, 09:00, 12:00, 15:00, and 18:00 hours. Photosynthetic rate, stomatal conductance, transpiration rate, and the ratio of leaf internal CO_2 to air (Pi/Pa) were measured on two mature leaflets (middle part of two separate shoots) per plant between 13:30 and 14:30 hours with a portable photosynthesis system (Li-Cor model 6200, Lincoln, Nebraska, USA). These measurements were made on 94, 105, and 130 DAS concomitant with the measurements of Ψ_{leaf} .

There was a single commercial harvest on 131 DAS when 95 % of fruit were at red-orange stage. The number of fruit, total fresh mass of fruit, and fruit size (in terms of mean fresh mass per fruit) were recorded. Fruit were cut into halves and oven-dried at 85 °C to constant mass to determine total dry mass. Plants were divided into roots, stems, and leaves and each plant organ was weighed individually and total vegetative fresh mass obtained. They were then oven-dried at 70 °C to constant mass and total vegetative dry mass per plant obtained by adding the mass of each individual organ (excluding fruit). Total dry mass of plant was the sum of total vegetative dry mass and total dry mass of fruit per plant. Dry mass partitioned into each organ was expressed in terms of percentage of the total plant dry mass. Irrigation water-use efficiency was calculated for each treatment by dividing total dry mass of fruit by the litres of irrigation water applied to the plant. Changes in total dry mass of plant (including fruit and roots) over the time were assessed by collecting one plant per replication per treatment on 95, 106 DAS, and at the end of the experiment on 131 DAS.

From the first trusses, 18 fruit per treatment (six per replication) were randomly chosen and tagged on 116 DAS at the green stage for quality measurements. Colour development was followed for 14 days and the fruit were then weighed at firm red colour stage on 129 DAS. Skin colour background was assessed in terms of hue angle on two opposite sides of the middle part of each fruit using a chromameter (CR-200 Minolta, Osaka, Japan). After sampling for colour, fruit were cut into halves and few drops from each half were used to measure total soluble solids concentration with a hand-held refractometer equipped with automatic temperature compensation (ATC-1 Atago, Tokyo, Japan). Fruit water content was expressed on a dry mass basis. Fruit used for these measurements were included in the data for total fresh and dry yields and number of fruit. Blossom-end rot incidence was evaluated over two harvests on 109 and 119 DAS and expressed in percentage of number of fruit affected per plant.

Ten leaves and fruit were randomly collected, weighed, washed with distilled water, and oven-dried at 70 °C and 85 °C, respectively, for 14 days. Leaf and fruit samples were separately ground into powder, and kept in an oven at 70 °C for 14 hours to remove any moisture before analysis. Leaf and fruit Ca^{2+} concentrations were determined from 0.1 g dry ground tissue. Tissue samples were digested in nitric acid followed by atomic absorption spectrometry determinations (model GBC 904AA Scientific Equipment Pty, Victoria, Australia).

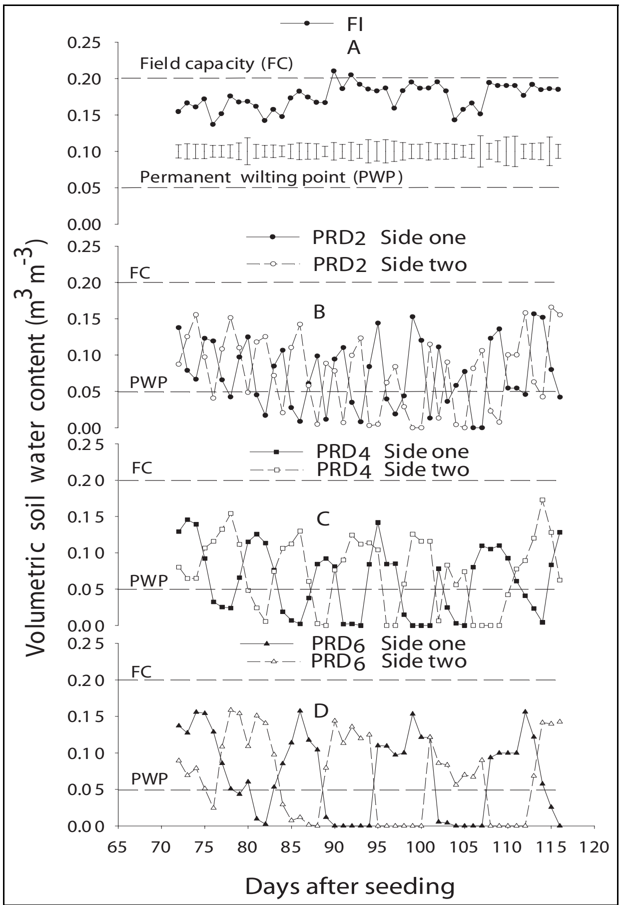

Fig. 1. Changes in soil water content (θ in the text) in FI (A) and in the two sides of plant root system for PRD_2 (B), PRD_4 (C), and PRD_6 (D). Vertical bars apply to all the treatments and represent the minimum significant difference (MSD) by Tukey's test at P≤0.05.

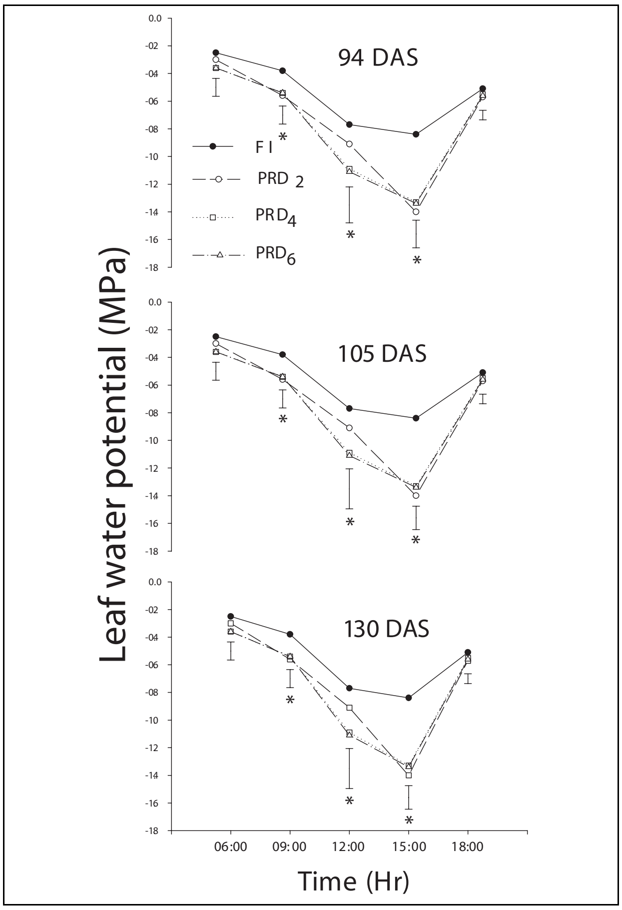

Fig. 2. Diurnal changes of leaf water potential (Ψ_{leaf} in the text) for three occasions under four irrigation treatments. The treatments are described in the text. Vertical bars represent the MSD by Tukey's test and the asterisks show significant differences at P≤0.05.

The data were analysed by a completely randomised model using the GLM procedure of SAS software (version 8.2, SAS Institute, Cary, N. C., USA). To stabilise the variance, the variables expressed in percentage and in discrete unit were arcsine- and square-root transformed, respectively. Means are reported after back transforming. Treatment means were separated by Tukey's Studentised range test at P≤0.05.

Results

For the FI treatment θ ranged from 0.15 to 0.21 $m^3\ m^{-3}$ with an average of 0.18 $m^3\ m^{-3}$ (Fig. 1A). It was simultaneously increasing or decreasing in both sides of the root system in PRD treatments (Fig. 1, B–D). For PRD treatments θ did not reach values close to field capacity. This could be because the growing medium had 30 % pumice by volume. As one side was kept dry and the irrigation time was relatively short, pumice re-hydration was partial compared with that in full irrigation where the dehydration was avoided at all times and this could mask TDR outputs. Moreover, it is likely that irregularity of soil porosity might reduce the irrigation efficiency, so that additional amount of water would have been necessary to fill all kinds of soil pores, but the drainage would have been also increased.

Ψ_{leaf} followed the typical diurnal pattern decreasing from early morning, reaching a minimum value after midday, and then starting to recover in late afternoon (Fig. 2). It was significantly lower for all the PRD treatments than the control at 9:00, 12:00, and 15:00 hours in three occasions measured (Fig. 2). The lowest Ψ_{leaf} value was observed at 15:00 hours and it was approximately –1.4 MPa in all PRD treatments on 130 DAS suggesting a severe water deficit.

In general, the rate of photosynthesis was significantly higher in FI plants than the PRD plants in the first two occasions measured and the same was true for stomatal conductance (Table 1). On 130 DAS low solar radiation could have overridden the PRD effect on stomatal closure.

Total fresh mass of plant and total fresh mass of fruit were lower in PRD plants than in FI plants (Table 2). However, the irrigation water-use efficiency (on a dry mass basis) was improved by 52 % in PRD plants compared to FI plants (Table 2). Total dry mass of plant was also reduced in all PRD plants compared to FI plants (Fig. 3).

Table 1. Effect of irrigation treatments (ITs) on photosynthesis and stomatal conductance. Photosynthetic photon flux (PPF) is given for each occasion. Different letters within columns indicate significant differences by Tukey's test at P≤0.05.

Parameter	ITs	Days after seeding (DAS)			Mean
		94	105	130	
Photosynthesis (A) (μmol m^{-2} s^{-1})	FI	19.2 a	13.6 a	8.0 a	14.4 a
	PRD_2	9.2 b	7.8b	7.5 a	8.1 b
	PRD_4	7.2 b	7.8b	6.3 a	7.0 b
	PRD_6	8.7 b	8.4 ab	6.3 a	7.8 b
Stomatal conductance (g_s) (mol m^{-2} s^{-1})	FI	3.5 a	1.3 a	1.9 a	2.3 a
	PRD_2	0.9 b	0.7 b	2.0 a	1.2 b
	PRD_4	0.5 b	0.5 b	1.8 a	1.1 b
	PRD_6	0.5 b	0.5 b	1.7 a	1.0 b
PPF (μmol m^{-2} s^{-1}±SD)		1254±235	836±346	669±289	

FI : Full irrigation (control)
One side irrigation of the root system for two (PRD_2), four (PRD_4), and six (PRD_6) consecutive days before irrigation was shifted over to the dry side.

Table 2. Effect of irrigation treatments (ITs) on total fresh mass of plant (TFMP), total fresh mass of fruit (TFMF), and irrigation water use efficiency (IUE_{TDMF}) per plant. Different letters within columns indicate significant differences by Tukey's test at P≤0.05.

ITs	TFMP (kg plant^{-1})	TFMF (kg plant^{-1})	IUE_{TDMF} (g L^{-1})
FI	9.6 a	7.4 a	1.1 b
PRD_2	6.8 b	5.0 b	1.6 a
PRD_4	7.1 b	5.3 b	1.8 a
PRD_6	6.8 b	5.0 b	1.6 a

FI : Full irrigation (control)
One side irrigation of the root system for two (PRD_2), four (PRD_4), and six (PRD_6) consecutive days before irrigation was shifted over to the dry side.

Table 3. Effect of irrigation treatments (ITs) on dry mass distribution per plant. Different letters within columns indicate significant differences by Tukey's test at P≤0.05.

ITs	Dry mass distribution per plant (%)			
	Root	Stems	Leaves	Fruit
FI	1.5 a	20.9 a	11.6 a	66.0 a
PRD_2	2.1 a	23.7 a	15.4 a	58.8 b
PRD_4	1.8 a	23.9 a	12.6 a	61.7 ab
PRD_6	1.8 a	24.7 a	13.6 a	59.9 b

FI : Full irrigation (control)
One side irrigation of the root system for two (PRD_2), four (PRD_4), and six (PRD_6) consecutive days before irrigation was shifted over to the dry side.

Dry mass partitioning into roots, stems, and leaves, was similar in all treatments (Table 3). However, there was a trend for increased partitioning into stems and leaves in PRD plants relative to FI plants. Dry mass partitioned into PRD_2 and PRD_6 fruit was significantly lower than that of FI fruit with a similar trend for PRD_4 fruit (Table 3).

The number of fruit for PRD_2 and PRD_6 treatments was significantly lower than that of FI with a similar trend for PRD_4 fruit (Table 4). The same was generally true for mean fresh mass per fruit, total dry mass of fruit, and fruit water content. TSSC was higher in PRD fruit which also had the highest blossom-end rot incidence (Table 4). Fruit skin colour, in terms of hue angle (HA°), was not significantly different among treatments. However, PRD fruit tended to have lower HA° values (Table 4), therefore having a tendency for being redder than FI fruit. Leaf calcium concentration was lower for PRD treatments than the control, but fruit values were the same among the treatments. For leaves the values (mg g^{-1} of dry mass ±SEM) were 10.0±1.8, 4.9±1.8, 1.8±0.9, and 4.8±1.3, for, respectively, FI, PRD_2, PRD_4, and PRD_6. The corresponding values for fruit were 0.19±0.02, 0.19±0.01, 0.15±0.02, and 0.14±0.04.

Discussion

The significant decrease, during the day, in Ψ_{leaf} for the PRD plants indicates that the dry part of the rhizosphere limited the plants' ability to meet the transpiration demand, possibly due to a lowering of root hydraulic conductivity (Lafolie et al. 1999) and water deficit in the rootzone. However, Ψ_{leaf} recovered during the late afternoon to that of the FI plants for all the three days of meas-

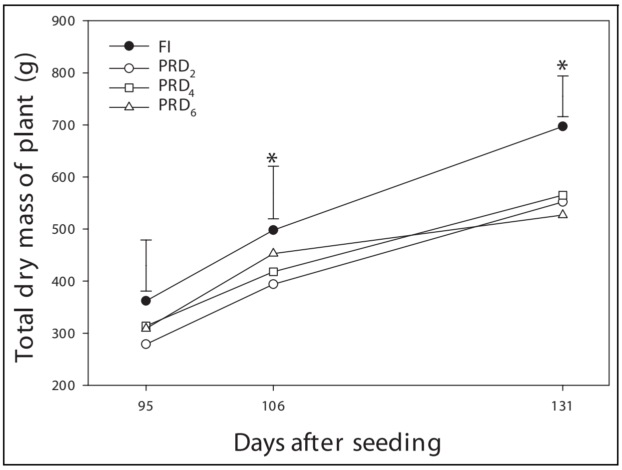

Fig. 3. Changes in total dry mass of processing tomato plants (including roots and fruit) under four irrigation treatments. Vertical bars represent the MSD by Tukey's test and the asteriks show significant differents at P≤0.05.

urement (Fig. 2). Root growth was not hampered by the PRD treatments. The root fresh mass (g ± standard error of the mean, SEM) for FI, PRD_2, PRD_4, and PRD_6 were 78±8, 80.6±6.3, 73.7±5.0, and 71.6±7.0, respectively. The corresponding dry mass values were 9.64±0.7, 11.5±0.8, 10.3±0.3, and 9.6±0.8. The root/shoot ratios were also the same among the treatments. The values were (MSD=5.4): 23.8, 20.2, 22.0, and 23.0 for FI, PRD2, PRD4, and PRD6, respectively.

Lower stomatal conductance was the main reason for reduced photosynthetic rate in PRD plants (Table 1). The ratios of leaf internal CO_2 concentration to that of the air (Pi/Pa) were the same for all the treatments. This indicates that once transported into the leaf, CO_2 did not accumulate and was fixed during photosynthesis. An example for typical values of Pi/Pa could be given for 105 DAS when the ratios (± SEM) of 0.9±0.01, 0.89±0.01, 0.87±0.01, and 0.87±0.01were calculated for, respectively, FI, PRD_2, PRD_4, and PRD_6. The corresponding transpiration rates (E, mmol m^{-2} s^{-1} ± SEM) were 18.5±1.3, 14.6±0.7, 14.6±0.4, and 13.8±0.6. The PRD plants had significantly reduced E. Stomatal conductance was therefore regulating the gas exchange rates. The conductance was reduced by lower leaf water potentials for PRD plants (Fig. 2) and possibly by root messages from the drying soil (Davies and Zhang 1991).

Soil water deficit has a more negative effect on shoot growth than on root growth (Wu and Cosgrove 2000). This is, at least partially, reflected in our results. Root growth was not affected by the irrigation treatment as discussed above, but fresh mass of stems and leaves, added together, was reduced in PRD treatments. The values (kg per plant ± SEM) were 1.08±0.08, 1.7±0.04, 1.7±0.05, and 2.1±0.06 for PRD_2, PRD_4, PRD_6, and FI, respectively. Dry mass was not affected by these treatments and the corresponding values were (kg per plant ± SEM): 0.22±0.01, 0.21±0.05, 0.20±0.06, and 0.21±0.07. Reproductive growth was reduced in the PRD treatments because it is a more sensitive phenological stage to water deficit than is vegetative growth (Srinivasa et al. 2000). This is reflected in the reduced values of total fresh mass of fruit for PRD treatments (Table 2) and also lower number of fruits (Table 4). A lower number of fruits is the result of flower abortion as tomato is very sensitive to water stress during flower and fruit set (Pulupol et al. 1996). Irrigation-water-use efficiency was significantly improved (Table 2) as the result of 50 % reduction in irrigation water in PRD plants despite their reduced fruit yield. There were no significant differences among the three PRD treatments in total fresh mass of plant, total fresh mass of fruit, and total dry mass of fruit. The soil and plant water status was the same for these treatments (Fig. 1, 2) and so was the rate of photosynthesis and value of stomatal conductance (Table 1).

When water supply is adequate, the tomato fruit is the strongest sink for assimilates compared with the rest of plant's organs (Ho 1996b). Reduction in fruit size under deficit irrigation is mainly attributed to reduced fruit water content (Ho et al. 1987; Ho 1996b). In this study, a lesser proportion of dry mass was partitioned into the PRD fruits than in FI fruits (Table 3). The same differences existed in total dry mass of fruit and fruit water content (Table 4). These findings are in disagreement, in part, to those reported by Ho et al. (1987) and Ho (1996b). We have found that the reduction of fruit size under PRD treatments could be due to a suppression of both water and as-

Table 4. Effect of irrigation treatments (ITs) on number of fruit per plant (NF), mean fresh mass per fruit (MFMF), total dry mass of fruit per plant (TDMF), fruit water content (FWC), total soluble solids concentration (TSSC), incidence of blossom-end rot (BER), and fruit colour in terms of hue angle (HA°) at green and red stage. Different letters within columns indicate significant differences by Tukey's test at P≤0.05.

ITs	NF	MFMF (g)	TDMF (g $plant^{-1}$)	FWC (%)	TSSC (%)	BER (%)	HA° Green stage (116 DAS)	HA° Red stage (129 DAS)
FI	68 a	110 a	438 a	94.1 a	4.5 b	5 b	111.1 a	39.3 a
PRD_2	49 b	101 ab	325 b	93.4 b	5.2 a	21 a	111.4 a	37.5 a
PRD_4	57 ab	93 b	366 b	93.0 b	5.2 a	21 a	111.8 a	38.1 a
PRD_6	51 b	99 ab	321 b	93.5 ab	5.3 a	17 a	111.5 a	37.5 a

FI : Full irrigation (control)
One side irrigation of the root system for two (PRD_2), four (PRD_4), and six (PRD_6) consecutive days before irrigation was shifted over to the dry side.

similate fluxes into the fruit. Midday leaf water potential of −1.1 MPa or lower for tomato could reduce sap flux by 90 % during the day and consequently will reduce fruit size (JOHNSON et al. 1992; ARAKI et al. 1998; BUSSIÈRES 2002). In our experiment Ψ_{leaf} dropped to −1.4 MPa (Fig. 2), hence water and dry mass imports into the fruit could have been limited. But we also expect the PRD fruit to have lost more dry mass to respiration than the FI fruit as shown for 'Virosa' cultivar by PULUPOL et al. (1996). As photosynthesis was not totally inhibited in PRD plants (Table 1), the available assimilates were attracted by stems, leaves, and roots (Table 3). These are stronger sinks for assimilates than fruit under water deficit (HSIAO 2000). In a split-root experiment, a similar dry mass partitioning was found for *Capsicum annuum* (CANTORE et al. 2000).

Total soluble solids concentration, which is an important quality factor for processing tomato, was higher in PRD fruit than in the FI fruit (Table 4). Water deficit induces a higher starch accumulation during the first stage of fruit growth (MITCHELL et al. 1991), followed by more conversion of starch into sugars during the maturation (DAVIS and COCKING 1965). Total soluble solids concentration and fruit water content were correlated ($r=-0.60$, $P\leq0.0001$) and therefore the increased soluble solids in PRD fruit might have been due to a lower fruit water content.

The incidence of blossom-end rot (BER) was higher in PRD fruit than in FI fruit (Table 4). This was accompanied by a reduction of Ca^{2+} concentration in PRD leaves compared to FI leaves, while fruit Ca^{2+} concentration was similar among the treatments. Fruit Ca^{2+} concentration *per se* may not be the sole reason for BER incidence (EL-GIZAWY and ADAMS 1986; ADAMS and HO 1992). In our case Ca^{2+} was measured in the bulk fruit which might not represent the BER-affected area of the fruit. Moreover, although low transpiration rates (induced by water stress) are expected to reduce calcium transport to the fruit, high transpiration rates could also induce BER by creating preferential flow to leaves inhibiting Ca^{2+} diversion to the fruit (STANGHELLINI et al. 1998). The scope of our data does not allow a conclusive explanation for higher BER incidence in the PRD fruit.

In summary, PRD reduced fresh yield by 34 % and dry yield by 23 %. But the fruit quality, in terms of lower fruit water content and higher total soluble solids concentration which are both advantageous for processing tomato, was improved. The irrigation use efficiency was increased by approx. 55 %. However, the same advantages found for the PRD treatments here, in terms of improved irrigation water-use efficiency, could be realised by the application of PRD in which wet and dry sides of the rhizosphere are alternated at every irrigation. The main purpose of this study was to find out to what degree a part of the rhizosphere could be left to dry in PRD irrigation. The main conclusion is that the drying should not be to the extent that a midday Ψ_{leaf} value of less than −1.0 MPa could be developed. This implies that more water must be supplied to the wet side of PRD to avoid yield reduction and therefore 50 % of water would not be saved, which must be particularly true for dry environments.

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