RESPONSE OF TOMATO TO PARTIAL ROOTZONE DRYING AND DEFICIT IRRIGATION

RESPUESTA DEL TOMATE AL RIEGO PARCIAL DE LA RAÍZ Y DÉFICIT HÍDRICO

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SUMMARY

Water is a limiting factor for plant production worldwide, and therefore it is necessary to adopt water saving irrigation practices. Partial rootzone drying (PRD) is a new water saving irrigation techique, which was compared with deficit irrigation (DI). The effects of PRD and DI on leaf water potential, plant growth, biomass allocation, yield, and fruit quality of 'Petopride' processing tomato (*Lycopersicon esculentum* Mill.) were studied. The treatments were: daily full irrigation (FI) on both sides of the root system (RS) considered as control; irrigation on one side of the RS with half the volume of water given to controls where the irrigation was shifted over from the wetted part to the drying part of the RS every day (PRD); and full irrigation every other day on both sides of the RS, considered as DI. Leaf water potential, total plant fresh weight and total dry weight of fruit were lower in DI than in FI and PRD. In PRD irrigation water use efficiency was improved by 83 % relative to FI. For DI dry mass partitioned into stems and leaves was higher, but dry mass partitioned into fruits was lower in PRD and DI than in FI. Fruit water content and fruit background skin colour were the same among treatments, but total soluble solids concentration was higher in PRD and DI fruits. Leaf calcium concentration was lower and the incidence of blossom-end rot was higher in DI and PRD than in FI. The PRD is more advantageous than DI and may be recommended for areas where water is scarce.

Index words: *Lycopersicon esculentum*, plant water status, dry biomass partitioning, fruit yield and quality, blossom-end rot.

RESUMEN

El agua es un factor limitante para la producción agrícola mundial, y por tanto es necesario adoptar prácticas de riego que ahorren agua. El riego parcial de la raíz (RPR) es una técnica nueva para el ahorro de agua de riego, la cual fue comparada con el riego deficitario (RD). Se estudió el efecto de RPR y RD en el estado hídrico de la planta, crecimiento, distribución de la biomasa, rendimiento y calidad del fruto del tomate (*Lycopersicon esculentum* Mill.) para proceso cultivar 'Petopride'. Los tratamientos fueron: riego completo (RC) diariamente en ambos lados del sistema radical (SR), considerado como testigo; riego en un solo lado del SR con la mitad del volumen de agua dado en el testigo donde el riego fue alternado diariamente de la parte húmeda a la parte del SR en proceso de secado (RPR); y riego completo cada tercer día en ambos lados del SR, considerado como RD. El potencial hídrico en la hoja, el peso fresco total de la planta y el rendimiento seco del fruto fueron menores en RD que en RC y RPR. En RPR la eficiencia en el uso del agua de riego se mejoró en 83 % en relación con RC. En RD la asignación de biomasa seca hacia tallos y hojas fue mayor, pero la asignada al fruto fue menor en RPR y RD que en RC. El contenido de agua y el color externo del fruto fueron iguales entre tratamientos, pero la concentración de sólidos solubles totales fue mayor en los frutos de RPR y RD. La concentración de calcio en las hojas fue menor y la incidencia de pudrición apical del fruto mayor en RD y RPR que en RC. El RPR es más ventajoso que el RD y se recomienda para áreas donde el agua es escasa.

Palabras clave: *Lycopersicon esculentum*, estado hídrico de la planta, partición de biomasa seca, rendimiento y calidad del fruto, pudrición apical del fruto.

INTRODUCTION

Water supplies are limited worldwide (Postel, 1998) and there is an urgent need to identify and adopt better irrigation management strategies. As irrigation of agricultural lands accounts for over 85 % of water use in the world (van Schilfgaarde, 1993), even a relatively minor reduction in irrigation water could substantially increase the water available for other purposes, and also would reduce contamination of agricultural lands and ground water tables (Bouwer, 2003). This is especially true for tomato (*Lycopersicon esculentum* Mill.) which has the highest acreage of any vegetable crop in the world (Ho, 1996) and in dry environments where irrigation is essential for higher yields (Geisenberg and Stewart, 1986).

Deficit irrigation (DI) has been used as a water saving irrigation technique in horticultural production (Mitchell *et al.*, 1991; Behboudian and Mills, 1997). DI implies giving less water to the entire rootzone of plants than the prevailing evapotranspiration. Depending on the extent of water deficit, DI reduces plant water status along with a reduction of gaseous exchange leading to poor marketable

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yield, as observed in tomato plants (Obreza *et al.*, 1996; Pulupol *et al.*, 1996; May and Gonzales, 1999).

Partial rootzone drying (PRD) is a relatively new water saving technique where at each irrigation only a part of the rhizosphere is wetted with the remaining part left to dry to a pre-determined level of soil water content (Davies *et al.*, 2002). Plant water status is expected to equilibrate with the wettest part of the rhizosphere (Hsiao, 1990), and therefore to maintain a high leaf water potential similar to well-watered plants, as observed in split-root experiments with tomato (Holbrook *et al.*, 2002; Davies *et al.*, 2000). Contrary to DI, PRD could maintain similar plant water status compared to fully irrigated plants with no deleterious effects on yield. It might enhance some aspects of fruit quality as observed in field-grown grapevines (*Vitis vinifera*) in a Mediterranean climate (dos Santos *et al.*, 2003) and in processing tomato (Zegbe *et al.*, 2004). On the other hand, fruit is considered as the strongest sink for photo-assimilates in tomato plants (Ho, 1996), but it may become a weaker sink in plants under reduced irrigation (Davies *et al.*, 2000; Zegbe-Domínguez *et al.*, 2003).

Based on the expectation that plant water status would be the same between PRD and control (fully irrigated), the objective of this research was to test the hypothesis that irrigation water use efficiency, fruit yield and quality, and dry biomass partitioning in PRD will be similar to that of the well watered control. Irrespective of plant water status, PRD is presumed to affect plants through a change in the hormonal balance (Davies *et al.*, 2000; Davies *et al.*, 2002) affecting processes such as the stomatal movements and photosynthesis, and therefore some yield and fruit quality parameters. Treatments were applied through drip irrigation to improve water application efficiency compatible with water conservation strategies.

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 (40°2' SL, 175°4' EL), 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 nine wooden boxes (253 cm length x 65 cm width x 20 cm height) each housing four compartments (60 cm length x 60 cm width x 20 cm height) with one experimental plant per compartment. To avoid lateral water movement, a piece of wood (60 cm length x 2.5 cm width x 5 cm height) was placed centrally on the base of each compartment (for more details, see Zegbe *et al.*, 2006). The compartments were lined with black polyethylene 125 μm thick and perforated laterally and at the bottom to allow drainage. Plants were grown in a mixture of bark: pumice: peat with a ratio of 6:2:1 (by volume). Substrate volume per compartment was 720 cm^3. The plants were fertilised (180 g/container) with a 1:2 (w:w) mixture of rapid- and slow-release fertilisers (Osmocote 15N-4.8P-10.8K and Osmocote 16N-3.5P-10K, respectively, Scotts Australia Pty. Ltd., Baulkam Hills, NSW, Australia).

Twenty-nine days after transplanting, the following three irrigation treatments were randomly applied to a total of 36 plants: daily full irrigation (FI) on both sides of the root system (RS), considered as control; irrigation on one side of the RS with half the volume of water given to the control, where the irrigation was shifted over from the wetted part to the drying part of the RS every day (PRD); and full irrigation every other day on both sides of the RS, considered as deficit irrigation (DI). The experiment had a completely randomised design with three treatments replicated three times. There were four plants per replication for each treatment.

Two drippers, that emitted 4 L h^{-1}, were placed 15 cm away from the main stem in the FI and DI treatments. One emitter was used in PRD and was manually shifted over to the side to be irrigated as required. The plants were irrigated twice a day (at 07 and 18 h) either daily (FI and PRD) or every other day (DI) by an automated irrigation system. A total of 192, 192, and 392 L of water (gross irrigation) per plant was applied during the experiment to PRD, DI, and FI, respectively. The amount of water supplied daily was calculated with a calibration curve previously obtained by using the relation between soil moisture readings against known volumes of water. The irrigation water use efficiency presented here might have been under-estimated considering the water losses by drainage.

Volumetric soil water content (θ) was vertically monitored daily, for both irrigated and non-irrigated parts of RS at 20 cm of soil depth and 5 cm apart from the emitters. This was done by time-domain reflectometry (TDR) (Trase Systems-Soil Moisture Equipment Corp., Santa Barbara, California, USA). The measurements were taken within 60 min after irrigation. The apparent field capacity (FC) and permanent wilting point (PWP) for the soil media were established according to Parchomchuk *et al.* (1997) before setting up the experiment, and they were approximately at θ values of 0.20 and 0.05 m^3 m^{-3}.

Diurnal changes of leaf water potential (Ψ_{leaf}) were measured using a pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, California, USA) on 94, 118, and

136 DAS on two mature and exposed leaflets per plant. Measurements were taken at 6, 10, 14, and 21 h.

There was a single harvest in which the number of fruits, total fresh weight of fruits, and fruit size (in terms of mean fresh weight per fruit) were recorded. Fruits were cut into halves and oven-dried at 85 °C to constant weight to determine their total dry weight. Plants were divided into roots, stems, and leaves and each plant organ was weighed individually and total vegetative fresh weight obtained. Then, they were oven-dried at 70 °C to constant weight and total vegetative dry weight per plant was obtained by adding the weight of each individual organ (excluding fruit). Total dry weight of plant was the sum of total vegetative dry weight and total dry weight of fruit per plant. Harvest index was calculated by dividing total dry weight of fruit by total dry weight of plant. Irrigation water use efficiency was calculated for each treatment by dividing total fresh weight of fruit by the litres of water (gross irrigation) applied to each plant. Destructive harvests were done to assess changes in total dry weight of plant (including fruit and roots) by collecting one plant per replication per treatment. This was done on 94, 118, and 136 DAS at harvest time.

From the first trusses, 18 fruits per treatment (six per replication) were randomly chosen for quality measurements. They were weighed and used for the assessment of total fresh weight of fruit and total dry weight of fruit. Fruits with similar colour were collected at the green stage and colour development was evaluated for 14 d 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 weight basis. Blossom-end rot incidence was expressed in percentage of fruit affected per plant.

Ten leaflets per treatment per replication were sampled randomly for mineral analysis. They were washed with distilled water and dried at 70 °C for 14 d. The samples were grounded, and kept in an oven at 70 °C for 14 h before analysis. Leaf K^+, Ca^{2+}, and Mg^{2+} concentrations were determined from 0.1 g dry and grounded tissue. Tissue samples were digested in nitric acid followed by measurements with an atomic absorption spectrometer (model GBC 904AA Scientific Equipment Pty, Victoria, Australia).

The data were analysed by a completely randomised model using the GLM procedure of Statistical Analysis System software (SAS, 1999-2001). To stabilise the variance, the variables expressed in percentage and in discrete units were arcsine- and square-root transformed, respectively. Means are reported after back transforming. Treatment means were separated by multiple t tests at $P \leq 0.05$ and when F test of treatments was significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

Volumetric soil water content (θ) in FI was maintained close to FC (Figure 1A). For PRD and DI treatments, it fluctuated between FC and PWP. It was lower than FC by 2 or 3 % for the irrigated DI or irrigated side of PRD plants (Figure 1A and 1B). In some occasions, θ reached the PWP value in PRD treatment. Mean (± standard deviation) of θ values for FI, two sides of PRD, and DI treatments were: 0.19 ± 0.02, 0.14 ± 0.05, and 0.13 ± 0.05, respectively.

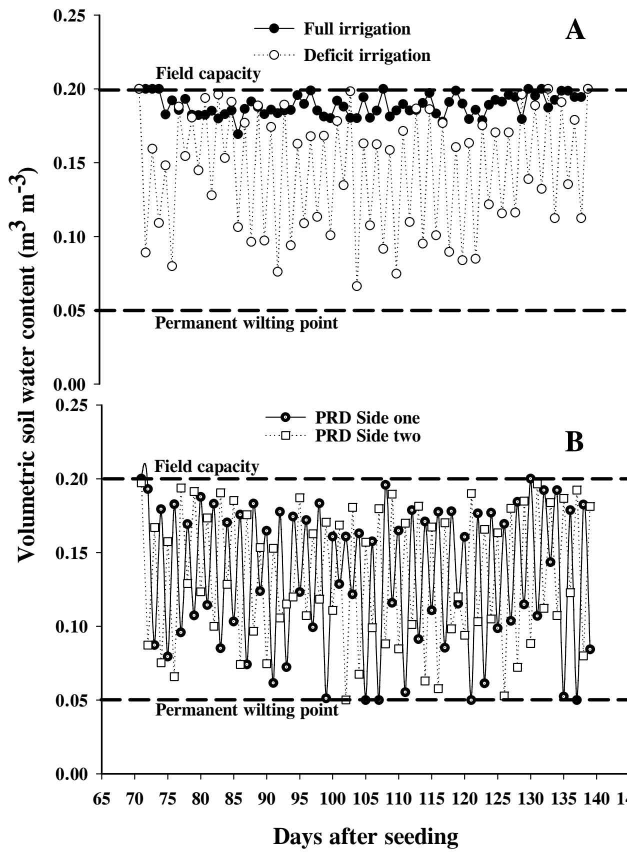

Figure 1. Changes in soil water content for full irrigation and deficit irrigation (A) and in both sides of plant root system of partial rootzone drying (PRD, B). Each side of PRD treatment had either a high or a low θ, depending on whether it was being irrigated or not. Treatments are described in the text.

Leaf water potential (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 (Figure 2). For DI plants, Ψ_{leaf} was significantly lower during the morning and tended to recover in the early afternoon on 94 DAS. It remained similar through the diurnal cycle for FI and PRD plants, suggesting that in PRD part of the rhizosphere may be allowed to drying without affecting Ψ_{leaf} (Figure 2A). On 118 DAS Ψ_{leaf} tended to be lower in both PRD and DI plants and this was significant at 14 h in DI plants only (Figure 2B). A similar trend was observed on 136 DAS for DI plants (Figure 2C). In general, Ψ_{leaf} in PRD plants was similar to FI plants as observed in split-root experiments with tomato (Holbrook *et al.*, 2002; Davies *et al.*, 2000), nevertheless, Ψ_{leaf} was always slightly lower in PRD plants than in FI plants.

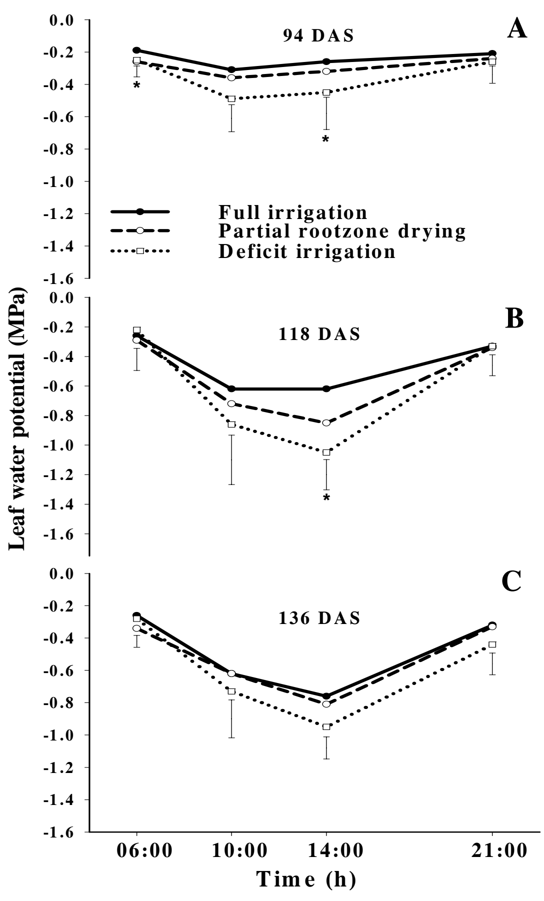

Figure 2. Diurnal changes of leaf water potential for three occasions under three irrigation treatments. Vertical bars represent the least significant difference (LSD) by t tests and the asterisks show significant differences at $P \leq 0.05$.

The number of fruits, total fresh weight of plant, total fresh weight of fruit and harvest index were lower in DI treatments than in FI treatment, but PRD plants were statistically placed in between (Table 1). As PRD plants maintained similar total fresh weight of plant, total fresh weight of fruit, and harvest index relative to FI, they did significant improve irrigation water use efficiency compared with FI and DI plants (Table 1). Total plant dry weight was also the same for PRD and FI during the entire growing season (Figure 3). However, at harvest total dry weight of plant in DI treatment was significantly reduced relative to FI and PRD treatments (Figure 3). The significant reduction in plant water status in DI plants was reflected in a significant reduction of total fresh weight of fruit and total dry weight of plant. The lowest number of fruits was found in DI plants. Tomato is sensitive to water deficit during flowering and fruit set (Pulupol *et al.*, 1996). Treatments were applied before the first trusses appeared and during the reproductive growth so that water deficit could have induced flower abortion (Pulupol *et al.*, 1996), hence reduction in number of reproductive sinks and harvest index (Hsiao, 1993; Zegbe *et al.*, 2006) in DI plants.

Dry biomass allocation into roots was similar in all treatments, but it tended to increase in PRD and DI plants (Table 2). Stems and leaves were apportioned with less dry biomass in FI and PRD plants than in DI plants. Dry biomass allocation to DI fruit was lower than in FI fruit, while PRD fruit were placed in between (Table 2).

The tomato fruit is the strongest sink for assimilates compared with the rest of the plant's organs (Ho, 1996). The reduction in fruit size under deficit irrigation, is mainly attributed to reduction of water rather than to reduction of assimilates imported into the fruit (Ho, 1996). Mingo *et al.* (2004) found significant reduction in biomass allocation into stems, leaves, and fruits, but root biomass was significantly enhanced. In this study, the lesser proportion of biomass was partitioned into the DI fruit. The same was true for mean fresh weight per fruit, total dry weight of fruit, and fruit water content. The reduction of the latter fruit parameters could be due to a suppression of both water and assimilates flux into the DI fruit. Tomato leaf water potential around −1.1 MPa at noon could reduce sap flux by 90 % during the day (Araki *et al.*, 1998), causing reduction in fruit size (Araki *et al.*, 1998; Johnson *et al.*, 1992).

Significant retention of assimilates in the tomato leaves (and in other plant organs as presented here) indicates the inability of alternative sinks (fruits) to consume the fixed carbon (Khan and Sagar, 1966). Larger fractions of

Table 1. Number of fruits (NF), total plant fresh weight (TPFW), total fruit fresh weight (TFFW), irrigation water use efficiency (WUE), and harvest index (HI), all per plant, in response to irrigation treatments¶.

Irrigation treatments	NF	TPFW (kg/plant)	TFFW (kg/plant)	IWUE ($g\ L^{-1}$)	HI
FI	70 a†	9.0 a	6.7 a	1.2 b	0.52 a
PRD	69 ab	8.9 ab	6.2 ab	2.2 a	0.50 ab
DI	52 b	6.0 b	4.0 b	1.5 b	0.43 b

†Different letters within columns indicate significant differences by *t* tests (least significant difference, LSD) at P ≤ 0.05. ¶FI= Daily full irrigation on both sides of the root system (RS); PRD= Irrigation on one side of the RS with half the volume of water given to FI where irrigation was shifted over from the wetted part to the drying part of the RS every day (PRD); DI= Full irrigation every other day on both sides of the RS.

Table 2. Dry biomass distribution per plant in response to irrigation treatments¶.

Irrigation treatments	Dry biomass (%)			
	Roots	Stems	Leaves	Fruits
FI	1.8 a†	28.3 b	17.5 b	52.4 a
PRD	2.0 a	29.8 ab	18.4 ab	49.8 ab
DI	2.2 a	34.1 a	20.4 a	43.3 b

†Different letters within columns indicate significant differences by *t* tests (LSD) at P ≤ 0.05. ¶FI= Daily full irrigation on both sides of the root system (RS); PRD= Irrigation on one side of the RS with half the volume of water given to FI control where irrigation was shifted over from the wetted part to the drying part of the RS every day (PRD); DI= Full irrigation every other day on both sides of the RS.

photoassimilates were allocated into stems and leaves. The vegetative fresh weight (including roots) values (kg/plant ± standard error of the mean, SEM) were 2.3 ± 0.28, 2.7 ± 0.11, and 2.0 ± 0.27 for FI, PRD, and DI, respectively. Therefore, the reduced total dry weight of plant in DI, relative to FI and PRD, was attributed to reduction in reproductive sinks (fruits) rather than total vegetative dry weight. Although not significant, biomass allocation into root tended to increase in PRD and DI plants, showing that this organ can eventually become a strong sink (Mingo *et al.*, 2004; Zegbe *et al.*, 2006).

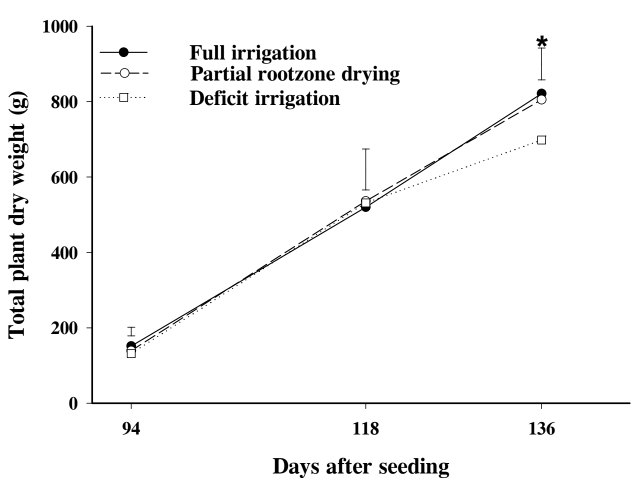

Figure 3. Changes in total plant dry weight (including roots and fruits) under three irrigation treatments. Vertical bars represent the LSD by t tests and the asterisk shows significant differences at P ≤ 0.05.

Mean fresh weight of fruit tended to be lower in DI and PRD plants than in FI plants (Table 3). The same was true for fruit water content, but total dry weight of fruit was significantly lower in DI. Total soluble solids concentration was higher in PRD and DI fruit than in FI fruit. Fruit colour was statistically the same at green stage among the treatments as well as 14 d after harvest (Table 3).

High tomato yields are the primary objective of producers while fruit quality, in terms of high total soluble solids concentration (TSSC) and fruit dry weight concentration and low fruit water content, is preferred by the processing industry (Ho, 1999; May and Gonzales, 1999). Fruit water content was the same in PRD and FI fruit, but TSSC was significantly enhanced in PRD fruit. This indicates that wetting half of the rhizosphere of PRD plants can supply water adequately to the fruit and keep similar or better metabolic activity to that of FI plants. Fruit of DI plants also improved TSSC. Reduced irrigation might have increased the starch concentration during the first stage of fruit growth (Ruan and Patrick, 1995), hence a possible higher conversion of starch into sugars at fruit maturity. The PRD and DI fruit tended to be redder (low hue angle value) than FI fruit. The mechanisms for redder colour for PRD and DI fruit was not investigated here, but during the ethylene biosynthesis, for which Pulupol *et al.* (1996) found a higher rate in DI fruit, higher accumulation of lycopene could have occurred (Campbell and Labavitch, 1991).

Leaf K^+ and Mg^{2+} concentrations, on a dry weight basis, were not affected by irrigation treatments at harvest. The values ($mg\ g^{-1}$ ± standard error of the mean, SEM) of K^+ in FI, PRD, and DI were 1.6 ± 0.5, 1.0 ± 0.1, and 1.0 ± 0.2, respectively. The corresponding values for Mg^{2+}

Table 3. Mean fruit fresh weight (MFFW), total fruit dry weight (TFDW), fruit water content (FWC), total soluble solids (TSS), blossom-end rot (BER), and fruit colour (in terms of hue angle, HA°) at green stage and 14 d after harvest (DAH), in response to irrigation treatments (ITs)¶.

ITs	MFFW (g)	TFDW (g/plant)	FWC (%)	TSS (°Brix)	BER (%)	HA° Green stage	HA° 14 DAH
FI	94.6 a†	452.3 a	94 a	5.3 b	10 b	107 a	38 a
PRD	88.6 a	425.2 a	94 a	6.0 a	22 ab	110 a	37 a
DI	77.4 a	291.7 b	93 a	5.9 a	37 a	107 a	37 a

†Different letters within columns indicate significant differences by *t* tests (LSD) at $P \leq 0.05$. ¶FI= Daily full irrigation on both sides of the root system (RS); PRD= Irrigation on one side of the RS with half the volume of water given to FI where irrigation was shifted over from the wetted part to the drying part of the RS every day; DI= Full irrigation every other day on both sides of the RS.

were 2.5 ± 0.4, 2.6 ± 0.1, and 2.0 ± 0.3, respectively. However, Ca^{2+} concentration was significantly lower in PRD and DI than in FI. The values (mg g^{-1} ± SEM) in FI, PRD and DI were 8.7 ± 0.9, 5.2 ± 0.7, and 4.2 ± 0.4, respectively. Likewise, PRD and DI treatments had the highest blossom-end rot (BER) incidence (Table 3).

Calcium transport is in proportion to the amount of water absorbed by the rhizosphere and the soil volume explored by the root system (Adams and Ho, 1993). Incidence BER is indicative of limitation of calcium transport. Here, leaf Ca^{2+} concentration decreased as the amount of water supplied was reduced, while the percentage of BER increased proportionally (Table 3). We did not determine fruit Ca^{2+} concentration, but lower Ca^{2+} import by fruit would be expected (Adams, 1986). Presence of BER has been associated with low fruit Ca^{2+} concentration and reduced irrigation (Adams and Ho, 1993; Taylor *et al.*, 2004). The findings found here could support this relationship, but Pulupol *et al.* (1996) and Sperry *et al.* (1996) found little or no effect on BER by reduced irrigation. On the other hand, the presence of BER in F1 fruit could be due to a preater root portion being allowed to dry by using drip irrigation. This would lead to low Ca^{2+} transport and distribution to leaf and fruit, at the start of fruit development from the first trusses, hence a high BER incidence in all treatments. Susceptibility to BER could also be associated with either the mode of irrigation (Carrijo *et al.*, 1983; Obreza *et al.*, 1996; Taylor et al., 2004) or by the phenological stage when PRD is applied (Zegbe *et al.*, 2006). Nevertheless, we have noticed no BER development in other PRD experiments where furrow irrigation was applied (Zegbe-Domínguez *et al.*, 2003; Zegbe *et al.*, 2004).

CONCLUSIONS

Plants ongoing PRD had a similar Ψ_{leaf} to those of FI plants. Therefore there were no adverse effects on plant growth, total fresh weight of fruit, total dry weight of fruit, and harvest index in PRD plants. Thus, PRD did not only improve irrigation water use efficiency by 83 %, but also saved water by 50 %. Biomass allocation into stems, leaves and fruits of PRD plants was intermediate between FI and DI plants. However, PRD treatment did not reduce fruit water content nor did it significantly intensify fruit skin colour; but it maintained total dry weight of fruit similar to FI and increased total soluble solid concentration compared to FI. PRD had a significantly higher incidence of blossom-end rot compared to the FI. It is concluded that PRD might be a more feasible irrigation strategy over deficit irrigation for the production of processing tomatoes. It might be implemented in dry areas where irrigation is needed to meet marketable tomato yield. In view of significantly higher blossom-end rot development in DI treatment, it cannot be recommended under similar circumstances.

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