Water Relations, Growth, and Yield of Processing Tomatoes Under Partial Rootzone Drying

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ABSTRACT. Water for irrigation is limited worldwide. Therefore water saving practices will have to be adopted. This experiment was carried out to compare deficit irrigation (DI) with partial rootzone drying (PRD) for their effects on the processing tomato (*Lycopersicon esculentum* Mill.) cv. Petopride. The treatments were: full watering of both sides of the root system (RS) at each irrigation as control (C), half of irrigation water in C divided equally to both sides of the RS with each watering (DI), and half of irrigation water in C given only to one side of the RS with each irrigation (PRD). Photosynthetic rate, transpiration, stomatal conductance, and leaf water potential were measured on five occasions, and were found to be the same among treatments. Total fruit fresh mass

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was lower in DI and PRD than in C, but total fruit dry mass was the same among treatments. Irrigation use efficiency was higher in DI and PRD than in C. Vegetative fresh mass was not affected by treatment. However, compared with C plants, vegetative dry mass was higher in DI and PRD plants. Percentage of dry mass allocated into roots was the same among treatments, but a higher allocation was into stems and leaves in DI and PRD plants than in C plants. This was the opposite for the fruit. Total fruit fresh mass was affected by the quantity of irrigation water applied, but not by the volume of soil wetted. Both DI and PRD treatments were found to be feasible water-saving practices for 'Petopride'.

KEYWORDS. *Lycopersicon esculentum*, dry mass distribution, plant water status, water conservation

INTRODUCTION

Water supply is 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 relatively minor reduction in irrigation water could substantially increase the water available for other purposes. Tomato (*Lycopersicon esculentum* Mill.) has the highest acreage of any vegetable crop in the world (Ho, 1996), therefore adoption of deficit irrigation (DI) or partial rootzone drying (PRD) could make substantial contribution to saving of water.

Deficit irrigation, where only a portion of the optimum volume of water is applied to plants over the entire root system (RS), has been assessed for tomato with mixed results. Pulupol et al. (1996) observed a significant reduction in dry mass yield for a glasshouse cultivar using DI, while Mitchell et al. (1991) reported no reduction for a field-grown processing cultivar. PRD is a relatively new irrigation strategy where at each irrigation time only a part of the RS is wetted with the remainder being left to dry to a pre-determined level. It could save water by 50% and yet maintain yield as shown for some grape cultivars (Loveys et al., 2000). PRD has not been studied for tomatoes.

The objective of the study was to compare the effects of DI and PRD on water relations, photosynthesis, yield, irrigation use efficiency, and dry mass distribution. The rootzone was expected to remain partially moist in the PRD treatment and therefore plant water potential could be maintained. For this reason we hypothesized that PRD would effect milder reactions in the plants than DI for which the entire rootzone could experience water deficit. The experiment was carried out in a glasshouse to avoid interference by rain and to minimize the adverse effects that frequently changing weather might have on plant responses.

MATERIALS AND METHODS

Experimental Conditions and Plant Material

The experiment was conducted under glasshouse conditions at the Plant Growth Unit, Massey University, Palmerston North (latitude 40° 2′ S, longitude 175° 4′ E), New Zealand, from January to July 2001. Seeds of the processing tomato cv. Petopride were sown on 22 January 2001 and seven-week-old individual plants were transplanted into nine wooden boxes each housing three containers with one experimental plant per container each with dimensions of $60 \times 60 \times 20$ cm^3. Plants were grown in a bark:pumice:peat mixture comprising 60:30:10 by volume. Plants were fertilized (180 g per container) with a 1:2 (w:w) mixture of, respectively, short-term (15 N-4.8 P-10.8 K) and long-term (16 N-3.5 P-10 K) slow release osmocote fertilizer (Scotts Australia Pty. Ltd., Baulkam Hills, NSW, Australia).

Treatments and Soil Water Measurements

Ten days after transplanting, the following three treatments were applied: full watering of both sides of the RS at each irrigation as control (C), half of irrigation water in C divided equally to both sides of the RS with each watering (DI), and half of irrigation water in C given only to one side of the RS with each watering (PRD). Each wooden box was considered as a block to randomly accommodate the above three treatments in a randomized complete block design with nine replications.

Saturation and field capacity (FC) for this growing medium and their relationship with volumetric soil water content (θ) were determined before the experiment was initiated using the method of Parchomchuk et al. (1997). Field capacity was reached at a θ of 20%. The amount of water to be applied was calculated by using θ readings in the control before each irrigation. The value of θ was also recorded after each daily irrigation in both sides of the RS at 20-cm soil medium depth and at 15-cm away from the main stem by time-domain reflectometry (Trase Systems-Soil Moisture Equipment Corp., Santa Barbara, California). Plants were hand-irrigated once a day with, on average, one litre per plant for DI and PRD and two litres per plant for C. The irrigation in PRD treatment was given 10 cm away from the main stem and covered an area of $60 \times 20\ cm^2$. The treatments started with full irrigation to both sides of the RS. In PRD treatment one side (Side 1) of RS was wetted while the other side (Side 2) was allowed to dry. Irrigation was reversed from the wetted side to the dry side when the value of θ was, on average, 10% in the dry side. This criterion allowed that the irrigation was alternated frequently from Side 1 to the Side 2 during the entire growing season. However, some days θ dropped below 10% due to unexpected higher evapotranspiration rates, making it difficult to control the predetermined level of θ.

Physiological Parameters

Midday leaf water potential (ψ_{leaf}), photosynthetic rate (A), transpiration (E), and stomatal conductance (g_s) were measured on two well-developed and sun-exposed leaves per plant between 11:30 and 13:30 hours with a portable photosynthesis system (Li-Cor model 6200, Lincoln, Nebraska, USA). This was done on five occasions and the values for only two of them, which are typical for other measurements, are presented here. The data presented are for 108 and 160 days after sowing (DAS) which corresponded to fruit-set and prior to harvest, respectively. On the same occasions, leaf water potential was measured in two well-developed and sun-exposed leaves per plants using a Scholander pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, California, USA).

Yield and Irrigation Use Efficiency

At harvest, fruit were weighed, cut into halves, and oven-dried at 85°C to a constant mass to assess the total fruit dry mass (TFDM). Plants were weighed and divided into roots, stems and leaves and oven-dried at 70°C to a constant mass and the total vegetative dry mass determined. Irrigation-use efficiency (IUE) was calculated for each treatment by dividing total fruit fresh mass per plant by the litres of irrigation water applied to the plant. From the first trusses (a truss being defined as an inflorescence-bearing stalk branching from the main stem), over four harvests, 45 fruit per treatment (five fruit per replication) were randomly chosen at the firm red stage for quality measurements. Fruit were cut into halves and few drops of their juice from each half were used to measure total soluble solids concentration (TSSC) with a handheld refractometer with automatic temperature compensation (ATC-1 Atago, Tokyo, Japan). After sampling for TSSC, the fruit were oven-dried at 85°C to a constant mass for measurement of TFDM. Fruit water content was expressed on a fresh-mass basis.

Data Analysis

The data were analyzed using GLM procedure in the Statistical Analysis System (SAS) software version 8.2 (SAS Institute, Cary, NC, USA). To stabilize the variance, dry mass components and fruit water content were arcsine-transformed and means are reported after back transforming. Treatment means were separated by least significant difference test at $P \leq 0.05$.

RESULTS

Volumetric Soil Water Content

Generally, the θ values were significantly lower in DI than in C. For the PRD treatment, each side had either a high or a low value of θ depending on whether it was irrigated or not (Figure 1).

Physiological Parameters

For the five measurement occasions, values of ψ_{leaf}, A, E, and g_s were the same among the treatments and levels of photosynthetic photon flux (PPF) were low on each measurement day. Values for two occasions are presented in Table 1. Although E appeared to be higher on 108 DAS than on 160 DAS, A appeared to be lower at 108 than at 160 DAS (Table 1). The vapour pressure deficit was lower at 108 DAS than at 160 DAS. The values (mb ± SE) were 13.2 ± 0.2 and 25.8 ± 0.5 for 108 DAS and 160 DAS, respectively. This accounts for the higher g_s on the former day (Atwell et al., 1999). The higher g_s could not have promoted A

FIGURE 1. Changes in volumetric soil water content (θ) in the control, deficit irrigation, and on both sides of the root system of partial rootzone drying (PRD) treatments. Each side of PRD root system had either a high or low θ depending on whether it was irrigated or not. Vertical bars represent the LSD at $P \leq 0.05$.

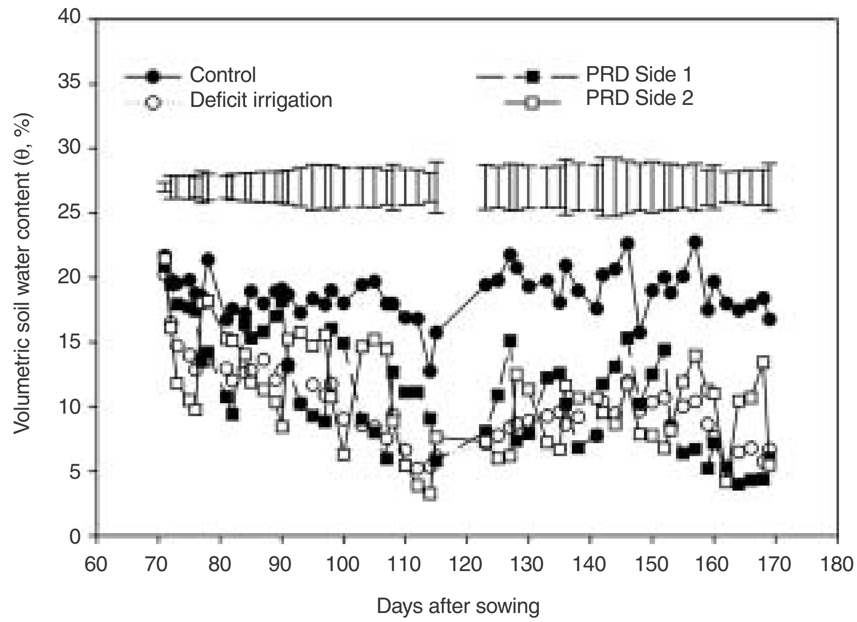

TABLE 1. Effect of irrigation treatments on leaf water potential (Ψ_{leaf}, MPa), photosynthetic rate (A, $\mu mol \cdot m^{-2} \cdot s^{-1}$), transpiration rate (E, $mmol \cdot m^{-2} \cdot s^{-1}$), and stomatal conductance (g_s, $mol \cdot m^{-2} \cdot s^{-1}$) for tomato plants.

Irrigation treatment[Z]	Days after sowing							
	108				160			
	Ψ_{leaf}	A	E	gs	Ψ_{leaf}	A	E	gs
C	−0.48a[Y]	5.57a	15.3a	2.62a	−0.52a	7.62a	6.7a	0.30a
DI	−0.51a	5.90a	14.9a	2.37a	−0.65a	7.77a	6.5a	0.28a
PRD	−0.45a	5.23a	14.9a	2.60a	−0.71a	7.84a	6.5a	0.29a
PPF[X]	213 ± 74				456 ± 193			

[Z]C = Control; DI = Deficit irrigation; PRD = Partial rootzone drying.
[Y]Means with same letters within columns are not significantly different using the LSD test at $P \leq 0.05$.
[X]PPF = photosynthetic photon flux ($\mu mol \cdot m^{-2} \cdot s^{-1} \pm$ SD).

at 108 DAS because of low radiation (Table 1). Although a higher g_s at 108 DAS could be a reason for the higher E, the latter quantity is expected to have been lower because of lower vapour pressure deficit.

Yield and Irrigation Use Efficiency

Total fruit fresh mass was lower in DI and PRD treatments than in C treatment (Table 2). However, total fruit dry mass was not affected ($P \leq 0.06$) by the treatments. Irrigation use efficiency was higher in DI and PRD plants than in C plants. Total fruit fresh mass was the same between DI and PRD treatments. Total vegetative fresh mass (including roots) was the same for all treatments. However, total vegetative dry mass (including roots) was higher in DI and PRD treatments than in C treatments (Table 2).

Dry Mass Distribution

Percentage values of dry mass partitioned into roots, stems, leaves, and fruit are presented in Table 3. Dry mass partitioning into root was similar among treatments. Higher dry mass was partitioned into stems and leaves in DI and PRD plants than in C plants. However, dry mass partitioning into fruit was highest for C plants (Table 3).

DISCUSSION

Here we focus on the effects of the irrigation treatments on plant water relations and gas exchange properties, fresh and dry mass of differ-

TABLE 2. Effect of irrigation treatments on total fresh and dry mass of fruit per plant, irrigation use efficiency, and total fresh and dry vegetative mass per plant.

	Total fruit mass			Total vegetative mass	
Irrigation treatment[Z]	Fresh (kg/plant)	Dry (g/plant)	IUE[Y] ($g \cdot L^{-1}$)	Fresh (g/plant)	Dry (g/plant)
C	5.4a[X]	253a	24b	1379a	122.0b
DI	4.4b	248a	39a	1377a	130.7a
PRD	4.4b	251a	39a	1418a	132.8a

[Z]C = Control; DI = Deficit irrigation; PRD = Partial rootzone drying.
[Y]IUE = Irrigation use efficiency.
[X]Means with same letters within columns are not significantly different using the LSD test at $P \leq 0.05$.

TABLE 3. Effect of irrigation treatments on dry mass distribution of tomato plants.

Irrigation treatment[Z]	Dry mass distribution per plant (%)			
	Root	Stems	Leaves	Fruit
C	1.4a[Y]	16.6b	13.2b	68.8a
DI	1.8a	19.0a	14.6ab	64.6b
PRD	1.5a	18.4a	15.4a	64.7b

[Z]C = Control; DI = Deficit irrigation; PRD = Partial rootzone drying.
[Y]Means with same letters within columns are not significantly different using the LSD test at $P \leq 0.05$.

ent parts of the plant, dry mass distribution in the plant, and we provide an assessment of PRD as a management tool. Values of ψ_{leaf}, A, E, and g_s remained unaffected by the treatments for the five occasions we measured them. This experiment was carried out during the winter months in the glasshouse and the radiation levels were generally low on those days. In a tomato leaf, photosynthesis is saturated at a PPF of approximately 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Venema et al., 1999). During a sunnier day the PPF values averaged at 456 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (160 DAS, Table 1). However, radiation was very variable on this day, hence the large value of standard deviation (SD) in Table 1, with no measurable effect of treatments on ψ_{leaf}, A, E, and g_s. Behboudian et al. (1994) showed that in Asian pear (*Pyrus serotina* Rehd.), low radiation overrides the effect of water deficit on photosynthesis and deficit-irrigated trees had the same low levels of photosynthesis as did fully-watered trees on a cloudy day.

Reproductive growth is the plant parameter most sensitive to water deficit (Hsiao, 1973) and the decrease in fresh mass in DI and PRD fruit, compared to the C fruit (Table 2), indicates that water deficit did develop in the former treatments. Tomato is sensitive to water deficit during flowering and fruit set (Pulupol et al., 1996). Our treatments were applied before the first truss appeared and water deficit could have developed during the reproductive growth. Tomato fruit contains at least 92% water, most of which is transported to the fruit through the phloem. Water transport is reduced during a mild water deficit although photoassimilates continue to be transported into the fruit (Ho, 1999). This might have been a reason that the fruit fresh mass was lower in DI and PRD fruit than in the C fruit while the fruit dry mass was similar among treatments. Total fruit fresh mass was the same between DI and PRD treatments. This suggests that the quantity of water was more important to yield than was the volume of soil irrigated.

In the DI and PRD plants, a lesser proportion of dry mass was partitioned into the fruit than in the C plants. The DI and PRD fruit had significantly lower water content than the C fruit ($P \leq 0.05$). The percentage of fruit water content was 95.1, 94.6, and 94.5 for C, DI, and PRD, respectively. The DI and PRD fruit also had a higher concentration of TSSC than the C fruit ($P \leq 0.05$). TSSC values were 4.18, 4.66, and 4.54 for C, DI and PRD, respectively. Although we did not measure fruit water potential, lower water content and higher soluble solid concentration in DI and PRD fruit than in C fruit is indicative of lower water potential in the former treatments. In this case, translocation of photoassimilates would be expected to have been higher into DI and PRD fruit than C fruit, as demonstrated for the roots of *Phaseolus vulgaris* L. (Lang and Thorpe, 1986). We expect more distribution of photoassimilates into the fruit of the DI and PRD treatment. However, this could have been counteracted by higher respiration rate in the DI and PRD fruit compared to the C fruit as shown for the fresh tomato cv. Virosa (Pulupol et al., 1996). Cantore et al. (2000), in a split-root experiment, reported a dry mass distribution pattern for *Capsicum annuum* L. similar to our experiment.

The higher yield, in terms of fruit fresh mass, in C than in DI and PRD treatments indicates the importance of water quantity applied, while the similarity of yield between DI and PRD shows that it does not matter what volume of soil is wetted with each irrigation. Tan et al. (1981) reported that for tomato, irrigating part of the rhizosphere (*ca* 50%) could be enough to meet the plant's water requirements rather than irrigating the entire root system.

CONCLUSIONS

We conducted this experiment to assess DI and PRD as water-saving irrigation techniques. In both DI and PRD treatments, dry mass was maintained and irrigation water was saved by 50%, compared to fully-watered plants. Irrigation-use efficiency increased 1.6 times. For processing tomatoes, a relatively lower water accumulation by the fruit should be desirable providing the marketable yield is acceptable (Ho, 1999). In both DI and PRD treatments, the dry mass concentration in the fruit was similar to the fully-watered control. Therefore PRD and DI could both be considered as feasible irrigation strategies for the production of processing tomatoes. However, field research is needed to corroborate these results.

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