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**Partial rootzone drying in apple  
and in processing tomato**

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**Partial rootzone drying in apple and in processing  
tomato**

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## Abstract

New water saving irrigation strategies need to be explored and partial rootzone drying (PRD) is such a strategy as it involves irrigating only part of the rootzone with the complement left to dry to a pre-determined level. In other deficit irrigation (DI) methods the entire rootzone is irrigated with less water than evapotranspiration. I focussed on PRD for its effects on apple and on processing tomato.

For apple three field experiments were done, two on 'Pacific Rose™' in Manawatu and one on 'Royal Gala' in Hawke's Bay. In all three, leaf water potential ( $\Psi_{\text{leaf}}$ ) was similar between PRD and commercially irrigated (CI) treatments and so were yield and fruit quality. However, 'Pacific Rose™' PRD fruit in one experiment had lower water loss in storage than did CI fruit. For 'Royal Gala', PRD fruit quality was improved in terms of flesh firmness and total soluble solids concentration. In all apple experiments PRD trees received only 50% of water given to CI trees. I recommend PRD as a feasible irrigation strategy for apples in New Zealand, but suggest further research for drier areas.

'Petopride' tomato was studied in six glasshouse experiments. Depending on the experiment, PRD irrigation was shifted to the previously-unwatered rootzone on the basis of volumetric soil water content, on a daily basis, and on intervals of 2, 4, and 6 days. Maintenance of  $\Psi_{\text{leaf}}$ , photosynthetic rate, stomatal conductance, yield, and fruit quality in PRD depended on the extent of soil drying. Irrigation use efficiency was almost twice higher in PRD plants than in CI plants. Blossom-end rot was higher in some of the PRD treatments, but in an especially-designed experiment I found out that PRD *per se* could not be the cause. From an experiment involving the measurement of root water potential, I concluded that water does not move from the wet roots to dry roots during PRD. I found that the tomato fruit, which is normally a stronger sink than vegetative parts, becomes a weaker sink during water stress. I recommend PRD for processing tomato, but with a suitable irrigation frequency to avoid lowering the midday  $\Psi_{\text{leaf}}$  to a value of less than  $-1.2$  MPa. This necessitates field trials in various environmental conditions.

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## List of Symbols and Abbreviations

A	Photosynthetic rate
ABA	Abscisic acid
BER	Blossom-end rot
°C	Degree Celsius
<i>ca</i>	Approximately
Ca <sup>2+</sup>	Calcium
CANDISC	Canonical discrimination analysis
CDF	Canonical discriminant function
CI	Commercially irrigated
DAA	Days after anthesis
DAS	Days after seeding
DAH	Days after harvest
DAFB	Days after full bloom
DI	Deficit irrigation
DMCF	Dry mass concentration of fruit
<i>E</i>	Transpiration rate
FC	Field capacity
FD	Fruit diameter
Fden	Fruit density
FF	Flesh firmness
FI	Fully irrigated
FSG	Final shoot growth
FV	Fruit volume
FWC	Fruit water content
FWL	Fruit water loss
g	Gram (s)
GLM	General linear model
<i>g<sub>s</sub></i>	Stomatal conductance
HA°	Hue angle
IEC	Internal ethylene concentration
ITs	Irrigation treatments
IUE	Irrigation use efficiency
IUE <sub>(TFMF)</sub>	Irrigation use efficiency on the basis of total fresh mass of fruit
IUE <sub>(TDMF)</sub>	Irrigation use efficiency on the basis of total dry mass of fruit
HI	Harvest index
Hr	Hour (s)
kg	Kilogram (s)
L	Litre
LSD	Least significant difference
μL	Microlitre (s)
μmol	Micromole (s)
m	Metre (s)
mb	Millibar (s)

m <sup>3</sup>	Cubic metre (s)
min	Minute
Mg <sup>2+</sup>	Magnesium
Mg	Milligram (s)
mm	Millimetre (s)
MFMF	Mean fresh mass per fruit
MSD	Minimum significant difference
N	Newton (s)
ns	Non-significant
NF	Number of fruit
<i>P</i>	Probability
P <sub>a</sub>	External CO <sub>2</sub>
P <sub>i</sub>	Internal CO <sub>2</sub>
PPF	Photosynthetic photon flux
PRD	Partial rootzone drying
PSRE	Potted split-root experiment (s)
RS	Root system
RWC	Relative water content
RWCR	Relative water content of root
SAS	Statistical Analysis System
SCC	Standardised canonical coefficients
SCS	Standardised canonical scores
SCSA	Shoot cross-sectional area
SD	Standard deviation
SEM	Standard error mean
SPAC	Soil-plant-atmosphere-continuum
SPI	Starch patten index
SRS	Split-root system
TM	Trade mark
TCSA	Trunk cross-sectional area
TFMP	Total fresh mass of plant
TDMP	Total dry mass of plant
TFMF	Total fresh mass of fruit
TDMF	Total dry mass of fruit
TSSC	Total soluble solids concentration
WD	Water deficit
W/D.	Wet/Dry
W/D/W/D	Wet/Dry/Wet/Dry
θ	Volumetric soil water content (m <sup>3</sup> m <sup>-3</sup> )
Ψ	Water potential
Ψ <sub>s</sub>	Osmotic potential
Ψ <sub>P</sub>	Turgor potential

# Chapter 1

## General introduction

### 1.1 Introduction

Apple and processing tomato are grown on a large scale in the world and an attempt at irrigation water reduction could lead to substantial saving of water. The world production of apple was 36, 343 million metric tonnes in 1997 (Pirog and Tyndall, 2002). The leading apple growing country is China, producing about 50% of the world's apples, followed by United States, Turkey and Iran (Table 1.1). The world production of processing tomato was 25, 212 million metric tonnes in 2002 (Pirog and Tyndall, 2002) and United States is the leading country producing about 38% followed by Italy and China (Table 1.1). In both crops the main production areas are situated in dry environments where evaporative demand is high (i.e., California and/or the Mediterranean countries). In these countries water is a valuable natural resource and important for crop irrigation to optimise yield. Partial rootzone drying (PRD) could have a large impact on saving water and on reducing ground water and land contamination by reducing nutrient and biocide leaching. PRD could increase the grower's income, depending on the growing area and water availability.

### 1.2 The concept of partial rootzone drying

PRD is a relatively new irrigation strategy which improves water use efficiency (by up to 50%) in crop production without significant yield reduction (Loveys et al., 1997; Stoll et al., 2000). This irrigation system was developed and tested successfully for grapes in Australia (Loveys, 2000) and it has been also evaluated in maize (Kang et al., 2000) and pear (Kang et al., 2002). In the latter two crops the results showed that PRD not only improved water use efficiency, but also the yield. However the effect of PRD on grape's yield and berry quality was cultivar dependent. Thus, the findings in grapes,

maize and pears need to be verified for others crops. Moreover, information is limited on PRD which is frequently referred to as split-root technique.

**Table 1.1** Worldwide production for apple in 1997\* and for processing tomatoes in 2002\*\*.

Apple			Processing tomatoes		
Country	Rank	Production (%)	Country	Rank	Production (%)
China	1	50	United States	1	38
United States	2	13	Italy	2	15
Turkey	3	7	China	3	8
Iran	4	5	Spain	4	6
France	5	5	Turkey	5	5
Poland	6	5	Brazil	6	5
Russian Federation	7	4	Portugal	7	4
Italy	8	4	Greece	8	3
Germany	9	4	Chile	9	2
Argentina and India	10	3	Others	10	14

Source: adapted from Pirog and Tyndall (2002)\* and from Tomatonews\*\*

This review will cover effects of PRD and split root experiments on plant growth, yield, and fruit quality attributes.

Partial rootzone drying is an irrigation strategy where at each irrigation one side of the root system receives water and the other one is allowed to dry to a certain pre-determined level. For the next cycle, the irrigation is reversed so that the dried roots are wetted and the wetted roots are allowed to dry (Loveys et al., 1997). However, PRD was recently re-defined by Stoll et al. (2000). They defined PRD as the “technique that requires that approximately half of the root system is always maintained in a dry or drying state while the remainder of the root system is irrigated”. The wetted and dried sides of the root system are alternated on a 10 to 14-day cycle. Both definitions are inaccurate because “one part of the root system’ is too vague, but to irrigate part of the root system is more practical. The phrase “half of the root system” is accurate, but it is difficult to ascertain whether irrigation is given to a half of the root

system. In my opinion, it is better to use “part” rather than “half” of the root system. Furthermore, if the quantity of water supplied at each irrigation is lower than the optimum, then the term “water deficit” must be included in the definition. Moreover, to establish a PRD irrigation schedule, it is imperative to know the crop water requirement, type of soil, and environmental conditions. This is because PRD has had different effects on crop physiology and crop productivity as observed in grapes (Loveys et al., 1997; Wiley, 1997; Dry and Loveys, 1999; Loveys et al., 2000; Stoll et al., 2000), maize (Kang et al., 2000), and pears (Kang et al., 2002). Therefore, I suggest the following definition: “partial rootzone drying is a deficit irrigation strategy where at each irrigation part of the root system receives water and the other part is allowed to dry to a certain extent of soil dryness. For the next irrigation, water is supplied to the dry part of the root system, while the formerly irrigated part is allowed to dry to the same extent of soil dryness. This irrigation sequence might be alternated several times during the growing season, depending on the crop, soil type and environmental conditions”. The experiments presented in this dissertation were based on the latter definition.

### 1.3 Physiological implications of PRD

Water flow across soil-plant-atmosphere-continuum (SPAC) is essential for mineral transport, food production, food translocation, transpiration to stabilise plant temperature, and respiration (Mengel and Kirkby, 1987, p. 193, 228-233). Water is crucial in the vacuole of plant cells to maintaining turgidity of plant organs and therefore carrying on the normal plant processes (Meidner, 1983). In general, the rates of photosynthesis ( $A$ ), transpiration ( $E$ ), and stomatal conductance ( $g_s$ ) are reduced as cell water deficit (WD) increase and/or the water energy in the cell, in terms of water potential ( $\Psi$ ), is reduced (Farquhar et al., 1989). However, plants can withstand different degrees of WD in terms of leaf water potential ( $\Psi_{\text{leaf}}$ ), and therefore, continue their normal growth and development until some extent of  $\Psi_{\text{leaf}}$  reduction (Mengel and Kirkby, 1987, p. 196-200). However, the effect of WD on plants depends on the plant species and their phenological stages (Jones et al., 1985; Kramer, 1983, p. 352-359).

### 1.3.1 Plant water status

Plant water status is commonly expressed in terms of plant water potential of the leaf ( $\Psi_{\text{leaf}}$ ). This parameter is altered by the soil water status, atmospheric conditions, and the plant properties (Jones et al., 1985).

Water status of any plant organ is better understood as the water flow through SPAC (Steudle, 2001), which can be described by the steady state model of  $\psi_{\text{leaf}}$  given by Jones et al. (1985):

$$E = (\Psi_{\text{soil}} - \Psi_{\text{leaf}}) / (R_{\text{soil}} + R_{\text{plant}}) \quad [\text{Eq. 1}]$$

where  $E$  is the transpiration rate,  $\Psi_{\text{leaf}}$  and  $\Psi_{\text{soil}}$  are water potentials of leaf and soil, and  $R_{\text{soil}}$  and  $R_{\text{plant}}$  are the resistances to water flow across soil and plant. Equation 1 can be re-written as:

$$\Psi_{\text{leaf}} = (\Psi_{\text{soil}}) - E(R_{\text{soil}} + R_{\text{plant}}) \quad [\text{Eq. 2}]$$

Equation 2 indicates that  $\Psi_{\text{leaf}}$  depends on  $\Psi_{\text{soil}}$ , flow rate through the plant, and hydraulic resistances.  $\Psi_{\text{leaf}}$  (or water potential of any part of the plant) consists of two major components: osmotic potential ( $\Psi_s$ ), which is generated by the presence of solute particles dissolved in the cell and turgor potential ( $\Psi_p$ ), which originates from the water pressure exerted on the cells (Mengel and Kirkby, 1987, p. 199). The generalised relationship among these three entities can be expressed as (Beadle et al., 1985, p. 56):

$$\Psi_{\text{leaf}} = \Psi_s + \Psi_p \quad [\text{Eq. 3}]$$

Each potential is expressed in pressure units, mainly in megapascal (MPa). When plant tissue loses water, the reduction in  $\Psi_{\text{leaf}}$  is sometimes compensated for by a similar decline in  $\Psi_s$  and  $\Psi_p$  (Beadle et al., 1985, p. 56). Depending on the extent of WD induced, plants might continue their metabolic and physiological process and growth by reducing both  $\Psi_{\text{leaf}}$  and  $\Psi_s$ , but maintaining  $\Psi_p$  through osmotic adjustment (Turner,

1986). Osmotic adjustment has been studied in both temperate fruit trees (Mills et al., 1996; Johnson and Handley, 2000) and tomatoes (Johnson et al., 1992; Srinivasa et al., 2000) subjected to deficit irrigation (DI). The effects of DI on tree physiology, growth, yield, and fruit quality have extensively reviewed by Behboudan and Mills (1997). Similarly, Mitchell et al. (1991a; 1991b) and Srinivasa et al. (2000) have reviewed research on processing tomato. However, PRD is a relatively new technology and its physiological and horticultural importance has not been assessed yet.

### 1.3.1.1 Partial rootzone drying and plant water status

$\Psi_{\text{leaf}}$  is an important physiological parameter and its changes have to be assessed under PRD. The information provided in this section, for both annual and perennial plants, is based on potted split-root experiments (PSRE), where the root system is divided in two parts and each separately potted.

#### 1.3.1.1.1 Perennial plants

Tan and BATTERY (1982) conducted a short-term experiment (*ca* 35 days) with one-year old peach seedlings. The root system was divided into four sections. The dawn  $\Psi_{\text{leaf}}$  was the same for fully irrigated (FI) trees and those whose 50% of root system was well watered and the rest allowed to dry (W/D).  $\Psi_{\text{leaf}}$  values (MPa) were -3.1 and -3.4 for FI and W/D treatments, respectively. Gowing et al. (1990) conducted a PSRE for 30 days to investigate the root to shoot communication in apple. They found that  $\Psi_{\text{leaf}}$  of W/D trees was similar to FI trees. The midday  $\Psi_{\text{leaf}}$  was *ca* -1.0 MPa for both treatments. Similarly, a PSRE was conducted by Poni et al. (1992) using one-year old trees of apple, pear, peach, and grape. The experiment was carried out over four months. Irrespective of species, the pre-dawn  $\Psi_{\text{leaf}}$  was the same between W/D trees and FI trees for the four times that this parameter was measured. On average,  $\Psi_{\text{leaf}}$  was *ca* -1.4 MPa. Dry and Loveys (1999) carried out a PSRE for up to 30 days with two-year-old grapes. The  $\Psi_{\text{leaf}}$ , which was measured at different days and hours, was the same between W/D vines and FI vines. These results were recently re-confirmed for grapes by Loveys et al. (2000) and Stoll et al. (2000) and for six deciduous tree species by

Crocker et al. (1998). However, there are three issues to be considered. Firstly, these experiments (except for the experiment of Poni et al., 1992) were done under controlled conditions, which might differ from those adult trees under field conditions (Glenn, 2000). Secondly, the experiments were conducted short-term and therefore not long enough time was allowed to develop measurable effects on  $\Psi_{\text{leaf}}$ . Thirdly, there was no sink strength competition, which would have modified  $\Psi_{\text{leaf}}$  as shown in apples (Erf and Proctor, 1987) and peaches (Blanco et al., 1995). However, under these conditions one could conclude that  $\Psi_{\text{leaf}}$  for FI and W/D treatments was the same for perennial plants.

#### 1.3.1.1.2 Annual plants

Studies of PRD in annual plants, including tomatoes, are lacking and the impact of PRD in both  $\Psi_{\text{leaf}}$  and  $\Psi_{\text{fruit}}$  of tomatoes has not been studied. Tan et al. (1981) conducted a tomato experiment, where the root system was equally divided into four fractions. Neither  $\Psi_{\text{leaf}}$  nor  $\Psi_{\text{fruit}}$  were assessed, but the authors noted that plants could meet the entire water requirements by irrigating only 50% of the rhizosphere. Their conclusion was based on the similarities in yield between W/D plants and FI plants. Yield values ( $\text{g} \pm \text{SEM}$ ) were  $1001 \pm 35$  and  $1124 \pm 135$  for W/D plants and FI plants, respectively. Griffiths and Bray (1996) found that in a short-term (up to 20 days) PSRE with tomatoes the relative water content (RWC) of W/D plants and FI plants was the same. However, when the whole root system was not watered the RWC was significantly reduced (*ca* 70%) in relation to W/D plants (*ca* 95%). In a similar experiment, the  $\Psi_{\text{leaf}}$  of W/D plants and FI plants of maize was the same (Blackman and Davis, 1985). In the last two experiments, the stomatal conductance was significantly reduced without detectable changes in  $\Psi_{\text{leaf}}$ , and thereby transpiration was reduced. The same relation was found in short-term experiments with sorghum (Augé et al., 1995) and in bell pepper (Yao et al., 2001). By contrast, in a long-term PSRE in pepper, Cantore et al. (2000) dried half of the root system during vegetative growth, while the other half was kept well watered. After 26 days, they shifted the irrigation over to the drier half and the former part was allowed to dry for the remainder of the growing season. A significant reduction in  $\Psi_{\text{leaf}}$  was observed and this was accompanied by a proportional reduction in stomatal conductance, rate of

photosynthesis and transpiration, and reduction in dry mass of fruit in W/D plants in relation to FI plants. This experiment gave opposite results to the former experiments and needs further corroboration. Moreover, whether  $\Psi_{\text{leaf}}$  of processing tomatoes is adversely modified or not under a PRD situation, and its possible deleterious effect on yield, is unknown. The maintenance of  $\Psi_{\text{leaf}}$  might have been achieved because possibly the wet root increases water absorption when fully irrigated as exemplified for apple by Green et al. (1997). The dry root can also contribute to water and nutrient balance of the tree (Glenn, 2000). In split-root experiments, stomatal conductance has contributed to  $\Psi_{\text{leaf}}$  maintenance by regulating transpiration rate (Kang et al., 2001), and this may also occur in plants exposed to PRD.

### 1.3.2 Stomatal conductance ( $g_s$ ) and transpiration ( $E$ )

Stomata are sensitive to irradiance, soil water availability, wind speed, and air vapour pressure deficit (Atwell et al., 1999, p. 469). Changes in water flow across SPAC are accompanied by changes in plant water status and the stomates are highly sensitive to these changes. Stomatal opening and closure is an important process by which plants regulate not only the gas exchanges ( $\text{CO}_2$  assimilation rate and  $E$ ) but also plant water balance (Mengel and Kirkby, 1987, p. 210). Experiments have shown that  $\Psi_{\text{leaf}}$  can be maintained when soil is dried. This has been shown either by using balancing pressure techniques (Gollan et al., 1986; Schurr et al., 1992; Yao et al., 2001) or by using plants with root split between wet and dry soil (W/D) (Blackman and Davis, 1985; Gowing et al., 1990; Griffiths and Bray, 1996; Yao et al., 2001; Holbrook et al., 2002). These studies demonstrated that stomates could close independently of  $\Psi_{\text{leaf}}$  by responding to messages from roots in drying soil. This mechanism has an important potential in regulating not only  $E$  but also  $\Psi_{\text{leaf}}$  which needs to be evaluated under PRD. However, in short-term PSRE with deciduous fruit trees, the response of stomates, as soil dried, was more consistent. For instance,  $g_s$  and  $E$  were reduced by 17% when half of the root system of peach seedlings was subjected to water deficit. Similar results were reported by Poni et al. (1992) in one-year old trees of apple, grape, peach and pear under W/D treatment. On the other hand, transpiration rate declined by 30% in apple trees under W/D without significant changes in leaf water potential (Gowing et al., 1990). The

latter effect was also observed in grape (Dry and Loveys, 1999; Loveys et al., 2000; Stoll et al., 2000) and in non-cultivated deciduous trees (Crocker et al., 1998). In conclusion, it seems that in plants where the root system was partially irrigated, stomatal closure is also partial with non-measurable changes in leaf water potential. Additionally, this suggests the involvement of non-hydraulic signals that promotes partial stomatal closure (Dry and Loveys, 1999), which have not been tested either in field-grown apples or processing tomatoes subjected to PRD.

Tan et al. (1981) found no significant reduction in  $g_s$  and  $E$  for tomato seedlings under W/D treatment in relation to FI plants. The authors concluded that, under field conditions irrigating only 50% of the root system rather than irrigating the entire root system, would be enough to meet plant water requirements. However, at the present there is no proof for this claim under PRD conditions. Opposite results to those of Tan et al. (1981) were observed by Griffiths and Bray (1996) and Holbrook et al. (2002) where the  $g_s$  was significantly reduced in split-root tomato plants. This result was confirmed in maize (Blackman and Davis, 1985), pepper (Cantore et al., 2000; Yao et al., 2001), and sorghum (Augé et al., 1995) evaluated under PSRE.

### 1.3.3 Photosynthetic rate (A)

Water deficit has a great influence on plant growth and productivity by reducing  $\Psi_{\text{leaf}}$ ,  $\Psi_p$ , cell enlargement,  $g_s$ ,  $E$ , and  $A$  and increasing abscisic acid (ABA) and solute concentration in the plant tissues (Hsiao, 2000). Among these responses, the limitation of  $A$  is central and often thought to be induced by stomatal closure that limits the diffusion of  $\text{CO}_2$  into the leaves (Farquhar et al., 1989). It is true to a certain extent, because it has been demonstrated that biochemical processes are more closely involved in  $A$  inhibition than stomatal closure (Farquhar and Sharkey, 1982; Lauer and Boyer, 1992). Following this, in perennial fruit trees, Tan and Buttery (1982) found that  $A$  was limited by 17% in one-year-old peach trees that had 50% of their root system irrigated and the complement left to dry. Similar results were obtained for one-year-old apple, grape, peach and pear trees under W/D treatment (Poni et al., 1992), and recently for a one-year-old grape under the same treatment (Dry et al., 2000a). In both experiments, both  $A$  and  $g_s$  tended to reduce at the onset of water deficit, but both

parameters recovered their levels similar to fully irrigated trees. This suggests that A was limited by internal CO<sub>2</sub> concentration (P<sub>i</sub>) rather than stomatal closure. P<sub>i</sub> behaviour must be studied because it might have an adverse impact on yield under PRD.

Tan et al. (1981) showed that A of tomato seedlings was not reduced when 50% of the root system was subjected to water deficit even when fruit were present. The experiment was conducted for up to 24 days, probably too short to observe measurable influence on A. In contrast, in a long-term PSRE with *Capsicum annuum* L. the reduction in A and yield was influenced by the extent of the soil dryness in W/D plants in relation to FI plants (Cantore et al., 2000; Kang et al., 2001). However, Kang et al. (2001) did not observe an adverse effect, either on A or on the yield, when irrigation to dry and wet sides of the roots was frequently alternated during the growing season.

One could conclude that A under PRD might respond differently not only between perennial and herbaceous plants, but also amongst PRD treatments. However, whether or not A is altered under PRD appears unknown.

#### **1.4 Impact of PRD on the vegetative and reproductive growth of plants**

Water deficit not only modifies physiological and biochemical processes, but it also induces morphological changes on root and tree growth that might affect tree productivity and fruit quality (Chalmers et al., 1981; Grierson et al., 1982; Johnson and Handley, 2000). In some cases, WD may increase cold hardiness (Yelenosky 1979) and promote bud break in some deciduous fruit trees (Jones et al., 1985). But, mild WD applied through regulated deficit irrigation may be beneficial in enhancing fruit quality and creating a good balance between vegetative and reproductive growth (Bebhoudian and Mills, 1997; Johnson and Handley, 2000). In processing tomatoes, WD has induced similar results as in fruit trees (Mitchell et al., 1991a; 1991b; Pulupol et al., 1996). However, except for the reports of Kang et al. (2000) on maize and Kang et al. (2002) on pears, no information was found for apples and processing tomatoes

regarding vegetative and reproductive growth under PRD. In the following sections, results from potted split-root experiments (PSRE) are mentioned for both fruit trees and vegetable crops as being similar to PRD.

### 1.4.1 Root growth

The root system has a central importance for the plants in giving not only the plant anchorage, but also in absorbing water and minerals and synthesising growth regulators for the successful growth of above ground parts (Kramer, 1983, p. 121). Water deficit tends to inhibit plant growth, where root growth is often favoured over that of leaves because the roots are less exposed to severe water deficit than the shoots (Hsiao and Xu, 2000). However, depending on the extent of soil dryness, total root growth may be decreased (Steudle, 2000). In short-term PSRE with one-year-old peaches under W/D treatment, the total dry mass of the roots was enhanced in W/D plants compared with FI plants. The values (g) were 294 and 315 for FI and W/D plants, respectively. Similar results were provided for one-year-old apple, grape, peach and pear trees by Poni et al. (1992), six non-cultivated deciduous trees by Croker et al. (1998), and recently for grape (Dry et al., 2000b). Poni et al. (1992), Dry et al. (2000b), and Loveys et al. (2000) explained that maintenance of root growth under W/D is possible because “the part of the root system in dry soil can survive because water moves from wet roots to dry roots”. However, if the root to shoot ratios between fully irrigated plants and split-root plants were the same, this cannot be explained as pointed out by Poni et al. (1992) and Dry et al. (2000b). Under water deficit roots tend to explore a higher volume of soil to reach water and to uptake it along with nutrients (Kirkham, 1983). This mechanism is used by plants to withstand soil water deficit in both fruit trees (Glenn, 2000) and annual crops (Xu and Bland, 1993). Another explanation, for the maintenance of root growth which perhaps applies to PRD, might be root osmotic adjustment (Hsiao and Xu, 2000). In fact, neither the root water potential ( $\Psi_{\text{root}}$ ) nor relative water content of the root (RWCR) have been evaluated under split-root experiments or PRD experiments yet. However, in terms of sap flow, in a PRD experiment with kiwifruit vines, Green and Clothier (1995) showed that there is a preferential uptake of water from the wetter parts of the soil and a corresponding reduction in water uptake from the drier parts of the soil. Moreover, wet roots have the

capacity to uptake water from local wet areas at much higher rates than normally occurs when the root zone is fully wet (Green et al., 1997). Roots in the dry soil remain inactive until next irrigation or rainfall and water uptake of dried roots occurs near the soil surface due to re-growth of the roots (Green and Clothier, 1999).

In a tomato experiment, where 50% of the root system was irrigated, the total fresh mass of root and the root to shoot ratio were not adversely affected (Tan et al., 1981). In PSRE with tomatoes, a recent study by Davis et al. (2000) revealed similar results to those of Tan et al. (1981). However, Davis et al. (2000) observed significant reduction in fresh mass of fruit, while Tan et al. (1981) did not, perhaps because the experiment was conducted for short-term, hence no negative impact on fresh mass of fruit. In pepper, mixed results, under PSRE, have been obtained. In long-term PSRE with pepper, Cantore et al. (2000) did not find significant differences in the dry mass of roots between W/D plants and FI plants, while Kang et al. (2001) did. The latter authors argued that there was no adverse effect on fresh mass of fruit, but the former authors found the opposite. Therefore, dry mass of roots needs clarification for both fruit trees and tomatoes under PRD. In a PRD setting, the dry mass allocation to root and root to shoot ratio would be relatively easier to evaluate in tomato plants than in fruit trees.

## 1.4.2 Plant

One of the most important aspects in fruit tree management is the control of tree size or vigour which is often related to productivity. Dwarfing rootstocks were the primary method for the control of apple tree size, followed by water deficit (Chalmers et al., 1981). Another method is the root restriction by root pruning (Schupp and Ferree, 1989). In fruit trees that have been exposed to split-root trials, a reduction in tree size has been observed (Tan and Buttery, 1982; Poni et al., 1992; Turner et al., 1996; Dry and Loveys, 1999). However, the reduction of tree size depends on the degree of WD and on the species. For example, Poni et al. (1992) showed that the shoot lengths of pear, apple, grape, and peach trees were unaffected under W/D treatments compared with their corresponding FI trees. However, a recent report showed that the shoot

growth of grape was significantly reduced under W/D treatment (Dry et al., 2000a). This needs to be clarified.

Mitchell et al. (1991a) reported contradictory results on the plant size for processing tomatoes subjected to WD. In contrast, Tan et al. (1981) found no plant size reduction in tomatoes when 50% of the root system was allowed to dry. Opposite results to those of Tan et al. (1981) were provided by Davis et al. (2000) for tomato under PSRE. The inconsistent effect of W/D treatment on tomato plants' size could be due to different degrees of soil water deficit and pot size that might induce root restriction. The duration of the experiment could make a difference as well. For instance, Tan et al. (1981) conducted the same experiment for up to 24 days and both sections were brought back to field capacity. By contrast, Davis et al. (2000) conducted the experiment over the growing season. The soil in one pot was allowed to dry down to 30% of the volumetric soil water content before being irrigated. This irrigation cycle was repeated several times during the growing season. My research was conducted under field conditions where the root system of apples did not have growth restrictions. For tomato, the root system was assumed uniformly distributed into the container, mimicking field conditions. Therefore, shoot growth in apples and plant size in processing tomato might be different under PRD here for those exposed to W/D treatment during a PSRE.

### 1.4.3 Leaf growth

Leaf area tends to reduce proportionally as shoot length decreases in response to WD. Therefore less solar radiation will be intercepted leading to less CO<sub>2</sub> assimilation and dry mass allocation (Hsiao, 2000). Turner et al. (1996) demonstrated that the leaf area of passion fruit was more reduced in WD plants than in W/D plants. Their results agree with previous findings for peach (Tan and Buttery, 1982); apple, grape, pear and peach (Poni et al., 1992), and oak trees (Fort et al., 1997). Whether leaf area is negatively affected by PRD or not is unknown, therefore this needs to be assessed.

In tomato plants, under split-root system the leaf area, was either unaffected (Tan et al., 1981) or slightly affected with a corresponding reduction in the whole plant dry mass

(Davis et al., 2000). The latter results agree with those of Kang et al. (1998) for maize under W/D treatment. If it is true, no reduction in leaf area and dry mass production might be expected in processing tomatoes under PRD, but it needs to be assessed.

#### 1.4.4 Yield and fruit quality

Crop yield reduction is almost always associated with water deficit. In fruit trees moderate water deficit might not reduce yield but might improve fruit quality (Behboudian and Mills, 1997). However, this is dependant on the timing of water deficit imposed (Behboudian and Mills, 1997), cultivar and environmental conditions (Kilili et al., 1996a; Mpelasoka et al., 2000). There are no reports of PRD effects on yield of apple, but there are for grape (Loveys et al., 2000) and for pear (Kang et al., 2002). Loveys et al. (2000) observed that the yield and berry quality, in terms of total soluble solids concentration (TSSC), were cultivar dependent but the irrigation use efficiency was always significantly improved under PRD compared with fully irrigated grapevines. Kang et al. (2002) tested two PRD treatments on pear by using row flood irrigation. In the first treatment the irrigation was supplied always only in one side of the row (W/D) over the growing season. In the second, the irrigation was frequently shifted to both sides of the row (W/D/W/D) for the entire growing season. There was also the fully irrigated (FI) control treatment. The yield values ( $\text{kg tree}^{-1}$ ) were: 244, 237, and 256 for FI, W/D/W/D, and W/D treatments, respectively. They concluded that W/D could increase the yield because of an enhanced root hydraulic conductivity. However, the crop load was not adjusted in this experiment. Number of fruit per treatment per tree was: 1232, 1321, and 1343 for FI, W/D/W/D, and W/D treatments, respectively. The latter two treatments improved the water use efficiency relative to the FI trees, which needs to be verified in apple. Moreover, there were no measurements on fruit quality attributes which are important in fruit marketing.

In processing tomato, lower fruit water content (FWC) and higher TSSC are the most important quality parameters for the industry. The former attribute is important because less energy would be needed to evaporate water from the fruit. The latter attribute is also important for paste quality. However, fruit quality improvement is achieved at the cost of yield reduction when tomatoes are grown under deficit irrigation

(Young et al., 1993; Pulupol et al., 1996; Phene, 1999). But Tan et al. (1981) observed no reduction in yield for W/D plants compared to FI plants. The yields ( $g \pm SEM$ ) were:  $1124 \pm 135$  and  $1001 \pm 35$  for FI and W/D treatments, respectively. By contrast, in a long-term PSRE with tomatoes, the fresh mass of fruit was significantly reduced in W/D plants relative to FI plants (Davis et al., 2000). The values ( $g \pm SEM$ ) were  $2,700 \pm 170$  and  $2,300 \pm 870$  for FI and W/D treatments, respectively. But the fruit dry mass concentration was the same in both treatments. The TSSC was significantly increased in W/D fruit compared with FI fruit. The percentage of fruit ripeness, fruit damage, fruit pH, and incidence of blossom-end rot was the same for both treatments. These results need corroboration under PRD conditions. Moreover, Davis et al. (2000) did not provide information on any other quality attribute (i.e., skin colour and fruit maturity advancement). Therefore, one of the objectives of my research was to assess the effect of PRD not only for the above mentioned quality attributes but also for the fresh mass and skin colour of the fruit. The incidence of blossom-end rot and the concentration of K, Ca, and Mg in both leaves and fruit were also studied.

## Chapter 2

### Research problem

#### 2.1 Introduction

Apple trees are grown in a wide range of weather and soil conditions with a large variation in soil water availability and evapotranspiration rates (Westwood, 1993, p. 52). Tomato is the most important vegetable crop in terms of production volume and acreage worldwide (Ho, 1996a). In both crops irrigation is essential to meet high yields, especially in dry areas. In many of the latter regions water is limited and therefore it is a valuable natural resource. In these areas saving water for irrigation has an important socio-economic consideration, because minimising water use not only reduces production costs but also encourages ground water conservation. Moreover, reduced water usage helps to meet the environmental conditions by decreasing nutrient leaching into the ground water and therefore reducing land contamination (Tanji, 1993). Therefore water saving practices need to be implemented, such as deficit irrigation (DI) and partial rootzone drying (PRD). The major problem associated with DI is the adverse effect on tomato yield (May, 1993; Obreza et al., 1996) and the yield of fruit trees growing in dry environments such as apple (Mpelasoka et al., 2000) and apricot (Torrecillas et al., 2000). In contrast, PRD could save water by 50% and yet maintain yields as shown for some grape cultivars (Loveys et al., 2000) and for pear (Kang et al., 2002) in Australia.

#### 2.2 Partial rootzone drying

Partial rootzone drying, which was defined in Chapter 1, is a relatively new deficit irrigation strategy that has not been assessed for apple or tomato. PRD could make a substantial contribution to improving irrigation and water-use efficiency and sustainability of production for these crops. There is no detailed research work done on long PRD experiments regarding plant water status, photosynthetic rate, yield, and fruit quality of both crops. PRD's possible beneficial effects on apple fruit after storage

have not been addressed either. So far, information on PRD has been published for maize (Kang et al., 2000), pear (Kang et al., 2002), and grape (Loveys et al., 2000) under field conditions. The yield and water use efficiency were significantly increased compared with fully irrigated plants in the maize and pear experiments. Additionally, Loveys et al. (2000) pointed out that the effect of PRD on yield was cultivar dependent. Although improvement in water use efficiency improvement is desirable, the yield implications should be examined.

Information regarding PRD has also been obtained from split-root potted experiment with annual crops (Kang et al., 1998; Cantore et al., 2000; Davis et al., 2000; Kang et al., 2000; Yao et al., 2001) and fruit trees (Tan and Buttery, 1982; Gowing et al., 1990; Poni et al., 1992; Turner et al., 1996; Dry et al., 2000a; Stoll et al., 2000). These experiments were conducted short-term and the plant root system was restricted to a pot, which might be at variance with field conditions. To split the plant root system for a commercial situation is impractical and expensive. For these reasons the apple experiments described here were carried out under field conditions with adult trees and with wetting part of the root system. White polythene covers were installed under the trees to exclude the rain. The tomato experiments were conducted under glasshouse conditions to avoid constant interference mainly with rain. However, the containers were designed to mimic field conditions so that the irrigation was supplied assuming uniform root distribution into the soil and therefore the rhizosphere was not divided into two parts.

### **2.3 General objective and hypothesis**

The overall objective of this research was to study PRD effects on seasonal and diurnal plant water status, photosynthetic rate, yield, and fruit quality of apples and tomato. Also, PRD's effect on fruit quality attributes after storage of apple was studied. Plant water status is expected to be equilibrated with the wettest part of the rhizosphere (Hsiao, 1990). I therefore expected that PRD plants would have the same water status as fully irrigated plants. My general hypothesis was that yield and fruit quality would be maintained in the PRD plants with the benefits of an improved irrigation use efficiency.

## Chapter 3

### General materials and methods

Material and methods common to all experiments are briefly described in this Chapter. Those specific to an experiment will be described in the corresponding Chapter.

#### 3.1 Measurements of soil water status

Volumetric soil water content ( $\theta$ ,  $\text{m}^3 \text{m}^{-3}$ ) was monitored by time domain reflectometry (TDR, model 1502C, Tektronix Inc., Beaverton, OR, USA). The TDR system measures  $\theta$  indirectly by measuring the travel time through the soil of a short pulse of high-frequency transverse electromagnetic waves. The travel time of an electromagnetic wave through a given thickness of material is directly proportional to the square root of the dielectric constant ( $K_a$ ). For soils the apparent  $K_a$  changes with  $\theta$  and ranges from 4 for dry soil to 40 for wet soil (Parchomchuk et al., 1997). More on the theory and practical use of TDR system for  $\theta$  measurements are detailed by Parchomchuk et al. (1997). For  $\theta$  measurements in apple experiments, two pairs of TDR probes were installed permanently at a soil depth of 500 mm (one pair each side of the row) at a distance of 250 and 500 mm away from the emitters and tree trunk, respectively. The measurements were done either weekly or fortnightly. In the tomato experiments TDR measurements were taken daily in both sides of the row at 200 mm media depth and 50 mm away from the emitters. In those hand-irrigated tomato experiments TDR measurements were taken 150 mm away from the main stem. This was done within 60 minutes after irrigation.

For the partial rootzone drying treatments in apple and tomato, each side of the root system had either a high or a low  $\theta$  depending on whether it was irrigated or not. This is reflected in Figures 5.1, 6.1, 7.1, 8.1, 9.1, 11.2, and 12.1.

## 3.2 Measurements of plant water status

### 3.2.1 Root water potential

Root water potential ( $\Psi_{\text{root}}$ ) was obtained using a Scholander pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, California, USA) (Steudle, 2001). Two root branches from two opposite sides (wet and dry sides for PRD treatments) were selected. They were excised and carefully removed from the soil minimising root damage and placed in the pressure chamber. Nitrogen gas was used to apply pressure to the chamber until root sap appeared at the cut cross-sectional area of the root branch. This was done between 09:00 to 09:30 hours. The roots were approximately 25 centimetres long and had an average diameter of  $1.44 \pm 0.4$  mm. It is expected that  $\Psi_{\text{root}}$  was affected by the sampling time and that some root damage might have occurred when removed from the soil. This could affect the root measurements as pointed out by Gee et al. (1974). However, when some damage was noticed, a new root was excised and measured.

### 3.2.2 Leaf water potential

Seasonal and diurnal leaf water potential ( $\Psi_{\text{leaf}}$ ) was measured using the pressure bomb described above. Fully expanded leaves were excised and placed immediately in the pressure bomb. Nitrogen gas was used to apply pressure into the chamber until leaf sap appeared at the cut cross-sectional area of the vascular tissue. Predawn  $\Psi_{\text{leaf}}$  measurements were obtained between 05:00 and 06:00 hours while midday  $\Psi_{\text{leaf}}$  measurements were obtained between 12:00 and 13:00 hours local time. Diurnal changes in  $\Psi_{\text{leaf}}$  were recorded in some occasions.

### 3.2.3 Fruit water potential in apple experiments

Fruit water potential ( $\Psi_{\text{fruit}}$ ) and fruit osmotic potential ( $\Psi_{\text{fs}}$ ) were measured using a dew point microvoltmeter (HR-33T microvoltmeter, Wescor, Inc., Logan, Utah, USA) equipped with psychometric chambers (C-52 sample chambers Wescor, Inc., Logan, Utah, USA). Fruit were picked at dawn and disks ( $0.45 \text{ cm}^2$ ) from the outer part of each fruit, excluding the skin, were punched and placed into individual C-52 chambers to be equilibrated for 90 min before  $\Psi_{\text{fruit}}$  determination. Disks were removed from the chambers and placed into vials and dipped into liquid nitrogen. Samples were then returned to the same chamber to be equilibrated for 60 min prior to measurement of  $\Psi_{\text{fs}}$ . Fruit turgor potential ( $\Psi_{\text{fp}}$ ) was calculated as the difference between  $\Psi_{\text{fruit}}$  and  $\Psi_{\text{fs}}$ .

### 3.3 Measurements of stomatal conductance, photosynthesis, and transpiration

The rate of photosynthesis ( $A$ ), transpiration ( $E$ ), stomatal conductance ( $g_s$ ), and photosynthetic photon flux (PPF) were obtained with a portable photosynthesis system (LI-6200, Li-Cor Inc., Nebraska, USA) on two or four mature and exposed leaves. Measurements were taken between 11:00 and 14:30 hours.

### 3.4 Measurements of plant growth in apple experiments

#### 3.4.1 Shoot growth

Shoot growth in apple was measured by selecting and tagging similar sized current-season shoots at the outer and middle part of the canopy at the start of the experiment. The shoot length was measured either once a week or at the end of the growing season.

### 3.4.2 Trunk and shoot cross sectional area

Tree diameter was measured before and at the end of the experiment at 400 mm above the ground level with a digital hand-calliper (Digimatic, model 50-321, Mitutoyo, Co., Japan). Tree diameter was expressed in terms of trunk cross-sectional area (TCSA,  $\text{cm}^2$ ). The basal diameter of two-year-old shoots were measured and expressed in terms of shoot cross-sectional area (SCSA,  $\text{cm}^2$ ).

### 3.4.3 Fruit growth

Fruit growth was recorded at weekly intervals, in terms of fruit diameter, on ten fruit randomly sampled at the outer and middle part of each tree canopy with a digital hand-calliper (Digimatic, model 50-321, Mitutoyo, Co., Japan) until growth ceased. The fruit diameter was obtained on the equatorial region of each fruit. Fruit volume was estimated by assuming a spherical shape.

## 3.5 Measurements of plant efficiency

### 3.5.1 Crop load

Crop load of apple trees was adjusted uniformly over the treatments. This was done in the experimental and guard trees as follows: TCSA from each was calculated as described in section 3.4.2. Number of fruit (NF) from each tree was counted. Crop load before thinning was calculated by dividing NF per tree by TCSA. Then, trees were hand-thinned at either 50 or 53 days after full bloom (DAFB) to 6 fruit per  $\text{cm}^2$  of trunk cross-sectional area (Tustin et al., 1999).

### 3.5.2 Fruit yield

At harvest, fruit were counted and weighed and the yield was recorded as sum of individual weight of fruit from each tree. Fruit yield is expressed in terms of gross yield in apple and total fresh mass of fruit (TFMF) for tomato. In both cases mean fresh mass per fruit (MFMF) was calculated by dividing the gross yield and/or TFMF by number of fruit (NF) per tree and/or per tomato plant.

### 3.5.3 Yield efficiency

Yield efficiency (YE) of apples was calculated by dividing the yield per tree by TCSA (kg per tree  $\text{cm}^{-2}$  TCSA) (Westwood, 1993. p. 281-283).

### 3.5.4 Harvest index

Harvest index (HI) was obtained by dividing the total dry mass of fruit (TDMF) by the total dry mass of plant (van Delden, 2001).

### 3.5.5 Irrigation use efficiency

Irrigation use efficiency (IUE) was obtained here by dividing the gross yield for apples and TFMF and/or TDMF for tomato by the number of litres of water supplied (kg or g yield per plant  $\text{L}^{-1}$   $\text{H}_2\text{O}$ ).

## 3.6 Dry mass distribution

At the end of the tomato experiments, plants were divided into roots, stems, and leaves, and each plant organ was weighed individually and total vegetative fresh mass obtained. Then, they were oven-dried at 70 °C to constant mass and the total vegetative

dry mass obtained. Fruit were weighed, cut into halves, and oven-dried at 85 °C to a constant mass and the total dry mass of fruit obtained. Dry mass distribution of each organ was expressed in terms of percentage of the total plant dry mass. Total fresh mass of plant is the sum of each fresh organ of the plant. Total dry mass of plant is the sum of each dry organ of the plant.

### **3.7 Determination of fruit maturity**

#### **3.7.1 Internal ethylene concentration**

Samples of internal ethylene concentration (IEC) were obtained from the core cavity from each fruit while submerged under water (Johnston et al., 2002). One mL gas sample was injected into a gas chromatograph (Pye Unicam GCD) fitted with a flame ionisation detector (set at 140 °C with H<sub>2</sub> and air flow of 30 and 300 mL min<sup>-1</sup>, respectively), an activated alumina column (set at 100 °C with N<sub>2</sub> as the carrier gas at 30 mL min<sup>-1</sup>), and a Hewlett Packard integrator (model 3390A) calibrated with external ethylene standards (certified as β-standard by B.O.C Gases New Zealand Ltd.).

#### **3.7.2 Starch pattern index**

Starch patten index (SPI) was determined by dipping cross-sectional fruit halves for 30 s into a solution of 20 g of potassium iodide plus 5 g of iodine in 2000 mL of water. Hydrolysis of starch was ranked on a scale of 0 (100% starch) to 6 (no starch) (Reid et al., 1982).

## **3.8 Determination of fruit quality**

### **3.8.1 Fruit density**

Fruit density ( $\text{g cm}^{-3}$ ) was determined as fruit mass per unit of volume. Individual fruit mass was measured using an analytical balance (Mettler Instrument AG CH-8606, Greifensee-Zurich, Switzerland). Fruit of volume was obtained by water displacement.

### **3.8.2 Fruit background skin colour**

Fruit background skin colour, in terms of hue angle ( $\text{HA}^\circ$ ) was taken on two opposite sides in the equatorial part of each fruit with a portable tristimulus chromameter (Minolta CR-200, Osaka, Japan) calibrated with a green plate (CR-A47 G) (Dixon, 1993).

### **3.8.3 Fresh firmness**

After removing the fruit skin, two flesh firmness (FF) determinations were done on two opposite sides in the equatorial part of each fruit using a press-mounted Effegi penetrometer (model FT 327, Alfonsine, Italy) with an 11.1-mm head. Firmness was expressed in Newton values (N).

### **3.8.4 Total soluble solids concentration**

Total soluble solids concentration (TSSC) was measured from some drops from each side of the fruit with a hand held refractometer with automatic temperature compensation (ATC-1 Atago, Tokyo, Japan).

### 3.8.5 Dry mass concentration of fruit

Dry mass concentration of fruit (DMCF mg g<sup>-1</sup> fresh mass) was determined from 25-g fresh cortical tissue and oven-dried at 85° C to constant mass. DMCF was calculated as mg dry mass per g fresh mass.

### 3.8.6 Fruit water content

Fruit water content (FWC), expressed on a fresh mass basis, was calculated according to the following formula:  $FWC = [(fresh\ mass - dry\ mass) / fresh\ mass] \times 100$ .

### 3.8.7 Fruit water loss

Individual fruit mass (g) was measured using an analytical balance (Mettler Instrument AG CH-8606, Greifensee-Zurich, Switzerland) at each sampling interval. Fruit weight loss (FWL, %) was calculated as percent reduction from initial weight.

### 3.8.8 Leaf and fruit mineral concentration

Leaves and fruit were randomly collected, weighted, 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 K<sup>+</sup>, Ca<sup>2+</sup>, and Mg<sup>2+</sup> concentration 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).

## 3.9 Statistical analysis

Statistical analysis was conducted using statistical analysis system (SAS) software version 8.2 (SAS Institute, Cary, North Carolina, USA).

## Chapter 4

### Responses of 'Pacific Rose™' apple to partial rootzone drying: first experiment in Manawatu

#### Abstract

No studies have been conducted detailing the effects of PRD in apple on a field scale. The effects of PRD on leaf and fruit water status, photosynthetic rate, yield, fruit quality, and fruit storage potential of 'Pacific Rose™' were therefore studied. The treatments were: commercial irrigation (CI) as control and partial rootzone drying (PRD). Irrigation in PRD trees was supplied only on one side of the tree row while the other side was kept dry during the growing season. Yield, mean fresh mass per fruit, trunk cross-sectional area (TCSA), yield efficiency (yield/TCSA), and shoot growth were the same between treatments, but the irrigation use efficiency did improve in PRD trees compared to the CI trees. Fruit quality at harvest in terms of dry mass concentration of fruit (DMCF), flesh firmness (FF), total soluble solids concentration (TSSC), starch pattern index (SPI), and background skin colour (in terms of  $HA^\circ$ ) was the same between treatments. FF and TSSC were also the same between treatments after storage at  $0 \pm 1$  and at  $20 \pm 1$  °C for 12 weeks and 18 days, respectively. However, fruit water loss was lower in PRD fruit than in CI fruit when stored at  $0 \pm 1$  and at  $20 \pm 1$  °C. PRD did not adversely affect yield and fruit quality and improved irrigation use efficiency. Therefore this irrigation method could be suggested as a water saving practice.

## 4.1 Introduction

Apples have been extensively studied under deficit irrigation as a water saving practice (Behboudian and Mills, 1997), but not under partial rootzone drying (PRD). PRD, which was defined in Chapter 1 (Section 1.2), has been tested in grape (Loveys et al., 2000) and in pear (Kang et al., 2002). Yield and berry quality for two grapevine cultivars were the same between PRD and fully irrigated plants, but irrigation use efficiency was improved in the former (Loveys et al., 2000). Kang et al. (2002) reported a significant increase in the yield of pear when water was supplied for the entire growing season to one side of the root system. This needs to be explored in apple. To my best knowledge, no field studies have been conducted detailing the seasonal and diurnal changes of plant water status (Glenn, 2000). Moreover, PRD's effect on fruit quality and storage potential is unknown. Therefore, I investigated the effect of PRD on plant and fruit water status, photosynthesis, yield, fruit quality, irrigation use efficiency, and fruit storage potential of "Pacific Rose™" apple. Although less water would be supplied, I hypothesised that PRD might not negatively affect the fundamental physiological parameters, yield, fruit quality, and fruit storage potential. This could be because some part of the rhizosphere is always wet in PRD and plant water status is expected to equilibrate with the wet part as observed in grapevines by Loveys et al. (2000).

## 4.2 Materials and methods

### 4.2.1 Experimental site, plant material, and treatments

The experiment was conducted at the Fruit Crops Unit, Massey University, Palmerston North (latitude 40° 2' S, longitude 175° 4' E), during the 2000-01 growing season. The area has humid-temperate climate with an average annual rainfall of 960 mm. The orchard soil is a Manawatu fine sandy loam.

The experimental block consisted of four rows of four-year-old 'Pacific Rose™' apple growing on M9 interstem and on MM-106 rootstock. The trees were spaced at 4 m between rows and 2 m within the row and trained as a central leader. Sixteen experimental trees were divided into four blocks. Each block had two plots of two experimental trees each. Two guard trees at each end surrounded the experimental plots.

Two treatments were randomly allocated within each block. They were: 1) commercial irrigation (CI) as control and partial rootzone drying (PRD). The CI trees were irrigated to maintain soil moisture at or close to field capacity. The irrigation water in PRD trees was applied only to one side of the tree row, while the other side was kept dry during the growing season. To ensure that only one side of the tree row was watered at each irrigation, the main irrigation pipe was divided into two lines and placed at 200 mm apart from the tree trunk. Two micro-sprinklers (one to each side of the tree row), covering 180° of soil area, were placed 500 mm away from the tree row and between pairs of trees as in CI. On-off valves controlled the irrigation in both sides of PRD trees. The irrigation was given automatically. A total of 181 and 362 L per tree was applied to, respectively, CI and PRD trees over 18 irrigation turns during the growing season. This was done on To exclude the rain, soil in the PRD plots was covered with clear polythene a month before full bloom which occurred on 23 October 2000. Trees received standard cultural practices for local commercial fruit production including fertilisation, pest and disease control, and weed control. Trees were hand-thinned at 53 days after full bloom (DAFB) as detailed in Chapter 3 (Section 3.51).

## **4.2.2 Pre-harvest parameters**

### **4.2.2.1 Measurements of volumetric soil water content**

Volumetric soil water content was monitored once a week as detailed in Chapter 3 (Section 3.1).

#### 4.2.2.2 Measurements of leaf and fruit water status

Seasonal predawn and midday leaf water potential ( $\Psi_{\text{leaf}}$ ) was measured weekly as detailed in Chapter 3 (Section 3.2.2) on six mature and fully expanded leaves per plot with a pressure bomb. Diurnal changes in  $\Psi_{\text{leaf}}$  were taken at 52, 87, 115, and 142 DAFB.

Fruit water potential ( $\Psi_{\text{fruit}}$ ) and fruit osmotic potential ( $\Psi_{\text{fs}}$ ) were measured in two fruit per plot picked at dawn. A dew point microvoltmeter (HR-33T microvoltmeter, Wescor, Inc., Logan, Utah, USA) equipped with psychometric chambers (C-52 sample chambers Wescor, Inc., Logan, Utah, USA) was used for the purpose. More general details are given in Chapter 3 (Section 3.2.3). Fruit turgor potential ( $\Psi_{\text{fp}}$ ) was calculated as the difference between  $\Psi_{\text{fruit}}$  and  $\Psi_{\text{fs}}$ . Fruit samples were collected on 88, 108, 127, 148, and 164 DAFB.

#### 4.2.2.3 Measurements of photosynthesis and stomatal conductance

Data on photosynthetic rate ( $A$ ), transpiration rate ( $E$ ), and stomatal conductance ( $g_s$ ) were obtained between 12:00 and 13:30 hours as detailed in Chapter 3 (Section 3.3) on eight mature and exposed leaves per plot.

#### 4.2.2.4 Shoot growth and fruit growth

Shoot growth and fruit growth were measured weekly in six shoots and ten fruit per plot following procedures given in Chapter 3 (Sections 3.4.1 and 3.4.3).

#### 4.2.2.5 Yield and fruit quality

At harvest, which occurred on 179 DAFB, fruit from each tree were harvested and fruit yield recorded as described in Chapter 3 (Section 3.5.2). Yield efficiency and irrigation use efficiency were calculated as detailed in Chapter 3 (Sections 3.5.3 and 3.5.5,

respectively). Six-fruit per plot were randomly selected to assess fruit quality parameters. Starch pattern index (SPI), fruit density (Fden), background skin colour, in terms of hue angle (HA°), flesh firmness (FF), total soluble solids concentration (TSSC), and dry mass concentration of fruit (DMCF), were determined following the procedures given in Chapter 3 (Sections 3.7.2 and 3.8.1-3.8.5).

### **4.2.3 Post-harvest parameters**

#### **4.2.3.1 Fruit quality at harvest and after storage**

At harvest three groups of 24 fruit each (four uniform fruit per treatment) were chosen. The first group was used to determine FF and TSSC as described in Chapter 3 (Sections 3.8.3 and 3.8.4). The remainder two groups were used to assess HA° at harvest and after storage. For fruit water loss determination, a group of fruit was weighed and placed in commercial carton boxes in a cool room at  $0 \pm 1$  °C and 93% relative humidity for 12 weeks. Another group of fruit was placed in another room at  $20 \pm 1$  °C and 72% relative humidity for 18 days. Then, fruit water loss (FWL) was recorded during storage as detailed in Chapter 3 (Section 3.8.7) at two weeks and two days intervals when stored at  $0 \pm 1$  and at  $20 \pm 1$  °C, respectively. The latter two groups of fruit were also used to evaluate FF and TSSC after storage as described Chapter 3 (Sections 3.8.3 and 3.8.4).

#### **4.2.3.2 Return bloom**

Return bloom was determined as follows. Four-two-year old shoots (25 cm length) per tree were selected a month before full bloom which occurred on 10 October 2001. The basal diameter of each shoot was determined and shoot cross-sectional area (SCSA) calculated. The flowers on each shoot were recorded and the fruit density (open flower clusters per cm<sup>2</sup> of SCSA) calculated.

#### 4.2.4 Statistical analysis

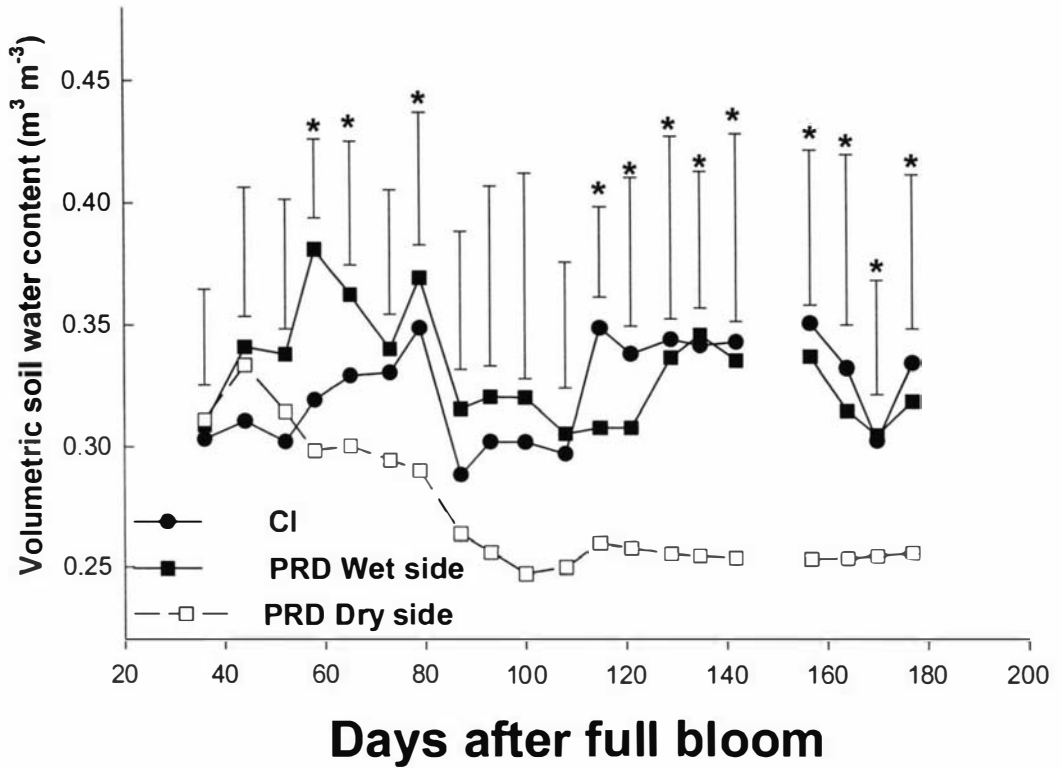
Data were analysed by complete randomised block model using GLM procedure of SAS software. To stabilise the variance, the variables expressed in percentage such as FWL, HA°, and  $\theta$  were arcsine-transformed. Number of fruit and starch pattern index were square root transformed. Means are reported after back transforming. Treatment means were separated by the least significant difference (LSD) test at  $P \leq 0.05$ .

### 4.3 Results

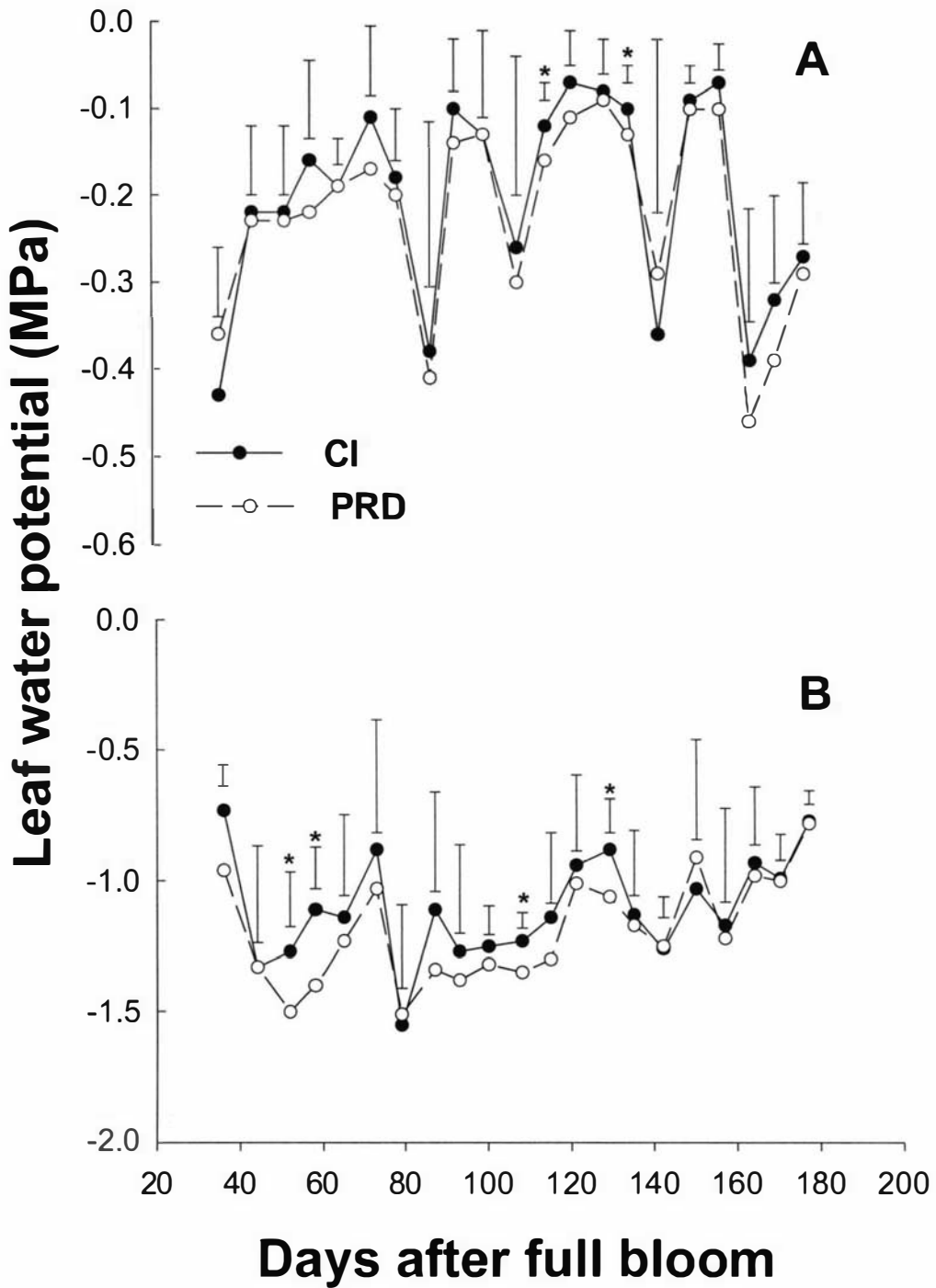
#### 4.3.1 Pre-harvest parameters

Throughout the growing season, the volumetric soil water content ( $\theta$ ) was consistently lower in the dry side of PRD trees than in the wet side of PRD and CI trees (Figure 4.1). Dry side of tree row in PRD trees resulted in a significant reduction in predawn leaf water potential ( $\Psi_{\text{leaf}}$ ) on two sampling dates out of twenty-one (Figure 4.2A). Midday  $\Psi_{\text{leaf}}$  was lower in PRD trees than in CI trees on four sampling dates out of twenty-one (Figure 4.2B).

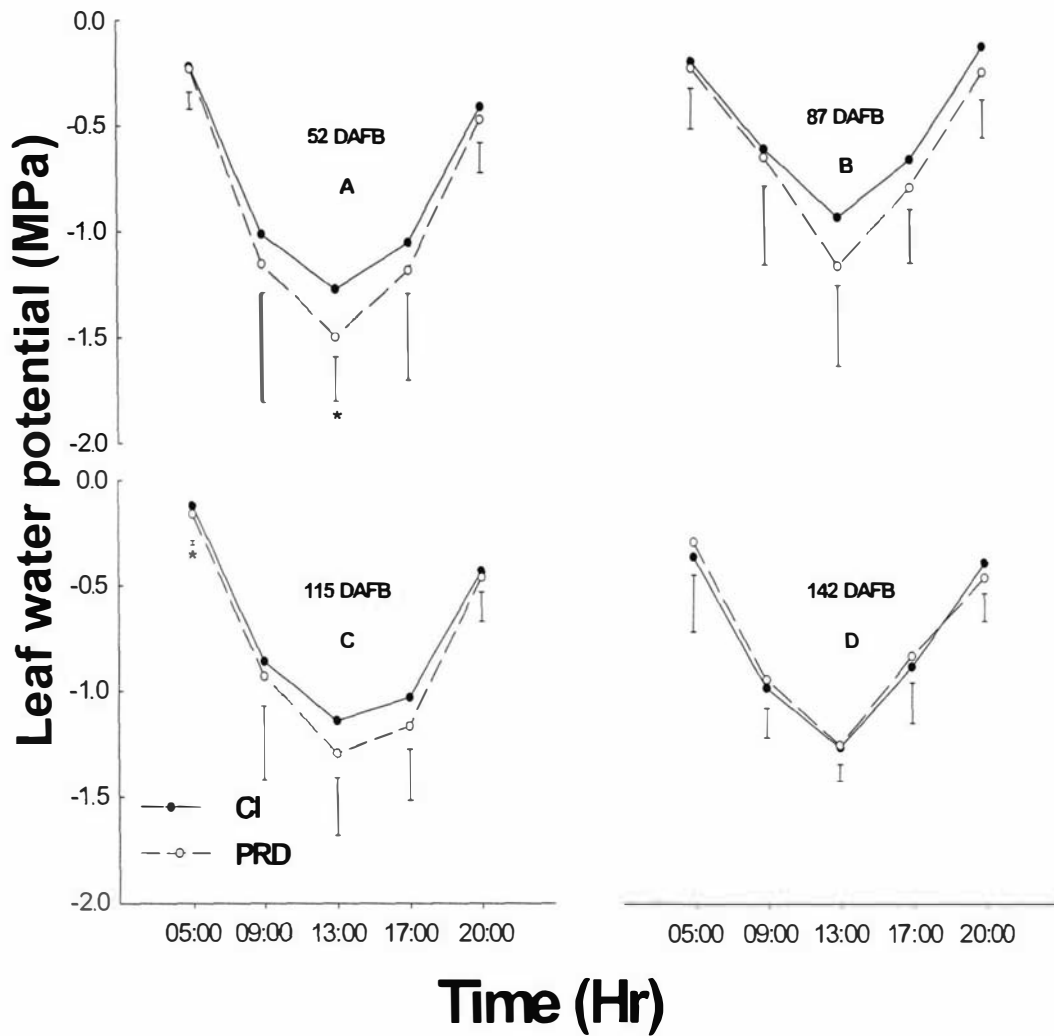
$\Psi_{\text{leaf}}$  was lower in PRD trees than in CI trees at 13:00 hours on 52 DAFB (Figure 4.3A) at 05:00 hours on 115 DAFB (Figure 4.3C). Nevertheless,  $\Psi_{\text{leaf}}$  was the same between treatments on 87 and 142 DAFB (Figure 4.3B and 4.3D). In all occasions  $\Psi_{\text{leaf}}$  tended to recover late in the afternoon (Figure 4.3A-D).



**Figure 4.1** Changes in volumetric soil water content in commercially irrigated (CI) trees and both sides of partial rootzone drying (PRD) trees. Vertical bars represent the least significant difference (LSD) at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .

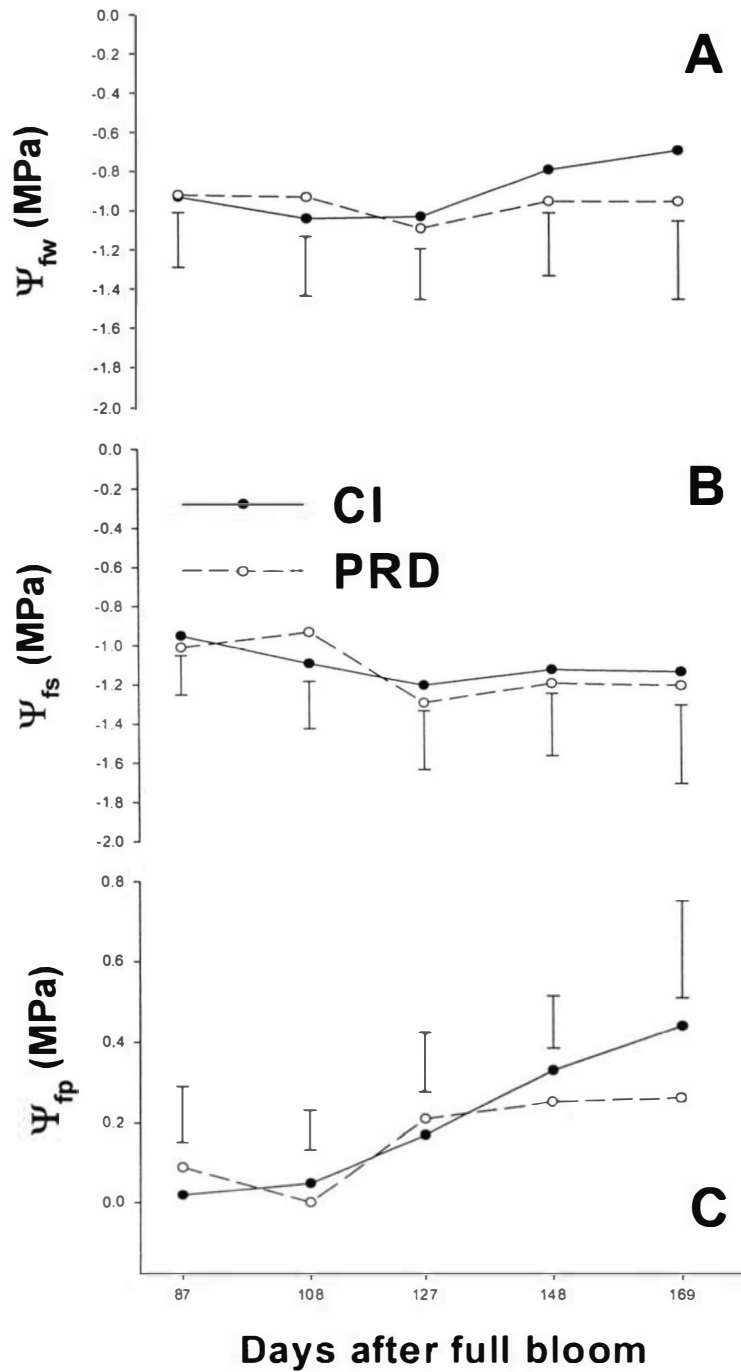


**Figure 4.2** Seasonal changes in predawn (A) and midday (B) leaf water potential in commercially irrigated (CI) and partial rootzone drying (PRD) trees. Vertical bars represent the LSD at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .



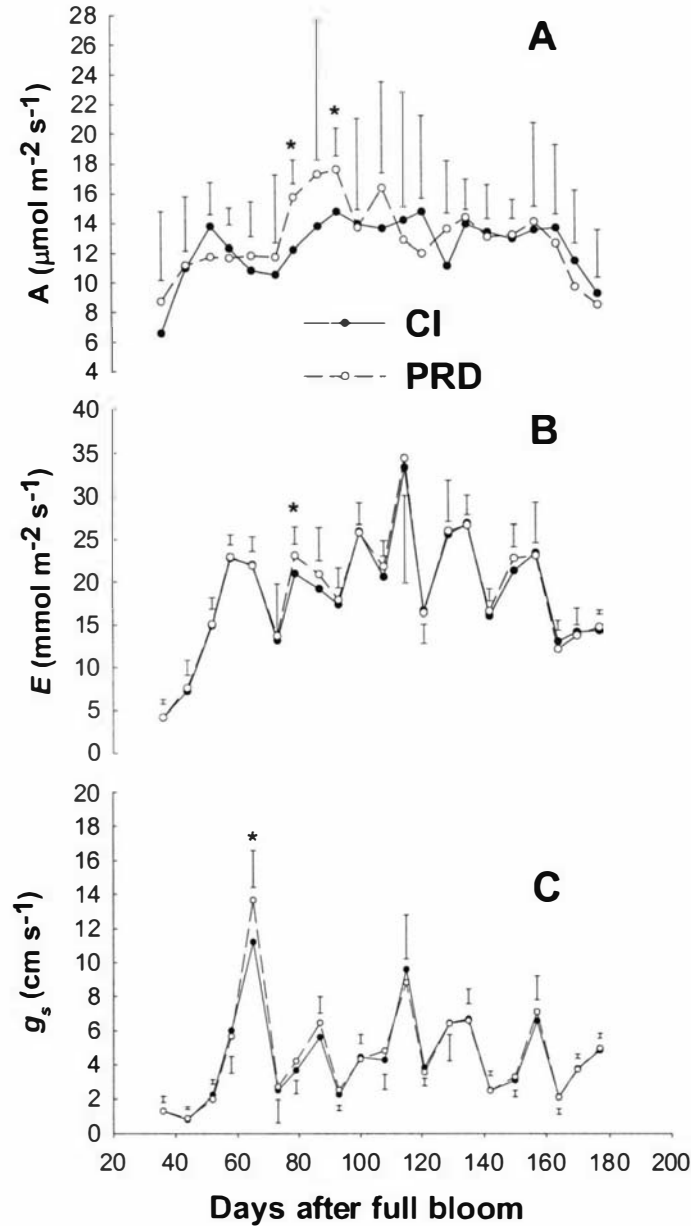
**Figure 4.3** Diurnal changes in leaf water potential in commercially irrigated (CI) and partial rootzone drying (PRD) trees. Vertical bars represent the LSD at  $P \leq 0.05$  and the asterisks indicate significant differences at the  $P \leq 0.05$ .

Fruit water potential ( $\Psi_{fw}$ ) tended to decrease in both CI and PRD fruit from 88 to 127 DAFB. Thereafter, while  $\Psi_{fw}$  in PRD fruit remained relatively constant for the rest of the season,  $\Psi_{fw}$  in CI fruit tended to increase (Figure 4.4A). Fruit osmotic potential ( $\Psi_{fs}$ ) tended to decrease similar to  $\Psi_{fw}$ , but did remain constant for the rest of the season in CI and in PRD trees (Figure 4.4B). As a result, fruit turgor potential ( $\Psi_{fp}$ ) tended to be higher in CI fruit than in PRD fruit (Figure 4.4C).



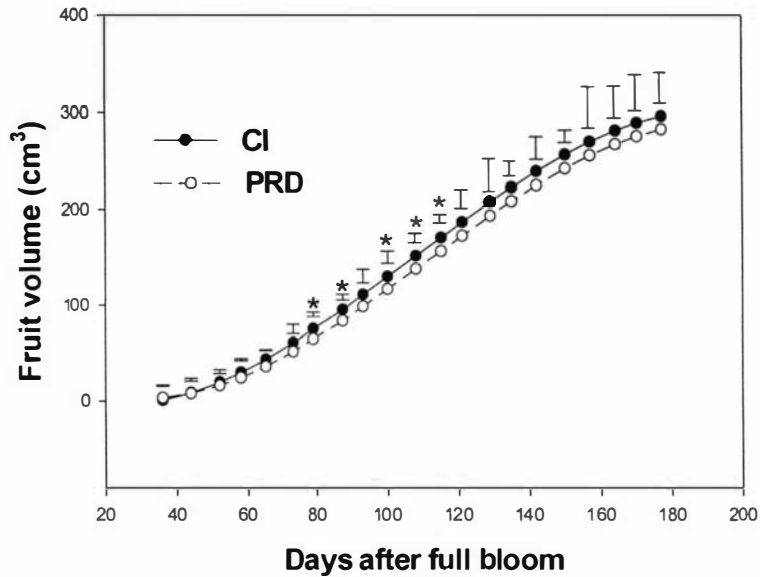
**Figure 4.4** Fruit water potential ( $\Psi_{fw}$ ), fruit osmotic potential ( $\Psi_{fs}$ ), and fruit turgor potential ( $\Psi_{fp}$ ) for 'Pacific Rose™' apple under partial rootzone drying (PRD) and commercially irrigated (CI) trees. Vertical bars represent the LSD at  $P \leq 0.05$ .

Photosynthetic rate ( $A$ ) was higher in PRD trees on two occasions out of 21 (Figure 4.5A). The rate of transpiration ( $E$ ) and stomatal conductance ( $g_s$ ) were higher in PRD trees on one occasion out of 21 for each parameter (Figures 4.5B and 4.5C).



**Figure 4.5** Seasonal variation in photosynthetic rate (A), transpiration rate (B), and stomatal conductance (C) in 'Pacific Rose™' apple under partial rootzone drying (PRD) and commercially irrigated (CI) trees. Vertical bars represent the LSD at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .

Cumulative fruit growth, in terms of fruit volume, was significantly lower in PRD fruit relative to CI fruit from 80 DAFB to 120 DAFB (Figure 4.6). Thereafter, fruit growth was similar between treatments (Figure 4.6). Yield, mean fruit mass, yield efficiency, trunk cross-sectional area, and shoot growth were the same between treatments, but the irrigation use efficiency was significantly improved in PRD trees relative to CI trees (Table 4.1). Fruit quality attributes were the same between treatments (Table 4.2).



**Figure 4.6** Cumulative fruit growth, in terms of fruit volume, of 'Pacific Rose™' apple under partial rootzone drying (PRD) and control irrigated (CI) trees. Vertical bars represent the LSD at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .

**Table 4.1** Effect of commercial irrigation (CI) and partial rootzone drying (PRD) on some yield attributes, mean fresh mass per fruit (MFMF), trunk cross-sectional area (TCSA), final shoot growth (FSG), and irrigation use efficiency (IUE) of 'Pacific Rose™' apple. Means within columns followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

	Gross yield (kg tree <sup>-1</sup> )	MFMF (g)	Yield efficiency (kg tree <sup>-1</sup> /cm <sup>2</sup> TCSA)	TCSA (cm <sup>2</sup> )	FSG (mm)	IUE (kg L <sup>-1</sup> H <sub>2</sub> O)
CI	23.80a	216.04a	1.22a	20.33a	142a	0.06b
PRD	24.38a	187.47a	1.20a	19.82a	163a	0.14a

**Table 4.2** Fruit quality attributes of 'Pacific Rose™' apples at harvest as influenced by commercial irrigation (CI) and partial rootzone drying (PRD). Means within rows followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

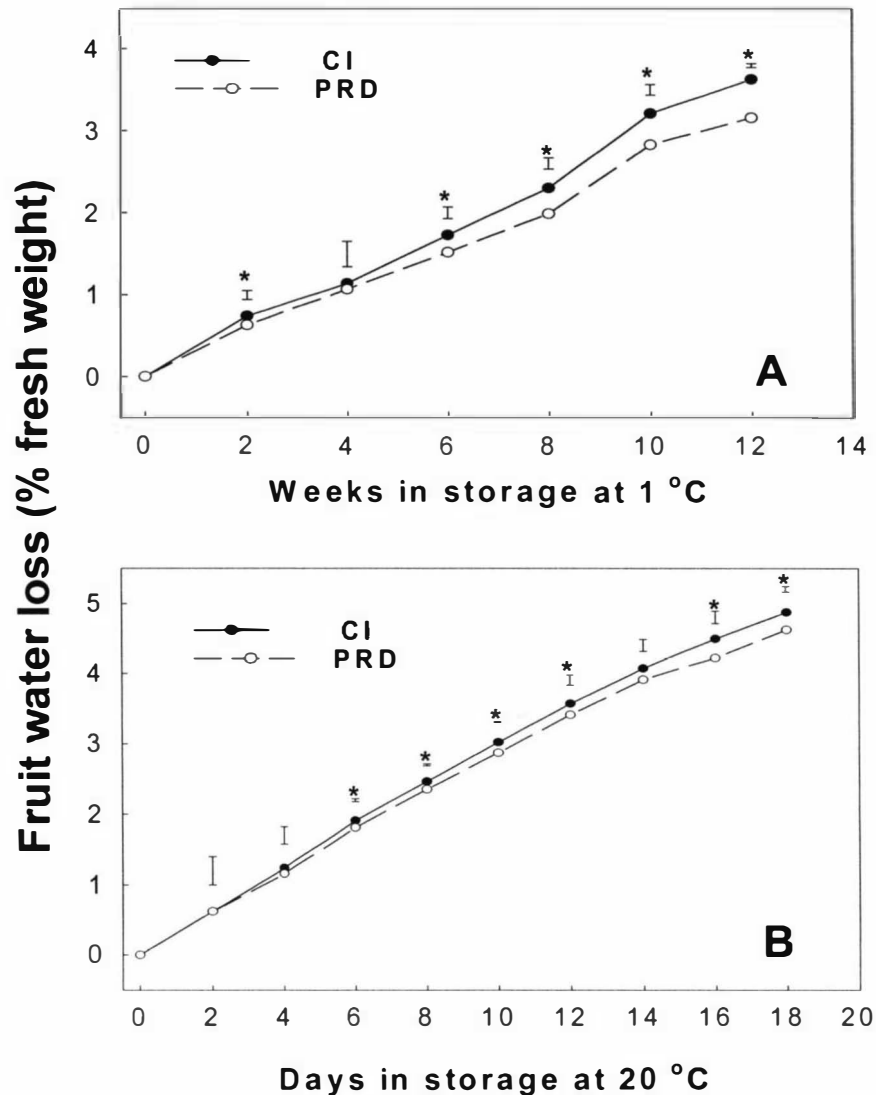
Fruit quality attributes	CI	PRD
Dry mass concentration of fruit ( $\text{mg g}^{-1}$ fresh mass)	126.1a	130.8a
Flesh firmness (N)	82.8a	81.5a
Total soluble solids concentration (%)	12.7a	12.1a
Starch pattern index	4a	3a
Hue angle	24.6a	22.2a

### 4.3.2 Post-harvest parameters

Fruit quality, in terms of total soluble solids concentration and flesh firmness, was the same between treatments at harvest or after storage for 12 weeks at  $0 \pm 1$  °C (Table 4.3). The same was true when fruit were stored at  $20 \pm 1$  °C for 18 days (Table 4.3). However, fruit water loss was lower in PRD fruit when stored at  $0 \pm 1$  °C and at  $20 \pm 1$  °C (Figure 4.7).

**Table 4.3** Influence of commercial irrigation (CI) and partial rootzone drying (PRD) on flesh firmness (FF) and total soluble solids concentration (TSSC) of 'Pacific Rose™' apple at harvest and after storage at  $0 \pm 1$  °C and at  $20 \pm 1$  °C for 12-week and 18-day, respectively. Means followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

	At harvest		After storage at $0 \pm 1$ °C		After storage at $20 \pm 1$ °C	
	TSSC	FF (N)	TSSC	FF (N)	TSSC	FF (N)
CI	13.0a	83a	14.0a	81a	15.0a	80a
PRD	12.0a	84a	14.0a	80a	14.5a	80a



**Figure 4.7** Cumulative fruit water loss as percentage of original weight during storage at  $0 \pm 1$  °C (A) and at  $20 \pm 1$  °C (B) for 12-week and 18-day, respectively, of 'Pacific Rose™' apple under partial rootzone drying (PRD) and commercial irrigation (CI) trees. Vertical bars represent the LSD at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .

Return bloom (number of open flower clusters per  $\text{cm}^2$  of shoot cross-sectional area  $\pm$  twice the SEM) recorded in the spring of 2001 was the same between treatments. The values were  $4.1 \pm 1.2$  and  $2.8 \pm 0.8$  for CI and PRD trees, respectively.

## 4.4 Discussion

Although  $\theta$  was significantly reduced in part of the root system of PRD trees (Figure 4.1), in general, seasonal and diurnal  $\Psi_{\text{leaf}}$  was not significantly reduced in relation to CI trees (Figure 4.2 and 4.3). This resulted in a similar fruit water potential,  $A$ ,  $E$ , and  $g_s$  to those in CI trees (Figure 4.4 and 4.5). The maintenance of  $\Psi_{\text{leaf}}$  in PRD trees could be explained, in part, by an increase of water absorption from the roots in the wet soil as mentioned by Green et al. (1997) and Green and Clothier (1999). The latter authors observed that when a portion of the apple root system is irrigated, this part of the rhizosphere has the capacity to transfer water from the soil at higher rates than when whole the root system is irrigated. Although I did not collect data to support it, roots in the dry soil must have continued their growth exploring deeper soil layers to absorb water and this might have contributed to maintenance of  $\Psi_{\text{leaf}}$  (Figure 4.2 and 4.3). Root growth, in dry soil, is possible because roots are dependant on shoots for assimilates and other substances (Kramer, 1983. p 161). As the rate of photosynthesis was unaffected here (Figure 4.5A), photoassimilates must be therefore available to maintain root growth (Salisbury and Ross, 1992. p. 406; Hsiao and Xu, 2000). Osmotic adjustment of roots in dry soil occurs and the root system is capable of absorbing water and nutrients from the soil contributing also to the water balance of the plant (Glenn, 2000). Under field conditions, which was the case here, both root osmotic adjustment and assimilates availability might allow the roots to explore more volume of soil and uptake water from the soil profile (Lafolie et al., 1999). Maintenance of similar  $\Psi_{\text{leaf}}$  between PRD and CI trees agrees with previous findings in apple under split root system (Gowing et al., 1990; Poni et al., 1992) and in grape under PRD in the field (Loveys et al., 2000). However, the latter three groups of authors reported significant reduction in  $A$ ,  $E$ , and  $g_s$  which was not observed in this study maybe because the  $\Psi_{\text{leaf}}$  of PRD trees was kept as high as CI trees.

Fruit growth of PRD trees, in terms of fruit volume, was reduced significantly from 80 to 120 DAFB possibly because of the onset of water deficit. Thereafter fruit growth became similar to CI fruit (Figure 4.6). This coincided with a reduction and increase of  $\Psi_{\text{fp}}$  for the same periods of time, respectively (Figure 4.4C). Osmotic adjustment must be the mechanisms to maintain fruit turgor and therefore fruit growth in PRD fruit after

120 DAFB, hence PRD fruit became similar to CI fruit. This would explain, in part, the similarity in yield and yield components between treatments (Table 4.1). This finding disagrees with those of Kang et al. (2002) for pear under PRD. They reported a significant increase in yield for PRD trees. However, they also reported higher number of fruit (111 more fruit) in PRD trees than in CI trees. Therefore, the pear crop load was unadjusted at the beginning of the experiment. In the present experiment, there were, on average, 20 fruit more in PRD trees than in CI trees. This occurred due to fruit bird damage in the latter trees, which were not included in the final yield count. The bird damage (%) was 6 and 13 for PRD and CI trees, respectively.

Yield produced and the amount of water supplied in PRD trees resulted in an increase by more than 2-fold in the irrigation use efficiency (IUE) (Table 4.1). Similarly, IUE was improved in grapevine (Loveys et al., 2000) and pear (Kang et al., 2002) by 1.9- and 1.3-fold, respectively.

Although PRD trees received only 50% of water given to CI trees, fruit quality, in terms of higher TSSC, FF, DMCF, and HA°, was the same in both treatments (Table 4.2). Apple fruit quality improves with deficit irrigation where the entire rhizosphere might experience a measure of water deficit (Ebel et al., 1993; Mills et al., 1996; Kilili et al., 1996b; Mpelasoka et al., 2001). The fruit quality improvement, in apple, is associated with the extent of deficit irrigation (DI). A midday  $\Psi_{\text{leaf}}$  of -1.5 to -2.5 MPa appears to induce changes in fruit quality (Ebel et al., 1993; Mills et al., 1996; Kilili et al., 1996a; Mpelasoka et al., 2001), which did not occur here (Figure 4.2 and 4.3). As a conclusion, fruit quality improvement is sensitive to plant water status and some improvement could be observed at  $\Psi_{\text{leaf}}$  lower than -1.5 MPa at midday. Therefore, fruit quality after storage at 0 or at 20 °C in PRD and CI fruit became similar (Table 4.3).

After harvest fruit continue respiring and transpiring. This reduces both fruit mass (Maguire et al., 2001) and flesh firmness (Johnston et al., 2002). This has significant economical implications for fruit destined for distant markets and long-term storage (Meberg et al., 2000). The loss of water from fruit by 5% may induce the development of a shrivelled appearance, which may result in the rejection of shipments and reduced

grower incomes (Johnston et al., 2002). Apple trees exposed to DI have improved fruit firmness and reduced fruit water loss in comparison with fully irrigated trees (Kilili et al. 1996b; Mpelasoka et al., 2000). Increase in firmness in DI fruit has been associated with an increase in cellular density and fruit size (Westwood, 1993, p. 264-265). In this study, fruit density was the same between treatments. The values ( $\text{g cm}^{-3}$ ) were: 0.86 and 0.85 for, respectively, CI and PRD fruit. Fruit water loss (FWL) was reduced in PRD fruit when stored at either 0 or at 20 °C (Figure 4.7). Reduced FWL has been attributed to changes in the cuticle of the fruit when fruit experience water deficit (Crisosto et al., 1994). This may have occurred in this experiment between 80 and 120 DAFB when PRD trees significantly reduced fruit growth (Figure 4.6). Water vapour permeance is a measure of the way by which water can escape from the fruit (Maguire et al., 2001). Reduced FWL in PRD fruit may be explained, in part, by the differences in the skin permeance to water vapour (Kilili et al., 1996b; Maguire et al., 2001). However, fruit firmness was similar between CI and PRD fruit and FWL was lower in PRD fruit. This suggests that other factors such as changes in the epidermal and cuticular structure of fruit may be involved in the maintenance of fruit firmness and reduced FWL in PRD fruit. I could also speculate that physical aspects such as reduced cuticle cracking might account for a reduction in FWL (Maguire et al., 1999). However, an investigation of the physical and chemical composition of the cuticle in PRD fruit needs to be carried out.

## 4.5 Conclusions

It was shown that PRD irrigation did not alter plant water status and photosynthetic rate during the entire growing season of 'Pacific Rose™' apple. Yield, yield components, and fruit quality were not adversely affected, but the irrigation use efficiency improved in PRD trees. Total soluble solids concentration and flesh firmness were the same at harvest and after storage at  $0 \pm 1$  °C for 12 weeks and at  $20 \pm 1$  °C for 18 days. However, at both storage temperatures, fruit water loss was significantly reduced in PRD fruit which is important for long distance transport and marketing. This finding needs to be confirmed. Although PRD could be suggested as water saving practice in a humid environment, PRD studies in a dry environment need to be conducted.

## Chapter 5

### Fruit quality responses of 'Royal Gala' apple to partial rootzone drying: an experiment in Hawke's Bay

#### Abstract

This study explored the potential of partial rootzone drying (PRD) applied during the entire growing season for its effect on fruit quality of "Royal Gala" apple growing in a commercial orchard in an apple growing area of New Zealand. The irrigation treatments were: commercially irrigated (CI) and PRD. Irrigation in PRD treatment was alternated from the wet side to the dry side when volumetric soil water content ( $\theta$ ) dropped between 0.12 and 0.18 m<sup>3</sup> m<sup>-3</sup>. Fruit growth, mean fresh mass per fruit (MFMF), fruit diameter, fruit volume, fruit density, and fruit skin colour (HA°) were the same between treatments. However, PRD fruit had the highest flesh firmness (FF), total soluble solids concentration (TSSC), and starch pattern index (SPI). Multivariate analysis suggested that the fruit quality attributes collectively accounted for the significant separation between CI and PRD fruit. The separation was weighed toward higher SPI, which was indicative of advancement in fruit maturity in PRD fruit. This has important implications in terms of early marketing. Higher FF and TSSC are important for the improvement of fruit quality which New Zealand apple exportation is based on. Fruit quality improvement was achieved in the PRD treatment while receiving only 50% of the water given to CI trees. Therefore, this water-saving practice could be suggested for Hawke's Bay and other dry areas.

## 5.1 Introduction

In Chapter 4, fruit quality of 'Pacific Rose™' apple was assessed as affected by PRD. Fruit quality was not improved by PRD. The experiment was conducted in the Manawatu region, which is a humid area and the need to irrigate is marginal. Hawke's Bay is a dry area where irrigation is important to maximise yield and fruit quality. Also, this production area is the most important apple growing area in New Zealand. Intensive research has been done on the effects of deficit irrigation (DI), as a water-saving practice, on the improvement of fruit quality in deciduous trees (Behboudian and Mills, 1997). However, there is no information of the use of PRD in a dry environment and its impact on fruit quality of apple. Therefore the objective of this study was to explore the effect of PRD on fruit quality of 'Royal Gala' apple growing in dry environmental conditions. PRD has been tested commercially in grapevine (*Vitis vinifera*) by Loveys et al. (2000). They reported that PRD did not improve berry yield and quality, in terms of TSSC and pH, but irrigation use efficiency was significantly improved. However, PRD implies applying water below the optimum needed to maximise yield. It was therefore hypothesised that PRD might influence fruit quality of apple growing in a dry region similar to the improvement observed under deficit irrigation (Behboudian and Mills, 1997).

## 5.2 Materials and methods

### 5.2.1 Experimental site, plant material, and treatments

The experiment was conducted in a commercial orchard in Havelock North, New Zealand (latitude 39° 39' S, longitude 176° 53' E), during the 2001-02 growing season. The area has a humid and temperate climate with an average annual rainfall and potential evapotranspiration of 565 mm and 781 mm, respectively. The orchard soil was a sandy silt loam.

The experimental block consisted of four rows of 25-year-old 'Royal Gala' apple on MM-106 rootstock. The trees were spaced at 5 m between rows and 4 m within the row and trained as a central leader. A total of 16 experimental trees were divided into four blocks of four trees each. Each block had two plots of two trees each. Two guard trees at each end surrounded the experimental plots.

Two treatments were randomly allocated within each block. The treatments were: 1) commercial irrigation (CI) as control and partial rootzone drying (PRD). The trees were trickle irrigated using two pipelines, one to each side of the tree row. Four emitters in CI trees and two emitters in PRD trees emitting 4 L per hour each were placed 500 mm away from the tree row and between pairs of trees. The irrigation in PRD trees was supplied only on one side during which the other side was allowed to dry. The Side one of PRD was firstly irrigated. The irrigation was manually shifted to the dry side when the volumetric soil water content ranged between 0.12 and 0.18 m<sup>3</sup> m<sup>-3</sup>. CI and the irrigated side of PRD trees were irrigated to maintain soil moisture at or close to field capacity. The irrigation was given automatically. Approximately 280 and 580 L per tree were applied to, respectively, PRD and CI trees over 7 irrigation turns during the growing season. To exclude rain, soil in the PRD plots was covered with clear polythene 36 days after full bloom (DAFB) which occurred on 30 September 2001. Trees received standard cultural practices for local commercial fruit production including fertilisation, fruit hand-thinning, pest and disease control, and weed control.

### **5.2.2 Measurements of volumetric soil water content**

Volumetric soil water content ( $\theta$ ) was monitored twice a month as described in Chapter 3 (Section 3.1).

### **5.2.3 Measurements of plant water status, photosynthesis, and stomatal conductance**

Midday leaf water potential ( $\Psi_{\text{leaf}}$ ) was measured once on four leaves per plot as detailed in Chapter 3 (Section 3.2.2). Measurements were obtained between 12:00 and 13:00 hours on 93 DAFB.

The rate of photosynthesis ( $A$ ), stomatal conductance ( $g_s$ ), and photosynthetic photon flux (PPF) were obtained from leaves as detailed in Chapter 3 (Section 3.3). Measurements were taken between 12:00 and 13:30 hours on 93 DAFB.

### **5.2.4 Fruit growth and fruit quality**

Fruit growth was recorded twice a month, in terms of fruit diameter as described in Chapter 3 (Section 3.4.3) on 10 fruit per tree. Measurements were taken from 55 DAFB until growth ceased which occurred on 135 DAFB.

At harvest (149 DAFB), 10 fruit per plot were randomly collected to assess fruit quality. Mean fresh mass per fruit, fruit volume, and fruit density were determined as described in Chapter 3 (Sections 3.5.2 and 3.8.1). Then, starch pattern index (SPI), background skin colour in terms of hue angle ( $HA^\circ$ ), flesh firmness (FF), total soluble solids concentration (TSSC), and dry mass concentration of fruit (DMCF) were measured as detailed in Chapter 3 (Sections 3.7.2, 3.8.2, 3.8.3, 3.8.4, and 3.8.5).

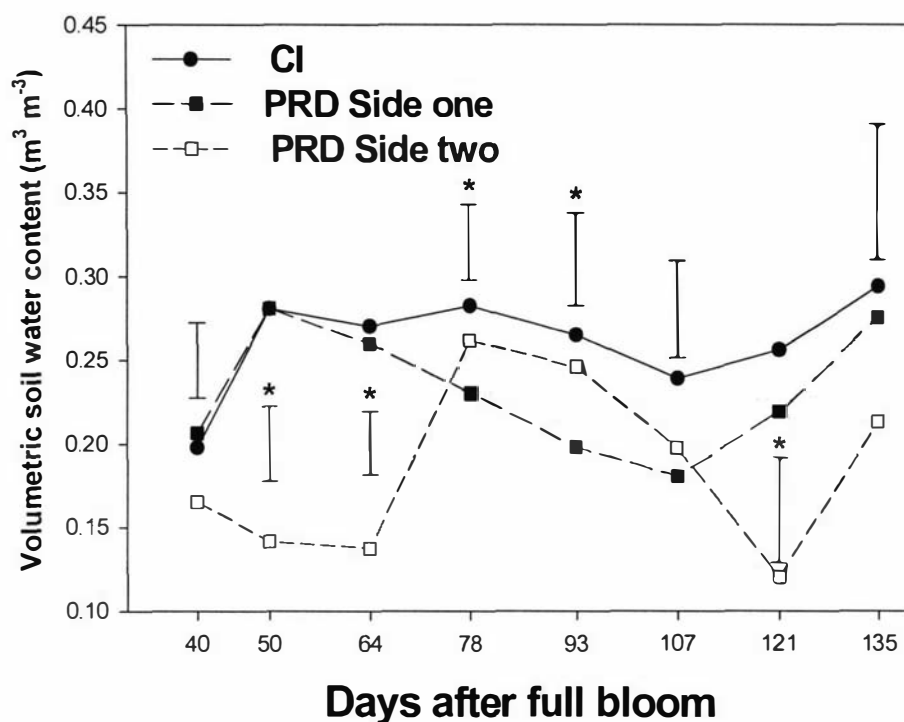
### **5.2.5 Statistical analysis**

The data were analysed by complete randomised block model using GLM procedure of SAS software. To stabilise the variance, the variables expressed in percentage and in discrete units were arcsine- and square-root transformed, respectively, as mentioned in Chapter 4 (Section 4.3). Means are reported after back transforming. Mean of treatments were separated using the least significant

difference (LSD) test at  $P \leq 0.05$ . Data were submitted to a canonical discriminant analysis. This allowed getting an overview of the fruit quality attributes collectively to separate the treatments and to identify the major sources of difference between irrigation treatments (Cruz-Castillo et al., 1994). This was achieved using CANDISC procedure of SAS.

### 5.3 Results

The difference in  $\theta$  was significant between both sides of PRD trees and they were alternatively increasing and decreasing during the growing season as the irrigation was shifted to both side of the row tree (Figure 5.1). However, this did not significantly affect  $\Psi_{\text{leaf}}$ ,  $A$ , and  $g_s$  (Table 5.1).

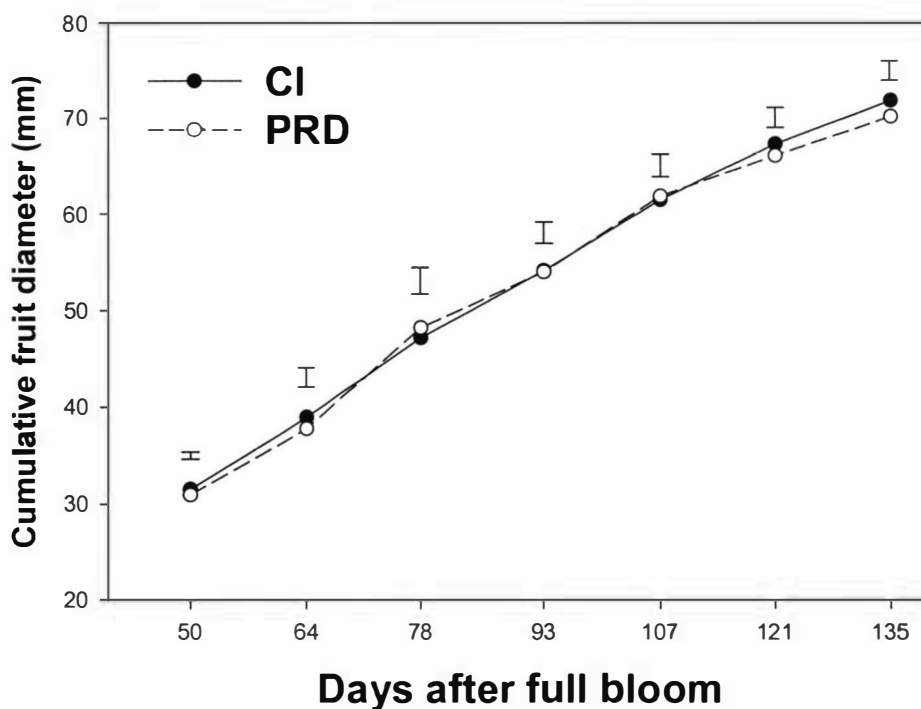


**Figure 5.1** Changes in soil water content in commercially irrigated (CI) trees and both sides of partial root zone drying (PRD) trees. Vertical bars represent the least significant difference (LSD) at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .

**Table 5.1** Effect of irrigation treatments (ITs) on leaf water potential ( $\Psi_{\text{leaf}}$ ), photosynthesis and stomatal conductance. Means separation by LSD test at  $P \leq 0.05$ , no significant (ns) at  $P \leq 0.05$ . The PPF ( $\mu\text{mol m}^{-2} \text{s}^{-1} \pm \text{SD}$ ) was  $669 \pm 26$  for this occasion.

ITs	$\Psi_{\text{leaf}}$ (MPa)	Photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Stomatal conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ )
CI	-1.0	16.1	0.65
PRD	-1.1	14.3	0.63
Significance	ns	ns	ns

Cumulative fruit growth, in terms of fruit diameter, was the same between treatments (Figure 5.2). The same was true for MFMF, fruit diameter, fruit volume, fruit density, DMCF, and fruit colour (Table 5.2). However, FF, TSSC, and SPI were higher in PRD fruit than in CI fruit indicating that the latter fruit were less mature (Table 5.2).



**Figure 5.2** Cumulative fruit growth, in terms of fruit diameter, of 'Royal Gala' apple under partial rootzone drying (PRD) and commercially irrigated (CI) trees. Vertical bars represent the LSD at  $P \leq 0.05$ .

**Table 5.2** Effect of irrigation treatments (ITs) on mean fresh mass per fruit (MFMF), fruit diameter (FD), fruit volume (FV), fruit density (Fden), flesh firmness (FF), dry mass concentration of fruit (DMCF), total soluble solids concentration (TSSC), starch pattern index (SPI), and fruit colour in terms of hue angle (HA°). Means separation by LSD test at  $P \leq 0.05$  (\*),  $P \leq 0.001$  (\*\*), or non-significant (ns).

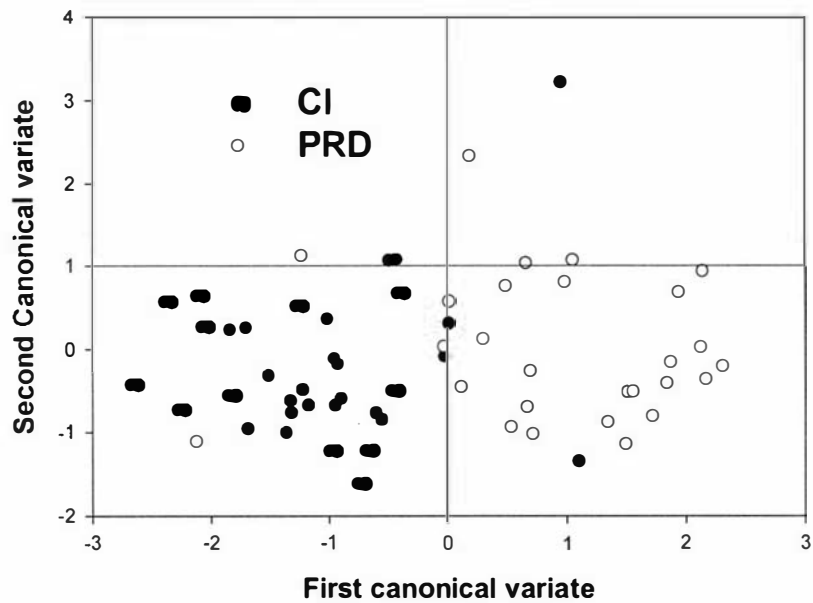
ITs	MFMF (g)	FD (mm)	FV (cm <sup>3</sup> )	Fden (g/cm <sup>3</sup> )	FF (N)	DMCF (mg g <sup>-1</sup> fresh mass)	TSSC (%)	SPI	HA
CI	167.3	70.3	182.9	0.92	94.2	139.4	11.0	4.4	35.8
PRD	146.2	67.1	160.0	0.92	96.9	136.0	11.9	5.1	34.3
	ns	ns	ns	ns	*	ns	**	**	ns

Fruit quality attributes were further examined by canonical discriminant analysis (CDA). This multivariate analysis was performed using MFMF, FF, DMCF, TSSC, SPI, and HA°, the remainders were excluded from the multivariate test because they are highly correlated among themselves and therefore would invalidate the analysis. The square Mahalanobis distance (15.4) and the multivariate statistics and F approximations ( $P \leq 0.0001$ ) suggested a clear difference between treatments. To corroborate the multivariate results, the standardised canonical scores (SCS) from the first canonical discriminant function (CDF) were subjected to a univariate analysis and mean separation by LSD test at  $P \leq 0.05$ . The latter statistical analysis supported the multivariate test where the six variables were considered collectively. Fruit quality attributes were significantly different between CI and PRD trees. Mean values (SCS, LSD = 0.87) from the first CDF were -1.0 and 0.9 for CI and PRD fruit, respectively.

The first CDF accounted, as expected, for 100% of the separation between treatments and the standardised canonical coefficients are weighed only toward MFMF and SPI, which were moderately and highly correlated with CDF1 (Table 5.3). Discrimination between CI and PRD fruit may be based only on higher SPI for PRD fruit (Figure 5.3)

**Table 5.3** Standardised canonical coefficients (SCC) and correlation coefficients (r) for the first canonical discriminant function (CDF) and six fruit attributes of 'Royal Gala' apple.

Variable	CDF1	
	SCC	r
Mean fresh mass per fruit	-0.6	-0.66
Flesh firmness	0.3	0.27
Dry mass concentration of fruit	-0.4	-0.29
Total soluble solids concentration	0.1	0.29
Starch pattern index	0.8	0.8
Hue angle	---	---
Canonical correlation	0.71	
Eigenvalue	1.0	
Variance explained (%)	100	
Significance	***	



**Figure 5.3** Canonical scores of the first two canonical discriminant functions for six fruit quality attributes of 'Royal Gala' apple (variables in Table 5.3) under partial rootzone drying (PRD) and commercially irrigated (CI) trees.

## 5.4 Discussion

Although  $\theta$  was significantly different between two sides of PRD trees (Figure 5.2), this was not reflected in significant differences in  $\Psi_{\text{leaf}}$  between CI and PRD trees for one occasion that it was taken on 93 DAFB (Table 5.1). The maintenance in  $\Psi_{\text{leaf}}$ ,  $A_s$ , and  $g_s$  in PRD trees could be explained by the increase in the rate of water absorption by the roots in the wetted soil as observed in apple roots by Green et al. (1997). Also, Green and Clothier (1995) observed that the roots of kiwifruit vines, that had been water deprived previously, enhanced the water absorption when re-watered. Both mechanisms may take place in apple roots resulting in similar  $\Psi_{\text{leaf}}$  in PRD trees to those of CI trees. Another reason for  $\Psi_{\text{leaf}}$  maintenance could be that the trees used in this experiment were very large with extensive root system. Therefore roots might have been absorbing water from soil beyond the experimental area.

SPI, FF, and TSSC were higher in PRD fruit than in CI fruit (Table 5.2). Ethylene production and SPI are indicators of apple fruit maturity (Mpelasoka et al., 2000). The higher value of SPI here indicates lower starch, therefore starch hydrolysis started early in PRD fruit (Table 5.2 and Figure 5.3). I did not measure ethylene production, but a higher range of SPI in PRD fruit is indicator of an early fruit maturity (Ebel et al., 1993), which is important in terms of early marketing. Multivariate analysis pointed out that the separation between CI and PRD fruit was weighed toward the higher range of SPI in the latter treatment when quality attributes were considered collectively (Table 5.3 and Figure 5.3). This confirmed the advancement in fruit maturity in PRD fruit. One week advancement in fruit maturity of processing tomato, subjected to PRD, was observed without measurable changes in  $\Psi_{\text{leaf}}$ ,  $A_s$ , and  $g_s$  (Zegbe et al., 2003b). This suggests that root to shoot and shoot to fruit signalling are taking place when plants are exposed to PRD (Davis et al., 2000) that allows ethylene production and hence the advancement in fruit maturity of PRD fruit as suggested in fruit exposed to water deficit by Mpelasoka et al. (2000). However, fruit quality of 'Pacific Rose™' apple was the same between fully

irrigated and PRD trees (Chapter 4, Section 4.5). This suggests that the PRD effect might be cultivar dependent.

Higher accumulation of starch in PRD fruit must have occurred to account for a higher sugar conversion, measured here, in terms of TSSC (Table 5.2). FF was higher in PRD fruit than in CI fruit (Table 5.2). This attribute is important for fruit destined for long distance transport. Higher FF is associated with small fruit and higher fruit density (Ebel et al., 1993). However, even when PRD fruit were 13% smaller relative to CI fruit, fruit density was the same between CI and PRD fruit (Table 5.2). Therefore other factors, that deserve further investigation, such as changes in the composition and thickness of the cuticle may occur in PRD fruit as shown in peaches (Crisosto et al., 1994) and suggested for apple (Mpelasoka et al., 2000) subjected to DI. Higher FF in apple fruit is associated with reduced fruit water loss during storage (Kilili et al., 1996b; Mpelasoka et al., 2000). Therefore, PRD in 'Royal Gala' apple might have great potential for fruit destined for long storage.

## 5.5 Conclusions

The study shown that PRD improved fruit quality of 'Royal Gala' in terms of higher TSSC and FF and advanced fruit maturity in terms of lower SPI. Multivariate analysis confirmed that separation between CI and PRD fruit was due to lower SPI in the latter fruit when fruit quality attributes were considered collectively. The rate of fruit growth was unaffected and therefore MFMF was the same between treatments. The study was conducted in a commercial orchard where irrigation use efficiency was improved by PRD as PRD trees were given 50% less water than that of CI trees. However, the latter advantage and fruit storage potential that PRD could have in apple deserve investigation.

## Chapter 6

### Responses of 'Pacific Rose™' apple to partial rootzone drying: second experiment in Manawatu

#### Abstract

Drip irrigation was used in this study and the partial rootzone drying (PRD) irrigation was shifted from one side of the tree row to the other side of 'Pacific Rose™' apple during the growing season. The treatments were: commercially irrigated (CI) as control and partial rootzone drying (PRD). Irrigation in PRD trees was applied only to one side of the tree row with the other side left to attain a volumetric soil water content below between 0.18 and 0.22 m<sup>3</sup> m<sup>-3</sup> and then the irrigation shifted over to the latter side of the tree. In general, diurnal leaf water potential ( $\Psi_{\text{leaf}}$ ) was the same for the two treatments. Stomatal conductance ( $g_s$ ) and photosynthetic rate ( $A$ ) were unaffected. Yield, mean fresh mass per fruit, trunk cross-sectional area (TCSA), yield efficiency (yield/TCSA), and shoot growth were the same between treatments, but the irrigation use efficiency did improve in PRD trees compared to the CI trees. Fruit quality at harvest, in terms of internal ethylene concentration (IEC), starch pattern index (SPI), flesh firmness (FF), total soluble solids concentration (TSSC), and fruit background skin colour (in terms of HA°), was the same between treatments. Dry mass concentration of fruit (DMCF) was lower in PRD fruit than in CI fruit. IEC was higher in PRD fruit after 10 weeks at  $0 \pm 1$  °C. FF was lower in PRD fruit than in CI fruit after storage for 16 days at  $20 \pm 1$  °C. Fruit water loss was the same between treatments after 10 weeks of storage at  $0 \pm 1$  and 16 days at  $20 \pm 1$  °C. PRD did not adversely affect yield and fruit quality and improved irrigation use efficiency.

## 6.1 Introduction

Yield, fruit quality, and storage potential of 'Pacific Rose™' under PRD were explored using micro-sprinklers (Chapter 4) and fruit quality of 'Royal Gala' apple was studied using drip irrigation (Chapter 5).

Drip irrigation system is more efficient in water use, application, and precision placement in comparison with flood and/or micro-sprinkler irrigation (Hartz, 1993). Reduced vegetative growth, but not adverse effects on yield and fruit quality in drip-irrigated fruit trees have been observed by Levin et al. (1979) and Proebsting et al. (1977). Drip irrigation has been tested in two grapevine cultivars under PRD by Loveys et al. (2000). They observed no negative effects on yield and berry quality, but the irrigation use efficiency was significantly improved. However, this has not been explored in 'Pacific Rose™'. Therefore, the objective of this study was to investigate the effect of PRD on yield, fruit quality, and storage potential of 'Pacific Rose™' apple using drip irrigation. Plant water status and the rate of photosynthesis were also studied to gain further knowledge on the effects of PRD on tree physiology. Because a large portion of the rhizosphere would be left to dry by using drip irrigation, I hypothesised that the yield might be reduced but fruit quality could be improved by PRD.

## 6.2 Materials and methods

### 6.2.1 Experimental site, plant material, and treatments

The experimental site and conditions were the same as described in Chapter 4. The study was carried out during the 2001-02 growing season in two rows of five-year-old 'Pacific Rose™' apples growing on M9 interstem and on MM-106 rootstock.

Two treatments were randomly allocated to each pair of trees and replicated four times. The treatments were: 1) commercially irrigated (CI) as control and partial rootzone

drying (PRD). The CI trees were irrigated to maintain soil moisture at or close to field capacity. The trees were trickle irrigated by using four emitters in CI trees and two emitters in PRD trees. The drippers, that dripped 4 L per hour each, were placed 500 mm away from the tree row and between pairs of trees. The irrigation in PRD trees was applied to one side of the tree row and the other side was allowed to dry. The irrigation in PRD treatment was manually shifted to the dry side when the volumetric soil water content ( $\theta$ ) in this side ranged between 0.18 and 0.22 m<sup>3</sup> m<sup>-3</sup>. CI and the irrigated side of PRD trees were irrigated to maintain soil moisture at or close to field capacity ( $\theta = 0.35$ ). However, in PRD trees the soil on both sides was left to dry from 70 to 120 days after full bloom (DAFB), thereafter irrigation was reversed only to one side of the tree row was irrigated. The irrigation was given automatically. Approximately 172 and 344 L per tree were applied to PRD and CI treatment, respectively, over 5-irrigation turns. To exclude the rain, soil in the PRD plots was covered with clear polythene from 71 DAFB which occurred on 3 October 2001. Trees received standard cultural practices for local commercial fruit production including fertilisation, pest and disease control, and weed control. Trees were hand-thinned on 50 DAFB as detailed in Chapter 3 (Section 3.51).

## **6.2.2 Pre-harvest parameters**

### **6.2.2.1 Measurements of volumetric soil water content**

Volumetric soil water content ( $\theta$ ) was monitored once a week as detailed in Chapter 3 (Section 3.1).

### **6.2.2.2 Measurements of leaf water status**

Diurnal changes in leaf water potential ( $\Psi_{\text{leaf}}$ ) were recorded as detailed in Chapter 3 (Section 3.2.2) on four mature and fully expanded leaves per plot with a pressure bomb at 06:00, 09:00, 12:00, 15:00, and 18:00 hours. This was done on 146, 155, 176, and 184 DAFB.

### **6.2.2.3 Measurements of photosynthesis and stomatal conductance**

Photosynthetic rate ( $A$ ), stomatal conductance ( $g_s$ ), and photosynthetic photon flux (PPF) were obtained between 12:00 and 13:30 hours local time as detailed in Chapter 3 (Section 3.3) on four mature and exposed leaves per plot. This was done on 146, 155, 176, and 184 DAFB.

### **6.2.2.4 Shoot growth**

Growth of four similar sized current-season shoots was measured as detailed in Chapter 3 (Section 3.4.1). The final shoot length was measured at the end of the experiment which occurred on 196 DAFB. Tree diameter was measured as detailed in Chapter 3 (Section 3.4.2).

### **6.2.2.5 Yield and fruit quality**

At harvest, which occurred on 196 DAFB, fruit from each tree were harvested and fruit yield recorded as described in Chapter 3 (Section 3.5.2). Yield efficiency and irrigation use efficiency were calculated as detailed in Chapter 3 (Sections 3.5.3 and 3.5.5). Six uniform fruit per plot were randomly selected to assess fruit quality parameters. Internal ethylene concentration (IEC) and Starch pattern index (SPI) were measured as described in Chapter 3 (Sections 3.7.1 and 3.7.2). Background skin colour, in terms of hue angle ( $HA^\circ$ ), flesh firmness (FF), total soluble solids concentration (TSSC), and dry mass concentration of fruit (DMCF) were determined following the procedures given in Chapter 3 (Sections 3.8.1-3.8.5).

## 6.2.3 Post-harvest parameters

### 6.2.3.1 Fruit quality at harvest and after storage

At harvest three groups of 24 fruit each (six uniform fruit per plot) were chosen. The first group was used to determine IEC, SPI, FF, and TSSC at harvest as described in Chapter 3. Fruit density was obtained as detailed in Chapter 3 (Section 3.8.1). The next two groups of fruit were used to assess HA° at harvest and after storage. For fruit water loss determination, a group of fruit was weighed and placed in commercial carton boxes in a cool room at  $0 \pm 1$  °C and 93% relative humidity for 10 weeks. Another group of fruit was placed in another room at  $20 \pm 1$  °C and 72% relative humidity for 16 days. Then, fruit water loss (FWL) was recorded during storage as detailed in Chapter 3 (Section 3.8.7) at two weeks and two days intervals when stored at  $0 \pm 1$  and at  $20 \pm 1$  °C, respectively. The latter two groups of fruit were also used to evaluate FF and TSSC after storage as described in Chapter 3 (Sections 3.8.3 and 3.8.4).

### 6.2.3.2 Return bloom

Return bloom was determined as described in Chapter 4 (Section 4.2.3.4). Data were recorded on 11 October 2002. The flowers on each shoot were counted and the fruit density (open flower cluster per mm<sup>2</sup> of SCSA) calculated.

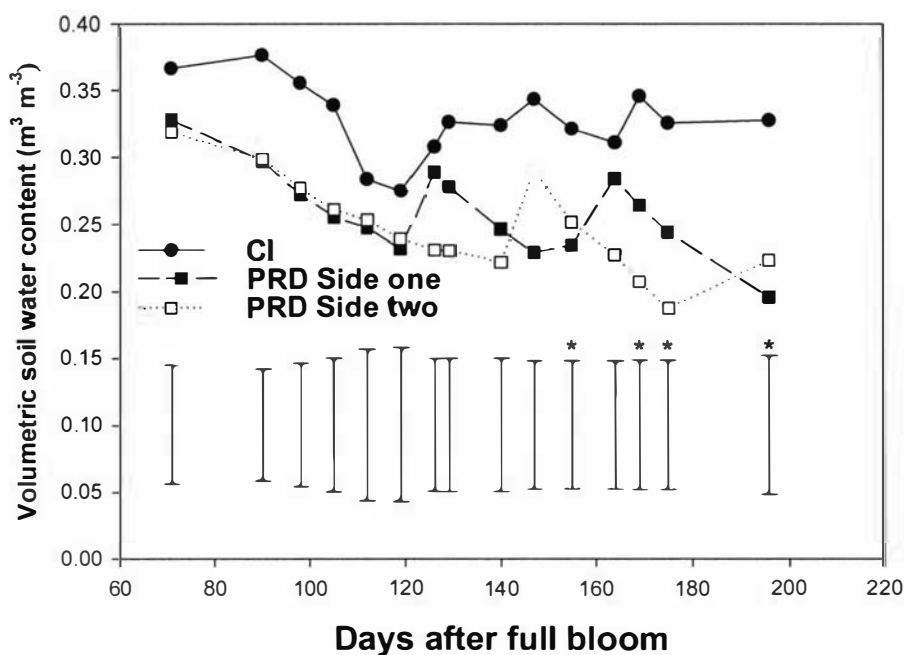
## 6.2.4 Statistical analysis

The data were analysed by a complete randomised model using GLM procedure of SAS software. To stabilise the variance, the variables expressed in percentage and in discrete unit were arcsine- and square-root transformed, respectively, as mentioned in Chapter 4 (Section 4.3). Means are reported after back transforming. Treatment means were separated using least significant difference (LSD) test at  $P \leq 0.05$ .

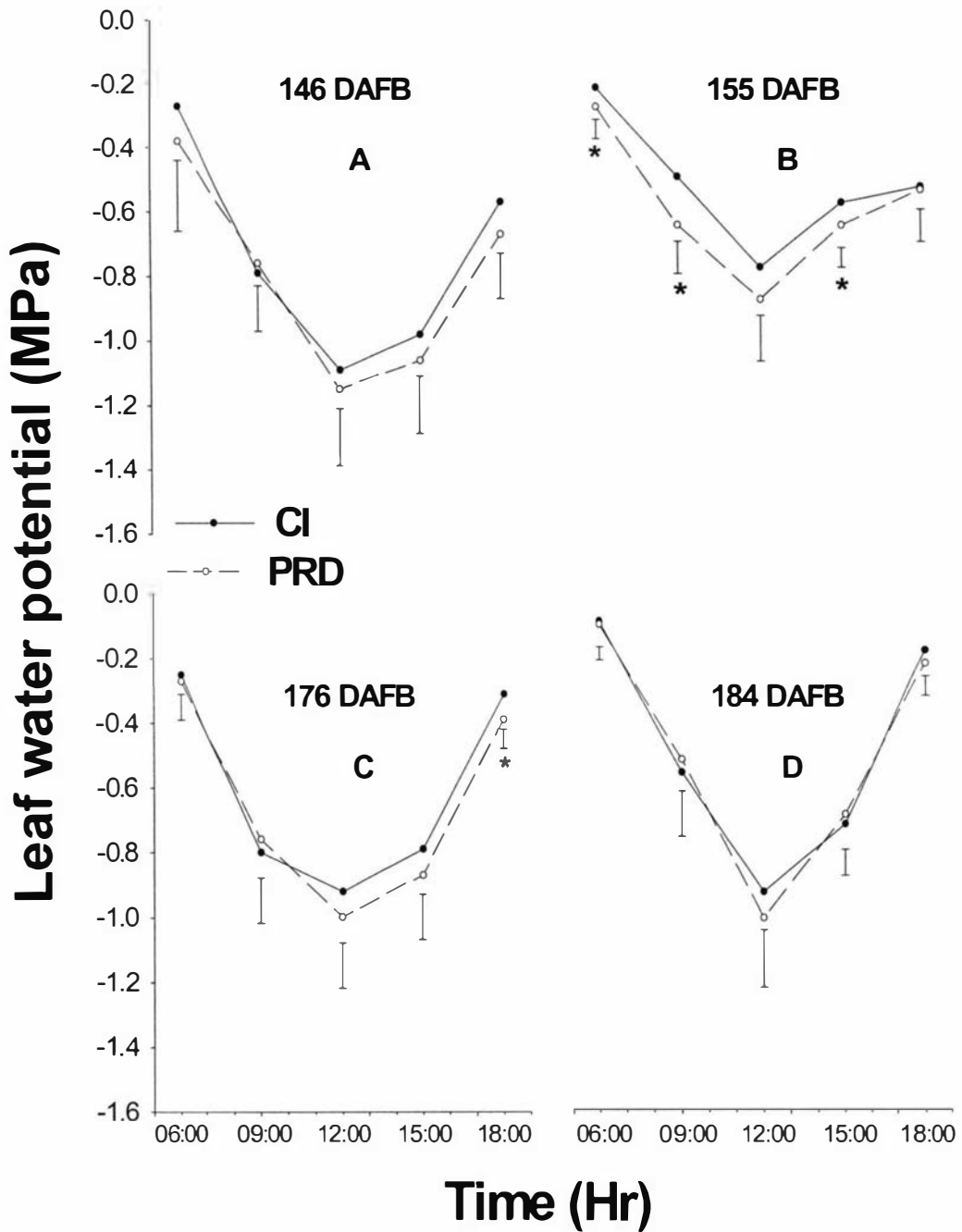
## 6.3 Results

### 6.3.1 Pre-harvest parameters

Volumetric soil water content ( $\theta$ ) was alternatively increasing and decreasing during the growing season as the irrigation was shifted from one side of the tree row to the other (Figure 6.1). However, the difference between side one and side two of the tree row was not significant during the growing season (Figure 6.1). Drying one side of the PRD tree row resulted in a significant reduction in  $\Psi_{\text{leaf}}$  at 06:00, 09:00, and 15:00 hours on 155 DAFB (Figure 6.2B) and at 18:00 hours on 176 DAFB (Figure 6.2C).



**Figure 6.1** Changes in the volumetric soil water content in commercially irrigated (CI) trees and in both sides of partial root zone drying (PRD) trees. Vertical bars represent the least significant difference (LSD) at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .



**Figure 6.2** Diurnal changes in leaf water potential in commercially irrigated (CI) and in partial rootzone drying (PRD) trees. Vertical bars represent the LSD at  $P \leq 0.05$  and the asterisks indicate significant differences at  $P \leq 0.05$ .

The rate of photosynthesis (A) was higher in PRD trees than in CI trees on 176 DAFB, but stomatal conductance ( $g_s$ ) was the same between treatments (Table 6.1). A and  $g_s$  values were the same between treatments in the other sampling dates (Table 6.1).

**Table 6.1** Effect of commercial irrigation (CI) and partial root zone drying (PRD) on photosynthesis and stomatal conductance of 'Pacific Rose™' apple. Photosynthetic photon flux (PPF  $\pm$  SD) values are also presented. Means within columns followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

Parameter		Days after full bloom				Mean
		146	155	176	184	
Photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	CI	8.5a	13.7a	9.0b	10.9a	10.5a
	PRD	10.2a	11.5a	11.6a	10.8a	10.8a
Stomatal conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ )	CI	1.0a	1.4a	0.8a	0.7a	1.0a
	PRD	1.1a	1.3a	0.6a	0.7a	1.0a
PPF ( $\mu\text{mol m}^{-2} \text{s}^{-1} \pm \text{SD}$ )		1052	1126	1167	1185	
		$\pm 495$	$\pm 622$	$\pm 234$	$\pm 374$	

Yield, mean fresh mass per fruit, yield efficiency, trunk cross-sectional area, and final shoot growth were the same between treatments, but the irrigation use efficiency improved in PRD trees relative to CI trees (Table 6.2). Except for fruit dry mass concentration, which was higher in CI fruit than in PRD fruit, the remaining fruit quality attributes were the same between treatments (Table 6.3).

**Table 6.2** Effect of commercial irrigation (CI) and partial rootzone drying (PRD) on mean fresh mass per fruit (MFMF), yield efficiency, trunk cross-sectional area (TCSA), final shoot growth (FSG), and irrigation use efficiency (IUE) of 'Pacific Rose™' apples. Means within columns followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

	Gross yield ( $\text{kg tree}^{-1}$ )	MFMF (g)	Yield efficiency ( $\text{kg tree}^{-1}/\text{cm}^2 \text{TCSA}$ )	TCSA ( $\text{cm}^2$ )	FSG (mm)	IUE ( $\text{kg L}^{-1} \text{H}_2\text{O}$ )
CI	18.7a	281.4a	0.53a	35.7a	30.1a	0.05b
PRD	18.0a	273.2a	0.58a	33.5a	24.9a	0.11a

**Table 6.3** Effect of commercial irrigation (CI) and partial root zone drying (PRD) on dry mass concentration of fruit (DMCF), internal ethylene concentration (IEC), starch pattern index (SPI), flesh firmness (FF), total soluble solids concentration (TSSC), and fruit skin colour in terms of hue angle (HA°). Means within columns followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

	DMCF (mg g <sup>-1</sup> fresh mass)	IEC (μL L <sup>-1</sup> )	SPI	FF (N)	TSS (%)	HA°
CI	146a	0.63a	4.0a	90.1a	13.4a	30.8a
PRD	137b	0.83a	4.4a	89.5a	13.4a	31.9a

### 6.3.2 Post-harvest parameters

In a second fruit quality evaluation, IEC, SPI, FF, and TSSC were similar between treatments (Table 6.4) as shown previously (Table 6.3). After 10 weeks in storage at  $0 \pm 1$  °C, SPI, FF, TSSC, and HA° were the same between treatments, but IEC was higher in PRD fruit compared to CI fruit (Table 6.5). Except for FF which was lower for PRD fruit (Table 6.6), IEC, SPI, TSSC, and HA° were the same after 16 days of storage at  $20 \pm 1$  °C between the two treatments. PRD fruit induced lower FF compared to CI fruit (Table 6.6). Fruit water loss was the same between treatments when the fruit were stored at  $0 \pm 1$  °C and at  $20 \pm 1$  °C (Figure 6.3). Return bloom, recorded during spring 2002, was similar between treatments. The values (number of flowers clusters per mm<sup>2</sup> of shoot cross sectional area) were 0.56 and 0.58 for CI and PRD trees, respectively.

**Table 6.4** Influence of commercial irrigation (CI) and partial root zone drying (PRD) on internal ethylene concentration (IEC), starch pattern index (SPI), flesh firmness (FF), and total soluble solids concentration (TSSC) of 'Pacific Rose™' apple at harvest. Means within columns followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

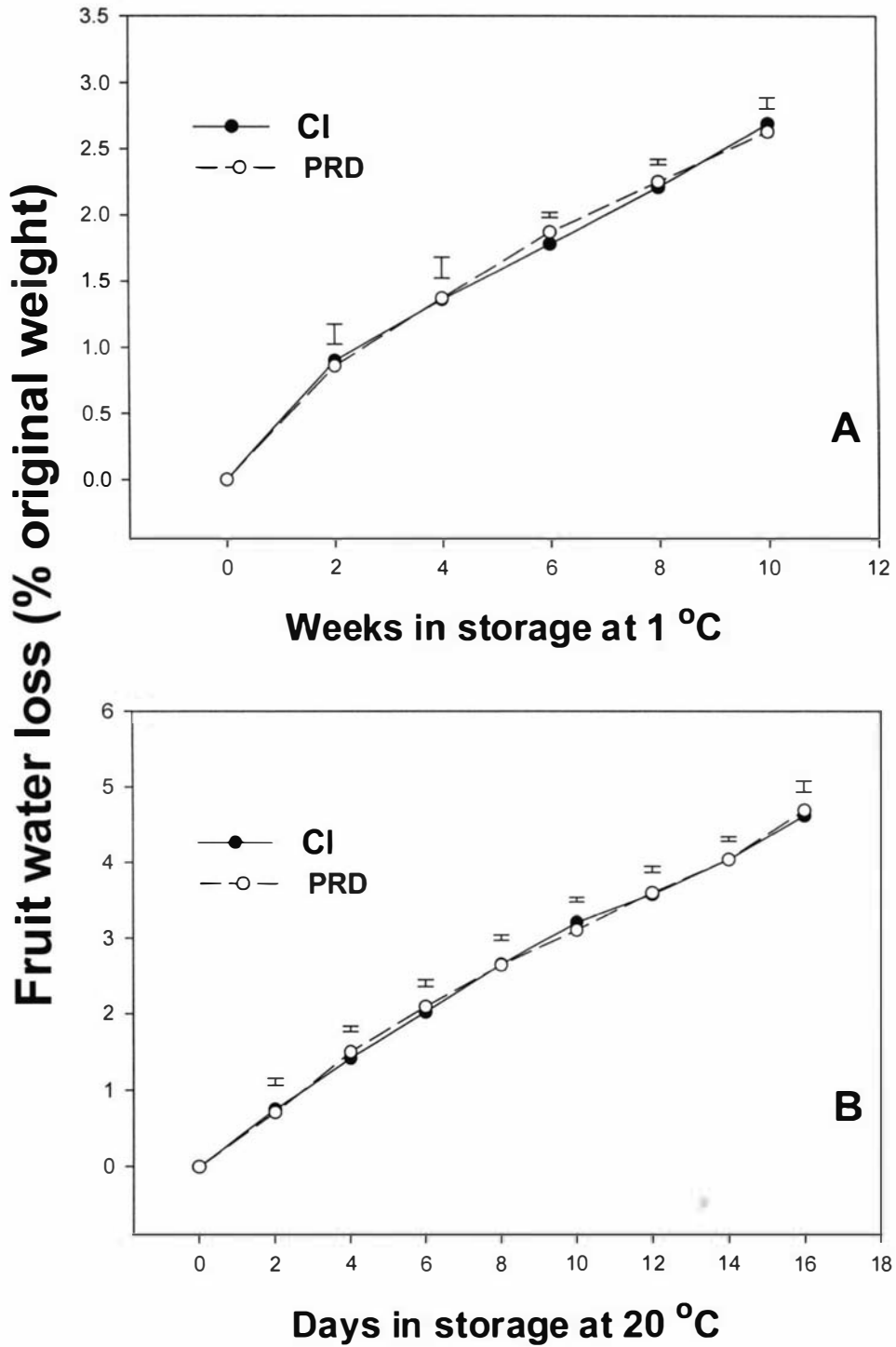
	IEC ( $\mu\text{L L}^{-1}$ )	SPI	FF (N)	TSSC (%)
CI	1.1a	4a	85a	13.4a
PRD	1.8a	5a	84a	12.9a

**Table 6.5** Influence of commercial irrigation (CI) and partial root zone drying (PRD) on fruit quality of 'Pacific Rose™' apple after 10 weeks in storage at  $0 \pm 1$  °C. Internal ethylene concentration (IEC), starch pattern index (SPI), flesh firmness (FF), total soluble solids concentration (TSSC), and fruit skin colour in terms of huge angle ( $\text{HA}^\circ$ ) are presented. Means within columns followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

	IEC ( $\mu\text{L L}^{-1}$ )	SPI	FF (N)	TSSC (%)	$\text{HA}^\circ$	
					At harvest	After storage
CI	18.6b	6a	84a	14.4a	31.6a	29.4a
PRD	27.5a	6a	86a	14.5a	29.5a	29.6a

**Table 6.6** Influence of commercial irrigation (CI) and partial root zone drying (PRD) on fruit quality of 'Pacific Rose™' apple after 16 days in storage at  $20 \pm 1$  °C. Internal ethylene concentration (IEC), starch pattern index (SPI), flesh firmness (FF), total soluble solids concentration (TSSC), and fruit skin colour in terms of huge angle ( $\text{HA}^\circ$ ) are presented. Means within columns followed by the same letter are not significant different by LSD test at  $P \leq 0.05$ .

	IEC ( $\mu\text{L L}^{-1}$ )	SPI	FF (N)	TSSC (%)	$\text{HA}^\circ$	
					At harvest	After storage
CI	35.3a	6a	85.2a	14.7a	35.0a	34.4a
PRD	36.7a	6a	73.6b	15.2a	34.7a	32.4a



**Figure 6.3** Cumulative fruit water loss as percentage of original weight during storage at  $0 \pm 1$  °C (A) and at  $20 \pm 1$  °C (B) for 10 weeks and 16 days, respectively, of 'Pacific Rose™' apple under commercial irrigation (CI) and partial rootzone drying (PRD). Vertical bars represent the LSD at  $P \leq 0.05$ .

## 6.4 Discussion

Although  $\theta$  was simultaneously increasing and decreasing between both sides of the row in PRD trees (Figure 6.1), this in general, was not reflected in significant changes on diurnal  $\Psi_{\text{leaf}}$  between CI and PRD trees (Figure 6.2). The unusual amount of rain occurring during the fruit growth and long cloudy periods could override the effect of PRD by reducing transpiration (Green and Clothier, 1995) and result in no measurable effect of treatments on  $\Psi_{\text{leaf}}$ . The monthly precipitation (mm) was: 166, 74, 102, 81, and 56 for December (2001), and January, February, March, and April (2002), respectively. However,  $\Psi_{\text{leaf}}$ ,  $A$ , and  $g_s$  were taken in sunny days (Table 6.1), then the maintenance in  $\Psi_{\text{leaf}}$  in PRD trees may be explained also by the increase in rate of water absorption by the roots in the wetted soil as observed in apple roots by Green et al. (1997). Also, Green and Clothier (1995) observed that the roots of kiwifruit vines, that had been water deprived previously, enhanced the water absorption when re-watered. Both mechanisms may take place in apple roots to keep similar  $\Psi_{\text{leaf}}$  in PRD trees to those of CI trees. Another important aspect is that the root system of apple is explorative and therefore they have the ability to explore large volumes of soil and to extract water from regions where it is more freely available (Green et al., 1997). This could take place here, hence  $\Psi_{\text{leaf}}$  in PRD trees became comparable to that observed in CI trees. The maintenance in diurnal  $\Psi_{\text{leaf}}$  in PRD trees agreed with those observed for grapevine by Loveys et al. (2000), but I did not observe reduction in  $g_s$  as Loveys et al. (2000) did. However,  $\Psi_{\text{leaf}}$ ,  $A$ , and  $g_s$  were also similar between CI and PRD tomato plants (Zegbe et al., 2003b).

$\Psi_{\text{leaf}}$  in both treatments did not account, in general, for a significant effect on  $A$  and  $g_s$ . (Table 6.1). However, lower  $A$  was observed in CI trees in comparison with PRD trees, but  $g_s$  was similar between treatments. Therefore, this was indicative that  $A$  could be impaired by biochemical activity (Lauer and Boyer, 1992). This was further investigated by the ratios of leaf internal  $\text{CO}_2$  concentration to that of the air ( $P_i/P_a$ ), which was significantly higher in CI trees. The values were 0.90 and 0.86 for CI and PRD trees, respectively. Higher  $P_i/P_a$  in CI trees suggested that  $A$  might have been biochemically limited when measurements were taken, because this did not negatively affected yield or other yield parameters.

As the basic physiological parameters were not adversely affected by PRD, this did account for the maintenance of fruit mass accumulation, therefore yield and yield components became similar between treatments. To this respect, Kang et al. (2002) observed that number of fruit (NF) was significantly increased in PRD trees relative to CI trees. However, there were on average 89 more fruit in PRD trees over CI trees. In this experiment, there were 8 more fruit in PRD than in CI trees. Therefore, in the experiment of Kang et al. (2002), the higher NF in PRD trees suggests that the crop load was unadjusted at the start of their experiment. The observed yield in PRD trees resulted in an increase of more than 2-fold in the irrigation use efficiency (Table 6.2) as observed in pears by Kang et al. (2002). Although A was the same between treatments, DMC of fruit was lower in PRD fruit (Table 6.3). This is indicative that higher fruit respiration must have occurred during the fruit growth in PRD trees, hence TSSC became the same between treatments. The slight increases in IEC and higher SPI are indicative of fruit maturity advancement (Kingston, 1991) in PRD fruit, which would support the reduction in DMC in that fruit. Although PRD fruit showed some differences in fruit maturity advancement, it is concluded that fruit quality was generally similar between treatments.

On a second fruit quality evaluation, PRD fruit had higher IEC and higher score of SPI compared to CI fruit (Table 6.4), which would support the advancement in maturity of PRD fruit. After 10 weeks in storage at 0 °C, the starch in both CI and PRD fruit had been converted to sugars because SPI had the highest value, but IEC was found still higher in PRD fruit compared to CI fruit (Table 6.5). Except for FF, after 16 days in storage at 20 °C, a similar pattern in IEC, SPI, TSSC, and HA° was observed between treatments. FF was lower in PRD fruit after 16 days of storage at 20 °C. Reduced firmness is indicative of a lower cellular density in large sized fruit (Westwood, 1993. p. 264-265). However, cellular density, measured here as fruit density (Fden, g cm<sup>-3</sup>) and fruit size (g) measured here as MFMF, was the same between treatments. The values for Fden were: 0.86 and 0.86 for CI and PRD fruit, respectively. The values for MFMF were: 328.3 and 317.2 for CI and PRD fruit, respectively. This suggests that other factors besides fruit size were involved in the reduction in FF for PRD fruit.

After harvest fruit continue respiring and transpiring. This can result in fruit water loss (FWL) (Mpelasoka et al., 2000). Excessive FWL has negative implications for fruit destined for distant markets and long-term storage (Meberg et al., 2000). In this study FWL was the same between treatments when fruit was stored at 1 and at 20 °C (Figure 6.3). This suggests that PRD did not induce significant changes in the cuticle of the fruit to reduce FWL as assumed in the Experiment 1, either observed in peaches (Crisosto et al., 1994) or hypothesised in apples exposed to deficit irrigation (Kilili et al., 1996b; Mpelasoka et al., 2000).

## 6.5 Conclusions

The study showed that drip-irrigated PRD trees did not experience significant changes in  $\Psi_{leaf}$ ,  $A$ , and  $g_s$ . Yield and yield components were the same between treatments, and the irrigation use efficiency improved more than 2-fold in PRD trees. Fruit quality, in general, was not enhanced by PRD, but PRD seemed to advance fruit maturity. Fruit performance in storage was similar between treatments at  $0 \pm 1$  °C and at  $20 \pm 1$  °C for 10 weeks and 16 days, respectively. PRD used 50% less water than CI without negative effects on either yield or quality. Therefore this irrigation method could be suggested as a water saving practice.

## Chapter 7<sup>1</sup>

### Comparing partial rootzone drying and deficit irrigation for their effects on water relations, growth, and yield of processing tomatoes

#### 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 ‘Petopride’, a processing tomato cultivar. The treatments were: full irrigation (FI) of both sides of the root system (RS) at each irrigation considered as the control, half of the irrigation water in FI divided equally to both sides of the RS with each watering (DI), and half of the irrigation water in FI given only to one side of the RS with each irrigation (PRD). Photosynthetic rate, stomatal conductance and leaf water potential were measured on five occasions, and were found to be the same among treatments. Total fresh mass of fruit (TFMF) was lower in DI and PRD than in FI, but total dry mass of fruit was the same among treatments. Irrigation use efficiency, in terms of TFMF ( $IUE_{TFMF}$ ), was higher in DI and PRD than in FI. Total vegetative fresh mass was not affected by the treatments. However, compared with FI plants, total vegetative dry mass was higher in DI and PRD plants. A higher percentage of dry mass was partitioned into stems and leaves in DI

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<sup>1</sup> This chapter has been accepted for publication by the *Journal of Vegetable Crop Production* under the same title and the following authors:

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A short communication from this chapter is in press in *Scientia Horticulturae* under the same authors and the following title:

**Deficit irrigation and partial rootzone drying maintain fruit dry mass and enhance fruit quality in ‘Petopride’ processing tomato (*Lycopersicon esculentum*, Mill.)**

and PRD plants than in FI plants and this was the opposite for the fruit. Total fresh mass of fruit was affected by the quantity of irrigation water applied, but not by the volume of soil wetted. Fruit water content was lower in DI and PRD fruit than in FI fruit. Total soluble solids concentration was higher in DI and PRD fruit than in FI fruit. The DI and PRD fruit were redder than FI fruit. Both DI and PRD treatments were found to be feasible water-saving practices for 'Petopride'.

## 7.1 Introduction

Water supply is limited worldwide (Postel, 1998) and there is an urgent need to identify and adopt effective irrigation management strategies. Tomato has the highest acreage of any vegetable crop in the world (Ho, 1996a), therefore adoption of deficit irrigation (DI) and partial rootzone drying (PRD) could make substantial contribution to saving of water. Deficit irrigation, where only a portion of evapotranspiration is given to plants over the entire root system (RS), has been assessed for tomato with mixed results. Pulpol et al. (1996) observed a significant reduction in dry matter yield for a glasshouse cultivar, while Mitchell et al. (1991a) 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 complement 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 by Loveys et al. (2000). PRD has not been studied for tomatoes and this technique might be more relevant for processing cultivars that are normally grown in the field. Our experiment was done using the processing cultivar 'Petopride' with the objective of comparing the effects of DI and PRD on water relations, photosynthesis, yield,  $IUE_{TFMF}$ , and dry mass partitioning. The rootzone was expected to remain partially moist in the PRD treatment and therefore plant water potential could be maintained. For this reason we hypothesised 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 minimise the adverse effects that frequently changing weather might have on plant responses.

## 7.2 Materials and methods

### 7.2.1 Experimental conditions and plant material

The experiment was conducted in a naturally-lit glasshouse (6.68 m width x 7.30 m length) with ventilation/heating set points of 25/15 °C 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 were sown on 22 January 2001 and seven-week-old individual 'Petopride' processing tomato plants (Webling & Stewart Seeds, Onehunga, Auckland, NZ) were transplanted into nine wooden boxes (spaced 1.64 x 0.70 m) each housing three compartments (600 mm length x 600 mm width x 200 mm depth) with one experimental plant per compartment. Plant spacing was 2.34 x 0.63 m. They were grown in a bark:pumice:peat mixture comprising 60:30:10 by volume. Media volume per compartment was 0.072 m<sup>3</sup>. They 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).

### 7.2.2 Treatments and soil water measurements

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

Saturation and field capacity (FC) for this growing medium and their relationship with volumetric soil water content ( $\theta$ ) were determined before setting up the experiment following Parchomchuk et al. (1997). Field capacity was reached at a  $\theta$  of  $0.20 \text{ m}^3 \text{ m}^{-3}$ . The amount of water to be applied was calculated by using  $\theta$  readings in the control before each irrigation. The value of  $\theta$  was also recorded after each daily irrigation as described in Chapter 3 (Section 3.1). 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 600 mm x 200 mm. The treatments started with full irrigation and then the south side (Side 2) of RS for the PRD treatment was allowed to dry while the north side (Side 1) was irrigated. Irrigation in PRD was shifted from the wet side to the dry side when the value of  $\theta$  ranged between  $0.02$  and  $0.10 \text{ m}^3 \text{ m}^{-3}$  in the latter side.

### 7.2.3 Physiological parameters

Midday leaf water potential ( $\Psi_{\text{leaf}}$ ), photosynthetic rate ( $A$ ), transpiration ( $E$ ), and stomatal conductance ( $g_s$ ) were measured as described in Chapter 3 (Sections 3.2.2 and 3.3). Measurements were taken on two leaves per plant between 11:30 and 13:30 hours. This was done on five occasions and the values for only two of them, which are typical for other measurements, are presented here. The presented data are for 108 and 160 days after sowing (DAS) which corresponded to fruit-set and prior to harvest, respectively.

### 7.2.4 Yield and irrigation use efficiency

There was a single harvest during which fruit were weighed and total fresh mass of fruit (TFMF) and total dry mass of fruit (TDMF) assessed as described in Chapter 3 (Section 3.5.2 and 3.6). Total vegetative fresh mass and total vegetative dry mass was obtained as detailed in Chapter 3 (Section 3.6). Irrigation use efficiency in terms of TFMF ( $IUE_{\text{TFMF}}$ ) was calculated as described in Chapter 3 (Section 3.5.5). Dry mass distribution was obtained as described in Chapter 3 (Section 3.6).

### 7.2.5 Fruit quality assessment

From the first trusses, over four harvests, 45 fruit per treatment (five fruit per replication) were randomly chosen at the firm red stage for quality measurements. Background skin colour, in terms of hue angle ( $HA^\circ$ ), and total soluble solids concentration (TSSC) were measured as detailed in Chapter 3 (Sections 3.8.2 and 3.8.4). After sampling for TSSC, the fruit were oven-dried at  $85^\circ\text{C}$  to a constant weight for measurement of TDMF. Fruit water content was calculated as described in Chapter 3 (Section 3.8.6).

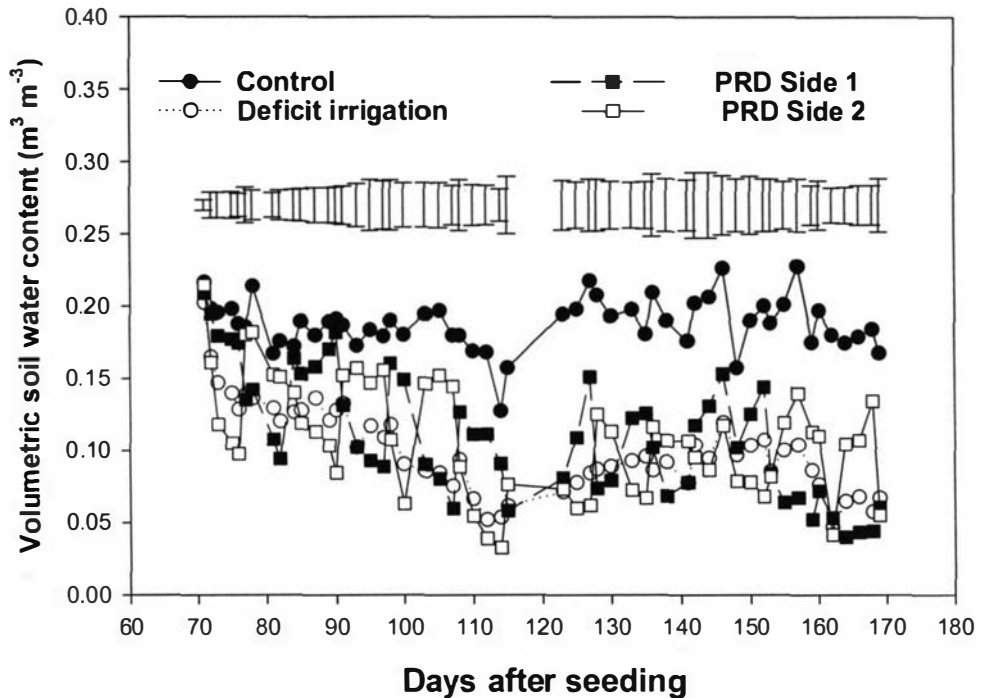
### 7.2.6 Statistical analysis

The data were analysed by randomised complete block model using GLM procedure of SAS. To stabilise the variance, the variables expressed in percentage and in discrete unit were arcsine- and square-root transformed, respectively, as mentioned in Chapter 4 (Section 4.3). Means are reported after back transforming. Treatment means were separated by least significant difference (LSD) test at  $P \leq 0.05$ .

## 7.3 Results

### 7.3.1 Volumetric soil water content

Generally, the  $\theta$  values were significantly lower in DI and in both sides of the row of PRD treatment (Figure 7.1).



**Figure 7.1** Changes in volumetric soil water content in the control, deficit irrigation, and north and south sides of partial rootzone drying (PRD) treatments. Vertical bars represent the least significant difference (LSD) at  $P \leq 0.05$ .

### 7.3.2 Physiological parameters

For the five measurement occasions, values of  $\Psi_{\text{leaf}}$ ,  $A$  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 7.1. Although  $E$  was higher on 108 DAS than on 160 DAS,  $A$  was lower in the former (Table 7.1). The vapour pressure deficit was lower on 108 DAS than on 160 DAS. The values ( $\text{mb} \pm \text{SEM}$ ) were  $13.2 \pm 0.2$  and  $25.8 \pm 0.5$  for, respectively, 108 DAS and 160 DAS. This accounts for the higher  $g_s$  on the former day (Atwell et al., 1999, p. 469-470). The higher  $g_s$  could not have promoted  $A$  on 108 DAS because of low radiation (Table 7.1). Although higher  $g_s$  on 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.

**Table 7.1** Effect of irrigation treatments (ITs) on leaf water potential ( $\Psi_{\text{leaf}}$ , MPa), net photosynthesis rate ( $A$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), transpiration rate ( $E$ ,  $\text{mmol m}^{-2} \text{s}^{-1}$ ), and stomatal conductance ( $g_s$ ,  $\text{mol m}^{-2} \text{cm s}^{-1}$ ) for tomato plants. Values of photosynthetic photon flux (PPF,  $\mu\text{mol m}^{-2} \text{s}^{-1} \pm \text{SD}$ ) are also shown. Means with same letters within columns are not significantly different using the LSD test at  $P \leq 0.05$ .

ITs	Days after seeding							
	108				160			
	$\Psi_{\text{leaf}}$	$A$	$E$	$g_s$	$\Psi_{\text{leaf}}$	$A$	$E$	$g_s$
FI	-0.48a	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	213 $\pm$ 74				456 $\pm$ 193			

### 7.3.3 Yield and irrigation use efficiency

Total fresh mass of fruit (TFMF) was lower in DI and PRD treatments than in FI treatment (Table 7.2). The DI and PRD plants had significantly lower number of fruit (NF) than the FI plants. The values of NF were 51, 57, and 64, respectively. However, total dry mass of fruit was not affected ( $P \leq 0.06$ ) by the treatments although there was a reducing trend in the following order: FI, PRD, and DI.  $IUE_{\text{TFMF}}$  was higher in DI and PRD plants than in FI plants. TFMF was, however, the same between DI and PRD treatments, suggesting that the quantity of water was more important to yield than was the volume of soil irrigated. Total vegetative fresh mass (including roots) was the same for all treatments. But total vegetative dry mass (including roots) was higher in DI and PRD treatments than in FI treatments (Table 7.2).

**Table 7.2** Effect of irrigation treatments (ITs) on total mass of fruit per plant, irrigation use efficiency ( $IUE_{TFMF}$ ), and total vegetative mass per plant. Means with same letters within columns are not significantly different using the LSD test at  $P \leq 0.05$ .

ITs	Total mass of fruit			Total vegetative mass	
	Fresh	Dry	$IUE_{TFMF}$ (g L <sup>-1</sup> )	Fresh	Dry
	(kg plant <sup>-1</sup> )	(g plant <sup>-1</sup> )		(kg plant <sup>-1</sup> )	(g plant <sup>-1</sup> )
FI	5.4a	253a	24b	1.4a	122.0b
DI	4.4b	248a	39a	1.4a	130.7a
PRD	4.4b	251a	39a	1.4a	132.8a

### 7.3.4 Dry mass distribution

Percentage values of dry mass partitioned into roots, stems, leaves, and fruit are presented in Table 7.3. 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 FI plants. However, dry mass partitioning into fruit was highest for FI plants (Table 7.3).

**Table 7.3** Effect of irrigation treatments (ITs) on dry mass partitioning of tomato plants. Means with same letters within columns are not significantly different using the LSD test at  $P \leq 0.05$ .

ITs	Dry mass distribution per plant (%)			
	Root	Stems	Leaves	Fruit
FI	1.4a	16.6b	13.2b	68.8a
DI	1.8a	19.0a	14.6ab	64.6b
PRD	1.5a	18.4a	15.4a	64.7b

### 7.3.5 Fruit quality assessment

The fruit water content (FWC) was lower and skin colour in terms of hue angle (HA°) was redder in DI and PRD fruit than in FI fruit, but the total soluble concentration (TSSC) was higher in DI and PRD fruit than in FI fruit (Table 7.4).

**Table 7.4** Effect of irrigation treatments (ITs) on fruit water content (FWC), total soluble solids concentration (TSSC), and fruit colour in terms of hue angle (HA°). Different letters within columns indicate differences by the LSD test at  $P \leq 0.05$ .

Its	FWC	TSSC	HA°
	(%)	(%)	
FI	95.1a	4.18b	48.29a
DI	94.6b	4.66a	46.46ab
PRD	94.5b	4.54a	46.03b

## 7.4 Discussion

Here I focus on the effects of the irrigation treatments on plant water relations and gas exchange properties, fresh and dry mass of different parts of the plant, dry mass partitioning in the plant, and I provide an assessment of PRD as a management tool. Values of  $\Psi_{\text{leaf}}$ ,  $A$ ,  $E$ , and  $g_s$  remained unaffected by the treatments for the five occasions I 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  $400 \mu\text{mol m}^{-2} \text{s}^{-1}$  (Venema et al., 1999). During a sunnier day the PPF values averaged at  $456 \mu\text{mol m}^{-2} \text{s}^{-1}$  (160 DAS, Table 7.1) resulting in a decreasing trend in  $\Psi_{\text{leaf}}$  for FI, DI, and PRD in this order. However, radiation was very variable on this day, hence the large value of standard deviation (SD) in Table 7.1, with no measurable effect of treatments on  $A$ ,  $E$ , 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 their deficit-irrigated trees had the same low levels of photosynthesis as did their fully-watered control on a cloudy day.

Growth is the plant parameter most sensitive to water deficit (Hsiao, 1973) and the decrease in fresh mass of the DI and PRD fruit, compared to the FI fruit (Table 7.2), indicates that a degree of 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. The tomato fruit contains at least 92%

water most of which is transported to the fruit through the phloem and is reduced during a mild water deficit, although photoassimilates continue to be transported to the fruit (Ho, 1999). This might have been a reason that the fruit fresh mass in the DI and PRD was lower than in the FI fruit, while the fruit dry mass was similar among treatments (Table 7.2).

In the DI and PRD plants, a lesser proportion of dry mass was partitioned into the fruit than in the FI plants (Table 7.3). The DI and PRD fruit had significantly lower water content than the C fruit (Table 7.4). The DI and PRD fruit also had a higher concentration of total soluble solids than the FI fruit (Table 7.4). Although we did not measure fruit water potential, lower water content and higher soluble solid concentration in DI and PRD fruit than in FI 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 FI fruit, as demonstrated for the roots of *Phaseolus vulgaris* by Lang and Thorpe (1986). We therefore expect more partitioning 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 FI fruit as shown for 'Virosa' cultivar by Pulupol et al. (1996). Cantore et al. (2000), for a split-root experiment, reported a dry mass partitioning pattern for *Capsicum annuum* similar to our PRD treatment (Table 7.3).

The higher yield, in terms of total fresh mass of fruit, in FI than in DI and PRD treatments indicates the importance of water quantity applied, while the similarity of total fresh mass of fruit between DI and PRD shows that it does not matter what volume of soil is wetted with each irrigation (Table 7.2). Tan et al. (1981) reported that for tomato irrigating part of the rhizosphere (ca 50%) could be enough to meet plant's water requirements rather than irrigating the entire root system.

The FWC was lower in DI and PRD than in FI (Table 7.4), and this is preferred by the processing industry because less energy would be needed to evaporate water from the fruit. The TSSC in fruit was higher in DI and PRD than in FI (Table 7.4), which is also important for processing industry (Mitchell et al., 1991a). The TSSC and FWC were highly correlated ( $r = -0.80$  and  $P \leq 0.0001$ ) and therefore the increased TSSC in the DI

and PRD fruit might have been due to a lower fruit water content. Higher conversion of starch to sugars under water deficit (Kramer, 1983, p. 364) could be another reason.

Although differences in red fruit colour were not visible among treatments at harvest and fruit were picked based on visual colour uniformity, PRD fruit had the lowest hue angle (Table 7.4) and were therefore redder. A higher lycopene accumulation under water deficit has been speculated as a reason by Pulupol et al. (1996). The PRD fruit were ready for picking one week before the other treatments and this has positive implications in terms of marketing. This advancement in fruit maturity observed in PRD treatment deserves further study.

## 7.5 Conclusions

I did this experiment to assess DI and PRD as water-saving irrigation techniques. In both DI and PRD treatments total dry mass of fruit was maintained and irrigation water was saved by 50%, compared to FI plants.  $IUE_{TFMF}$  increased 60% (Table 7.2). For processing tomatoes, a relative lower water content in fruit and higher total soluble solids concentration are important fruit quality attributes for marketing (Ho, 1999). These attributes were improved by DI and PRD treatments. In both DI and PRD treatments, the dry mass concentration in the fruit was similar to FI fruit. Therefore PRD and DI could both be considered as feasible irrigation strategies for the production of processing tomatoes. However, field research at a more stressful time of the year is needed to corroborate these results.

## Chapter 8

### Maintenance of yield and fruit quality in processing tomatoes by partial rootzone drying

#### Abstract

Drip irrigation is more efficient in water application and precision placement than other irrigation systems, but this has not been tested under partial rootzone drying (PRD) irrigation. Therefore, PRD and DI were assessed using drip irrigation for their effects on water relations, photosynthesis, yield, plant growth, and fruit quality. The treatments were: daily full irrigation (FI) on both sides of the root system (RS) considered as the control, daily irrigation on one side of the RS with half the volume of water given to the control (PRD<sub>1</sub>), full irrigation every other day of both sides of the RS (DI), and irrigation only on one side of the RS at a time every other day with half the volume of water given to the control (PRD<sub>2</sub>). Photosynthetic rate ( $A$ ), stomatal conductance ( $g_s$ ), leaf water potential ( $\Psi_{\text{leaf}}$ ), total plant fresh mass, and total dry mass of fruit (TDMF) were lower in DI and PRD<sub>2</sub> plants than in FI and PRD<sub>1</sub> plants. Irrigation use efficiency was improved by 1.8 times in PRD<sub>1</sub> relative to FI. Dry matter partitioning into stems and leaves was increased, but total dry mass of fruit was reduced in DI and PRD<sub>2</sub> plants relative to FI and PRD<sub>1</sub> plants. Fruit quality in terms of fruit water content (FWC), total soluble solids concentration (TSSC), and fruit background skin colour ( $HA^\circ$ ) were the same for PRD<sub>1</sub> and FI. As levels of water deficit increased, so did the percentage of blossom-end rot, while leaf calcium concentration decreased. PRD<sub>1</sub> can be seen as a feasible water-saving irrigation protocol for processing tomatoes and might be important for production in areas where water is scarce.

## 8.1 Introduction

In Chapter 7  $\Psi_{\text{leaf}}$ ,  $A$ ,  $E$ , and  $g_s$  were studied in relation to DI and PRD. However, the results were not conclusive because most of the measurements had to be done in cloudy days and low radiation over-rode the possible effects on water deficit. TDMF was reduced by 11% in PRD plants relative to FI plants. Fruit quality; in terms of FWC, TSSC, and HA°; was improved in PRD and DI in comparison to FI plants. However, low radiation levels and low evaporative demand could have overestimated the benefits of PRD and DI. Also, the plants were irrigated mimicking furrow irrigation. This experiment was conducted during the spring and early summer using drip irrigation which is a more effective water-saving irrigation strategy.

Tomato production under DI has saved considerable amounts of water and reduced production cost (May and Gonzales, 1999). However, plant growth and fresh fruit yield have been reduced (Mitchell et al., 1991a; Pulupol et al., 1996), but TDMF has not (Mitchell et al., 1991b). Under DI plants inevitably experience water deficit because transpiration rate exceeds water supplied long-term, and then, the plant water status is reduced to such an extent that the plant's normal growth and development are adversely affected (Kramer, 1983, p. 343). This might not happen with PRD where part of the rhizosphere is kept moist.

Recent PRD experiments on grapes showed that stomatal conductance and transpiration rate decreased without changes in plant water status. This led to higher water use efficiency, but PRD's effect on yield was cultivar dependent (Loveys et al., 2000). In fact, in a short-term split-root tomato experiment, Tan et al. (1981) concluded that the entire root system of tomatoes does not need to be irrigated to maintain high rates of transpiration and photosynthesis as well as plant growth and yield comparable to fully irrigated plants. If this is true, DI's adverse effects on processing tomato might not happen under PRD. This could be possible if the well-watered part of the root accomplishes equilibrium between water absorption and transpiration rates so that total plant water potential is maintained and therefore allowing normal metabolic activity between source and sink. Green and Clothier (1999) have observed that when part of the apple root system is irrigated, water uptake is doubled by the wetted part.

The fruit quality of tomatoes, in terms of low FWC, HA°, and high TTSC, have been enhanced under DI (Mitchell et al., 1991a; Mitchell et al., 1991b; Pulupol et al., 1996; May and Gonzales, 1999). A reduced FWC and related increase in TSSC in processing tomatoes is desirable when paste production is the aim. The PRD plants might achieve this because less water would be supplied, but photosynthetic rate is not expected to reduce nor does the assimilate transport to the fruit. However, FWC could be reduced since less water will be applied. The objective of this study, therefore, was to compare the effect of PRD and DI on  $\Psi_{\text{leaf}}$ ,  $A$ ,  $g_s$ , yield, yield components, dry mass partitioning, and fruit quality of 'Petopride' processing tomatoes. PRD might be more relevant for processing tomatoes, which are normally grown in the field, rather than in glasshouse tomatoes. I also carried out this experiment by using drip-irrigation to improve water application efficiency and water precision supply in good agreement with water conservation strategies.

## **8.2 Materials and methods**

### **8.2.1 Experimental conditions and treatments**

The general experimental conditions and plant material were the same as detailed in Chapter 7 (Section 7.2.1). The experiment was conducted from July to December 2001. Seeds were sown on 31 July 2001 and 40-day old individual seedlings were transplanted and spaced as detailed in Chapter 7 (Section 7.2.1). In this experiment, twelve wooden boxes were used as described in Chapter 7 (Section 7.2.1) each housing four compartments. The compartments were improved in two aspects. Firstly, to avoid lateral water displacement, a small piece of wood (600 mm x 50 mm x 26 mm) was placed centrally on the base of each compartment. Secondly, the compartments were lined with black polyethylene with a thickness of 125  $\mu\text{m}$  and perforated laterally at the bottom to allow drainage.

Twenty-nine days after transplanting, the following four irrigation treatments were randomly applied to a total of 48 plants. The treatments were: daily full irrigation (FI)

on both sides of the root system (RS) considered as the control, daily irrigation on one side of the RS with half the volume of water given to the control (PRD<sub>1</sub>), full irrigation every other day of both sides of the RS (DI), and irrigation only on one side of the RS at a time every other day with half the volume of water given to the control (PRD<sub>2</sub>). The experiment was conducted in a completely randomised design with the four treatments replicated three times. There were four plants per treatment for each replication.

### **8.2.2 Measurements of soil water content**

Two drippers, that emitted 4 L per hour each, were placed 150 mm away from the main stem in the FI and DI treatments, while one emitter was used in PRD<sub>1</sub> and PRD<sub>2</sub> treatments, which was manually shifted over when needed. The plants were irrigated twice a day (7:00 and 18:00 hours) either daily or every other day for 30 minutes by an automated irrigation system. The PRD<sub>1</sub> and FI plants were daily irrigated with 4 and 8 L, respectively. Every other day 8 and 4 L were given to DI and PRD<sub>2</sub> plants, respectively. A total of 101, 202, 202, and 404 L of water (gross irrigation) per plant was applied during the experiment to PRD<sub>2</sub>, PRD<sub>1</sub>, DI, and FI, respectively. 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 was monitored every other day as described in Chapter 3 (Section 3.1). This was done when the irrigation was cut off in DI and PRD<sub>2</sub>.

### **8.2.3 Measurements of photosynthesis, stomatal conductance, and plant water status**

Photosynthetic rate ( $A$ ), stomatal conductance ( $g_s$ ), and photosynthetic photon flux (PPF) were measured on two leaves per plant between 12:00 and 13:30 hours as described in Chapter 3 (Section 3.3). This was done on 95, 119, and 137 days after seeding (DAS) when the irrigation was withheld in DI and PRD<sub>2</sub> treatments. Diurnal changes of leaf water potential ( $\Psi_{\text{leaf}}$ ) were made on the same dates on two leaves as

detailed in Chapter 3 (Section 3.2.2). Measurements were taken at 06:00, 10:00, 14:00, and 21:00 hours.

#### **8.2.4 Measurements of plant growth, yield, harvest index, irrigation use efficiency, and dry mass distribution**

There was a single harvest during which the number of fruit (NF), total fresh mass of fruit (TFMF), mean fresh mass per fruit (MFMF) were obtained as described in Chapter 3 (Section 3.5.2). Total dry mass of fruit (TDMF), total fresh mass of plant (TFMP), and total dry mass of plant (TDMP) were recorded as described in Chapter 3 (Section 3.6). Harvest index (HI) and irrigation use efficiency, in terms of TFMF ( $IUE_{TFMF}$ ), were calculated as detailed in Chapter 3 (Sections 3.5.4 and 3.5.5). Destructive harvests were done to assess changes in TDMP (including fruit and roots) by collecting one plant per replication per treatment. This was done on 95, 119, and 137 DAS (at harvest). Dry mass distribution was done as detailed in Chapter 3 (Section 3.6).

#### **8.2.5 Fruit quality assessment**

From the first trusses, 18 fruit per treatment (six per replication) were randomly chosen for quality measurements. They were weighed and considered for the assessment of TFMF and TDMF. Fruit with similar colour were collected at the green stage and colour development was evaluated for 14 days in terms of hue angle ( $HA^\circ$ ). After  $HA^\circ$  evaluation, fruit were assessed for TSSC as detailed in Chapter 3 (Sections 3.8.2 and 3.8.4). FWC was calculated as described in Chapter 3 (Section 3.8.6). Blossom-end root (BER) incidence was expressed in percentage of fruit affected per plant.

#### **8.2.6 Leaf mineral analysis**

Ten leaflets were taken randomly per treatment per replication for mineral analysis. Concentration of leaf  $K^+$ ,  $Ca^{2+}$ , and  $Mg^{2+}$  were determined as detailed in Chapter 3 (Section 3.8.8).

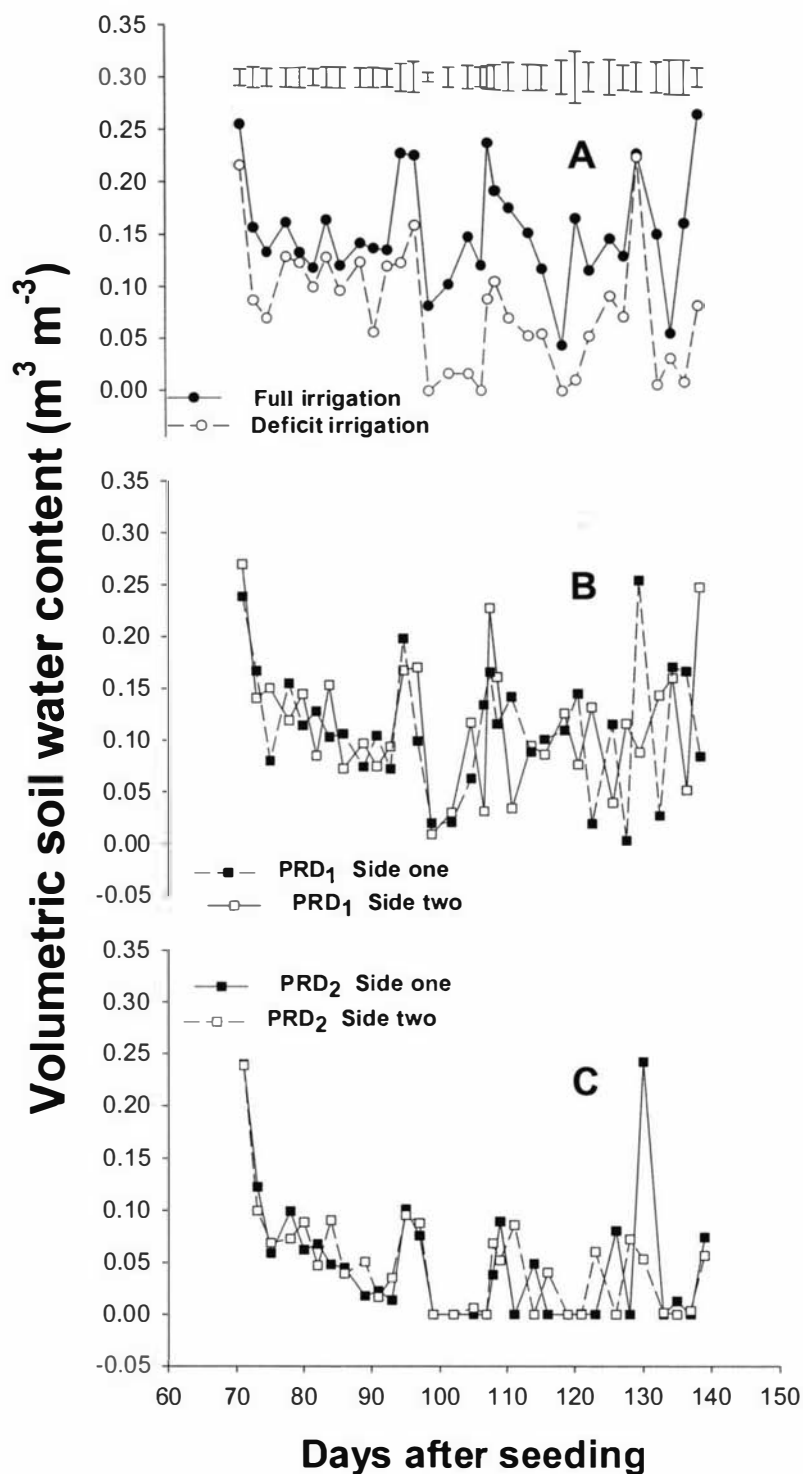
### 8.2.7 Statistical analysis

The data were analysed by a completely randomised model using the GLM procedure of SAS. To stabilise the variance, the variables expressed in percentage and in discrete unit were arcsine- and square-root transformed, respectively, as mentioned in Chapter 4 (Section 4.3). Means are reported after back transforming. Treatment means were separated by Tukey's test at  $P \leq 0.05$ .

## 8.3 Results

### 8.3.1 Volumetric soil water content

Generally,  $\theta$  ranged from high to low for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub>, respectively (Figures 8.1A-8.1C).  $\theta$  was simultaneously increasing or decreasing in both sides of the rhizosphere in PRD<sub>1</sub> and PRD<sub>2</sub> treatments during the experimental period (Figures 8.1B and 8.1C). The lowest  $\theta$  values were observed in DI and PRD<sub>2</sub> treatments, suggesting the irrigation was not enough for wetting the dry soil, hence slight changes in  $\theta$  (Figure 8.1C).

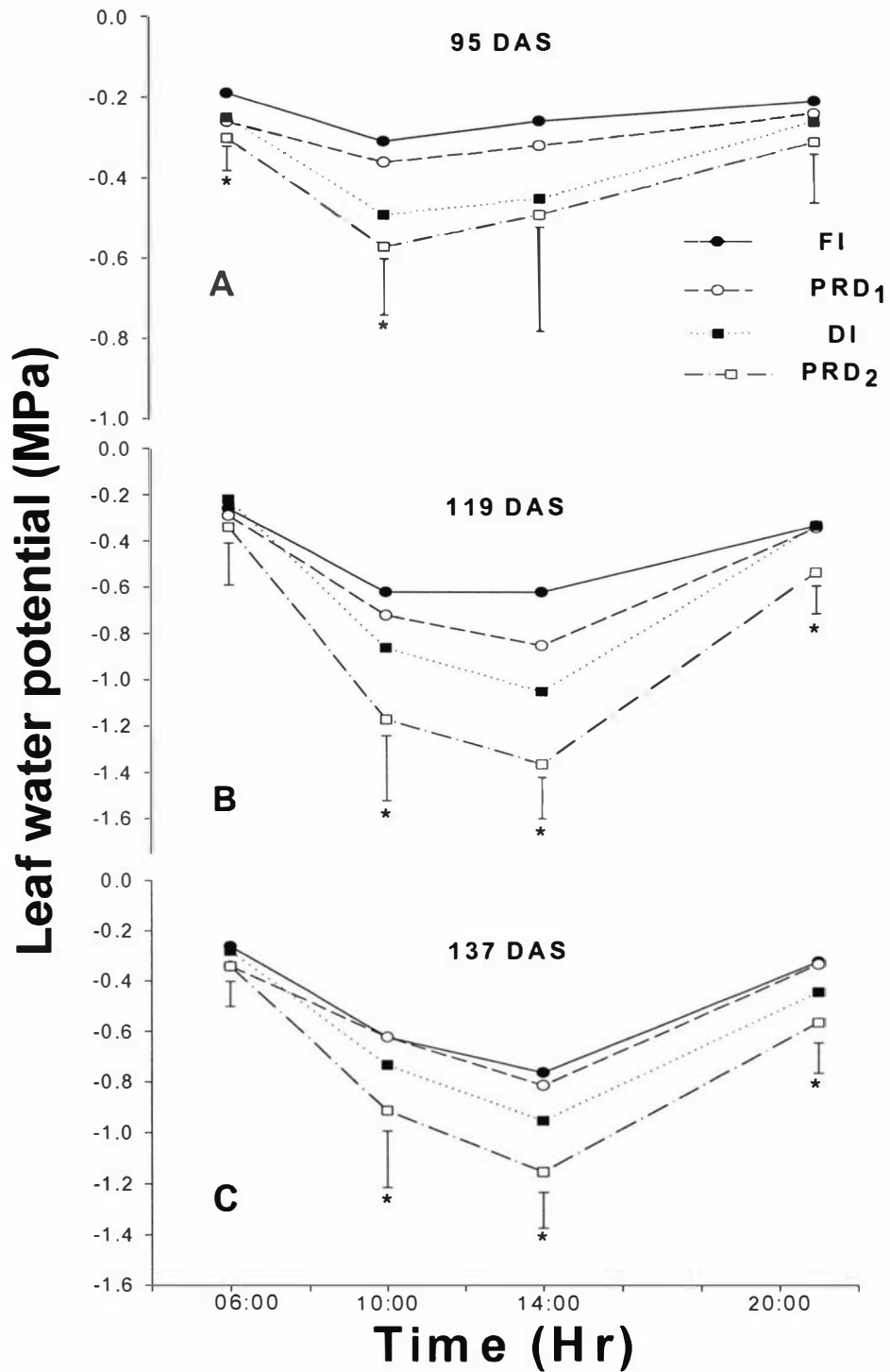


**Figure 8.1** Changes in soil water content for the full irrigation and deficit irrigation (A), the two sides of plant root system in PRD<sub>1</sub> (B) and in PRD<sub>2</sub> (C). The treatments are described in the text. Vertical bars represent the minimum significant difference (MSD) by Tukey's test at  $P \leq 0.05$ .

### 8.3.2 Plant water status, photosynthesis, and stomatal conductance

Leaf water potential ( $\Psi_{\text{leaf}}$ ) followed the typical diurnal pattern, decreasing from early morning, reaching a minimum value after midday, and then starting to recover in late afternoon (Figure 8.2). For DI and PRD<sub>2</sub> plants,  $\Psi_{\text{leaf}}$  was significantly lower during the morning and tended to recover in the early afternoon on 95 DAS. It remained unaffected through the diurnal cycle for FI and PRD<sub>1</sub> plants, suggesting that part of the rhizosphere may be allowed to dry without affecting  $\Psi_{\text{leaf}}$  (Figure 8.2A). On 119 and 137 DAS,  $\Psi_{\text{leaf}}$  of PRD<sub>2</sub>, was significantly lower from late morning to late afternoon than any other treatment (Figures 8.2B and 8.2C). The lowest  $\Psi_{\text{leaf}}$  values of PRD<sub>2</sub> in the afternoon suggest severe water deficit. The values (MPa) were -1.36 and -1.15 MPa on 119 and 137 DAS, respectively.

In general, A ranged from low to high for PRD<sub>2</sub>, DI, PRD<sub>1</sub>, and FI (Table 8.1). On 95 DAS, A was significantly higher in FI treatment than in any other treatment. This was not the case for 119 and 137 DAS, where PRD<sub>2</sub> had the lowest A compared with the other treatments. Similar results were observed for stomatal conductance ( $g_s$ ) (Table 8.1). However, the vapour pressure deficit was lower on 95 DAS than on 119 DAS and 137 DAS. The values (mb  $\pm$  SEM) were  $7.1 \pm 1.4$ ,  $23.45 \pm 4$ , and  $25.8 \pm 6.1$  for 95, 119, and 137 DAS, respectively. This accounts for the higher  $g_s$  on 95 DAS (Atwell et al., 1999, p. 469-470). The higher  $g_s$  could not have promoted A on 95 DAS because of low solar radiation (Table 8.1). However, the ratio of leaf internal CO<sub>2</sub> concentration to that of the air ( $P_i/P_a$ ) was significantly higher in PRD<sub>1</sub>, DI and PRD<sub>2</sub> relative to FI. The values ( $P_i/P_a \pm$  SEM) were  $0.95 \pm 0.02$ ,  $0.98 \pm 0.01$ ,  $0.98 \pm 0.01$ , and  $0.98 \pm 0.01$  for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub>, respectively. This is indicative of non-stomatal (mesophyll) limitation to photosynthesis (Lauer and Boyer, 1992; Srinivasa et al., 2000). In contrast, the  $P_i/P_a$  ratios along with  $P_i$  did follow  $g_s$  (data not shown) for PRD<sub>1</sub>, DI and PRD<sub>2</sub> on 119 DAS and 137 DAS. This indicates stomatal limitation to A because of water deficit (Farquhar et al., 1989).



**Figure 8.2** Diurnal changes of leaf water potential 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  $P \leq 0.05$ .

**Table 8.1** 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  $P \leq 0.05$ .

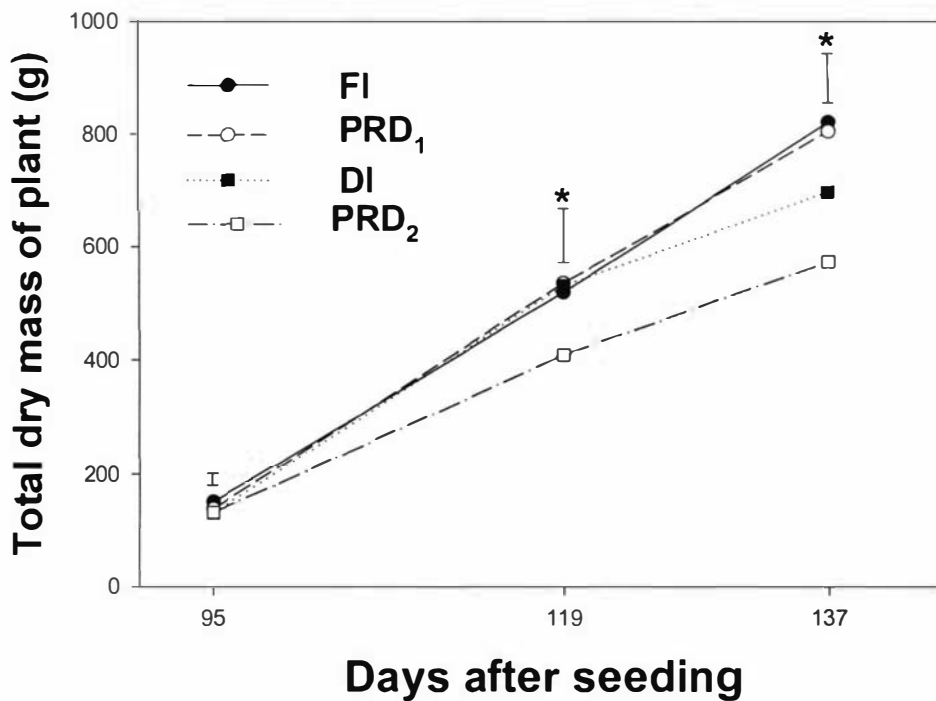
		Days after sowing		
ITs		95	119	137
Photosynthesis ( $\mu\text{mol m}^{-2} \text{ s}^{-1}$ )	FI	4.3a	6.12ab	11.2a
	PRD <sub>1</sub>	2.03b	7.1a	7.7ab
	DI	1.7b	7.3a	7.1b
	PRD <sub>2</sub>	1.3b	4.3b	4.6b
Stomatal conductance ( $\text{mol m}^{-2} \text{ s}^{-1}$ )	FI	1.4a	0.5a	1.7a
	PRD <sub>1</sub>	2.2a	0.5a	1.2ab
	DI	5.3a	0.4a	1.1ab
	PRD <sub>2</sub>	3.9a	0.2b	0.6b
PPF ( $\mu\text{mol m}^{-2} \text{ s}^{-1} \pm \text{SD}$ )		205 $\pm$ 4	468 $\pm$ 70	867 $\pm$ 75

### 8.3.3 Plant growth, yield, harvest index, and irrigation use efficiency

The number of fruit, total fresh mass of plant (TFMP), and total fresh mass of fruit (TFMF) were lower in PRD<sub>2</sub> treatments than in FI, PRD<sub>1</sub>, and DI treatments (Table 8.2). The PRD<sub>1</sub> plants maintained similar TFMP, TFMF, and harvest index relative to FI, but they also had significantly improved  $\text{IUE}_{\text{TFMF}}$  (Table 8.2). The total dry mass of plants (TDMP) appeared unaffected in PRD<sub>1</sub> relative to FI (Figure 8.3). However, TDMP in DI and PRD<sub>2</sub> treatments was significantly reduced relative to FI and PRD<sub>1</sub> treatments (Figure 8.3).

**Table 8.2** Effect of irrigation treatments (ITs) on the number of fruit (NF), total fresh mass of plant (TFMP), total fresh mass of fruit (TFMF), irrigation use efficiency ( $IUE_{TFMF}$ ), and harvest index (HI) per plant. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	NF	TFMP (kg plant <sup>-1</sup> )	TFMF (kg plant <sup>-1</sup> )	$IUE_{TFMF}$ (g L <sup>-1</sup> )	HI
FI	70a	9.0a	6.7a	16.7b	0.52a
PRD <sub>1</sub>	69a	8.9a	6.2ab	30.5a	0.50a
DI	52ab	6.0ab	4.0bc	19.7b	0.43ab
PRD <sub>2</sub>	56b	4.6b	2.4c	23.4ab	0.37b



**Figure 8.3** Changes in total dry mass of plants (including root and fruit) 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  $P \leq 0.05$ .

### 8.3.4 Dry mass distribution

Dry mass allocation into roots was similar in all treatments (Table 8.3). Stems were apportioned with less dry mass in FI and PRD<sub>1</sub> plants than in DI and PRD<sub>2</sub> plants (Table 8.3). PRD<sub>2</sub> plants had the highest dry mass allocation in leaves while dry mass allocations to PRD<sub>2</sub> fruit were less than those in DI, PRD<sub>1</sub>, and FI fruit (Table 8.3).

**Table 8.3** Effect of irrigation treatments (ITs) on dry mass distribution per plant. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	Dry mass distribution per plant (%)			
	Root	Stems	Leaves	Fruit
FI	1.8a	28.3b	17.5b	52.4a
PRD <sub>1</sub>	2.0a	29.8b	18.4b	49.8a
DI	2.2a	34.1ab	20.4b	43.3ab
PRD <sub>2</sub>	2.1a	37.0a	24.4a	36.5b

### 8.3.5 Fruit quality

The mean fresh mass per fruit was significantly lower in PRD<sub>2</sub> treatment than in DI, PRD<sub>1</sub>, and FI treatments (Table 8.4). The same was true for fruit water content. The PRD<sub>2</sub> fruit were the reddest among the treatments by having the lowest hue angle (Table 8.4). Moreover, TSSC was higher in PRD<sub>2</sub> fruit, but this treatment had the highest blossom-end rot incidence (Table 8.4). The total dry mass of fruit per plant was higher in FI and PRD<sub>1</sub> plants than in DI and PRD<sub>2</sub> plants (Table 8.4).

**Table 8.4** Effect of irrigation treatments (ITs) on mean fresh mass per fruit (MFMF), total dry mass of fruit per plant (TDMF), fruit water content (FWC), total soluble solids concentration (TSSC), blossom-end rot (BER), and fruit colour (in terms of hue angle (HA°)) at green stage and 14 days after harvest (DAH). The treatments are described in the text. Different letters within columns indicate significant differences by Turkey's test at  $P \leq 0.05$ .

ITs	MFMF	TDMF	FWC	TSSC	BER	HA°	
	(g)	(g plant <sup>-1</sup> )	(%)	(°Brix)	(%)	Green stage	14 DAH
FI	94.6a	452.3a	94a	5.1a	18c	107a	38a
PRD <sub>1</sub>	88.6a	425.2a	94a	5.4a	24bc	110a	37a
DI	77.4a	291.7b	93a	5.5a	36ab	107a	37a
PRD <sub>2</sub>	43.5b	217.2b	92b	7.0b	43a	111a	35b

### 8.3.6 Leaf mineral concentration

Neither leaf K<sup>+</sup> nor Mg<sup>2+</sup> concentration, on a dry weight basis, was affected by irrigation treatments at harvest. The values (mg g<sup>-1</sup> ± SEM) of K<sup>+</sup> in FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub> were 1.6 ± 0.5, 1.0 ± 0.1, 1.0 ± 0.2, and 0.8 ± 0.2, respectively. The corresponding values for Mg<sup>2+</sup> were 2.5 ± 0.4, 2.6 ± 0.1, 2.0 ± 0.3, and 2.2 ± 0.4. However, as the level of water deficit increased, leaf Ca<sup>2+</sup> concentration was significantly reduced. The values (mg g<sup>-1</sup> ± SEM) in FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub> were 8.7 ± 0.9, 5.2 ± 0.7, 4.2 ± 0.4, and 3.6 ± 0.4, respectively.

## 8.4 Discussion

Leaf water potential in PRD<sub>1</sub> was the same as that for FI (Figure 8.2). However, in PRD<sub>1</sub> A tended to be reduced along with  $g_s$ , which was observed only on 137 DAS in a sunny day (Table 8.1). This trend was similar for the same parameters in apple (Gowing et al., 1990), grape (Dry et al., 2000a), and bell pepper (Yao et al., 2001) under split-root system experiments. My data suggest that water, supplied to the wetted part of rhizosphere, was sufficient to maintain the leaf water potential in equilibrium in PRD<sub>1</sub>. Stomata of tomato become sensitive to water deficit when  $\Psi_{\text{leaf}}$  drops to  $-0.9$  MPa (Duniway, 1971), which did not occur in PRD<sub>1</sub> plants, but it did in DI and PRD<sub>2</sub> plants. The  $\Psi_{\text{leaf}}$  values (MPa) for DI plants on 119 and 137 DAS at 02:00 hours were  $-1.05$  and  $-0.95$  respectively. For PRD<sub>2</sub> they were  $-1.36$  and  $-1.15$ , respectively. In a split-root experiment with tomato, Holbrook et al. (2002) observed stomatal closure in absence of leaf water deficit. They explained that stomates might respond to abscisic acid (ABA) synthesised *in situ* (leaves) rather than produced in the dried root and transported toward leaves via the xylem as re-iterated by Davis and Zhang (1991). This could be the case here for the PRD<sub>1</sub> treatment which had the same  $\Psi_{\text{leaf}}$  as that of FI but its  $g_s$  tended to be low.

PRD<sub>1</sub> not only saved the irrigation water by 50%, but also maintained TFMF, TFMP, and HI at the same level as FI plants, therefore doubling the irrigation use efficiency (Table 8.2). The significant reduction in plant water status in DI and PRD<sub>2</sub> plants led to reductions in TFMF and TDMP (Table 8.2, Figure 8.3). NF was lower in PRD<sub>2</sub> plants than in FI, PRD<sub>1</sub>, and DI plants (Table 8.2). Tomato is sensitive to water deficit during flowering and fruit set (Pulupol et al., 1996). Treatments were applied before the first truss appeared and during the reproductive growth so that water deficit could have induced flower abortion (Pulupol et al., 1996), hence reduction in NF and harvest index (Hsiao, 1993) in PRD<sub>2</sub>.

The tomato fruit is the strongest sink for assimilates compared with the rest of the plant's organs (Ho, 1996b). But the reduction in fruit size, under deficit irrigation, is mainly attributed to reduction of water rather than to reduction of assimilates imported to the fruit (Ho, 1996b). In this study, a lesser proportion of dry mass was partitioned

into the PRD<sub>2</sub> fruit than to FI, PRD<sub>1</sub>, and DI fruit (Table 8.3). The same was true for MFMF, TDMF, and FWC (Table 8.4). These findings are in disagreement to those previously reported (Ho, 1996b). Data suggest that the reduction of the latter fruit parameters was due to a suppression of both water and assimilate flux into the PRD<sub>2</sub> fruit. Tomato leaf water potential around  $-1.1$  MPa at noon could reduce sap flux by 90% during the day (Araki et al., 1998) and consequently fruit size will be reduced (Araki et al., 1998; Johnson et al., 1992). At this stage, photosynthesis was not totally inhibited in DI and PRD<sub>2</sub> plants (Table 8.1). Therefore, while fruit become weaker sinks, larger fractions of photoassimilates are allocated into the roots, stems, and leaves. The dry mass partitioning into the latter organs could be the result of osmotic adjustment. During osmotic adjustment, turgor is maintained because the decrease in leaf water potential is compensated for a similar decline in osmotic potential. I did not measure osmotic potential, but osmotic adjustment could have offered a mechanism by which the vegetative fresh mass among plants became similar. The vegetative fresh mass (including roots) values ( $\text{kg plant}^{-1} \pm$  two times the SEM) were  $2.3 \pm 0.56$ ,  $2.7 \pm 0.22$ ,  $2.0 \pm 0.54$ , and  $2.2 \pm 0.17$  for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub>, respectively. Therefore, the reduced TDMP, in DI and PRD<sub>2</sub> plant relative to FI and PRD<sub>1</sub>, was attributed to reduction in reproductive sinks (fruit) rather than total vegetative dry mass (Figure 8.3).

Contrary to my hypothesis, PRD<sub>1</sub> did not improve fruit quality in terms of TSSC and FWC compared with FI fruit (Table 8.4). The fruit TSSC was higher in PRD<sub>2</sub> than in any other treatment (Table 8.4). This treatment also had the lowest  $\Psi_{\text{leaf}}$  and FWC, therefore, these two factors could increase the starch concentration during the first stage of fruit growth (Ruan and Patrick, 1995), hence the higher conversion of starch to sugars at fruit maturity. This could be a reason by which fruit postharvest respiration was higher in water deficit fruit than irrigated fruit (Pulupol et al., 1996). The PRD<sub>2</sub> fruit were found to be redder (low hue angle value) than fruit from any other treatment (Table 8.4). I did not investigate the mechanisms for redness of colour for PRD<sub>2</sub> fruit, but during the ethylene biosynthesis (Campbell and Labavitch, 1991) a higher accumulation of lycopene could be the reason (Pulupol et al., 1996).

As the level of water deficit increased so did the percentage of BER (Table 8.4) while leaf  $\text{Ca}^{2+}$  concentration was reduced. I did not determine fruit  $\text{Ca}^{2+}$  concentration, but lower  $\text{Ca}^{2+}$  import by fruit would be expected (Admas, 1986; El-Gizawy and Adams, 1986). Presence of BER has been associated with low fruit  $\text{Ca}^{2+}$  concentration and water deficit (Adams and Ho, 1992). My findings could support this relationship, but Pulupol et al. (1996) and Sperry et al. (1996) found little or no effect on BER by water deficit. However, I suggest that the presence of BER in FI fruit could be due to a greater root portion being allowed to dry by using drip irrigation. This would lead to low  $\text{Ca}^{2+}$  distribution to leaf and fruit, hence a high BER percentage in all treatments. Susceptibility to BER of this tomato cultivar could also be associated with the mode of irrigation (Carrijo et al., 1983; Obreza et al., 1996), because I have noticed no BER development in another PRD experiment, which was furrow-irrigated (Zegbe et al., 2003b).

## 8.5 Conclusions

I have shown that  $\Psi_{\text{leaf}}$ ,  $A$ , and  $g_s$  of PRD<sub>1</sub> plants tended to be similar to those of FI plants. Therefore there were no adverse effects on plant growth, TFMF, TDMF, and HI in PRD<sub>1</sub>. The dry mass distribution of PRD<sub>1</sub> plants was also the same as those of FI plants. Thus, PRD<sub>1</sub> not only doubled the irrigation use efficiency, but also saved water by 50%. However, PRD<sub>1</sub> treatment did not increase TSSC nor did it intensify fruit skin colour, but maintained TDMF similar to FI treatment. Nevertheless, a significant presence of BER was noticed. I conclude that partial rootzone drying might be a more feasible irrigation strategy over deficit irrigation for the production of processing tomatoes. Its use might be motivated in dry production areas where the irrigation is needed to meet marketable tomato yield. However, more research is needed under field conditions to confirm the results presented here. In view of significantly higher BER development in DI and PRD<sub>2</sub> fruit, I cannot recommend these irrigation practices under similar circumstances.

## Chapter 9

### The extent of soil drying affects yield and fruit quality in processing tomatoes under partial rootzone drying

#### Abstract

'Petopride' processing tomato plants were exposed to partial root zone drying in which alternating sides of the root system (RS) were exposed to a different extent of dryness. The irrigation 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<sub>2</sub>), four (PRD<sub>4</sub>), and six (PRD<sub>6</sub>) consecutive days; before the irrigation was shifted over to the dry side of the RS for the same period of time. Leaf water potential ( $\Psi_{\text{leaf}}$ ), photosynthetic rate (A), total fresh mass of fruit (TFMF) and total dry mass of fruit (TDMF), harvest index (HI) were significantly reduced in PRD treatments relative to FI, but the irrigation use efficiency, in terms of TFMF ( $IUE_{\text{TFMF}}$ ) was improved in the PRD treatments. Fruit dry mass allocation was lesser in PRD treatments which had lower fruit water content (FWC) and higher total soluble solids concentration (TSSC). Fruit skin colour ( $HA^\circ$ ) was the same for all treatments. Blossom-end rot incidence was higher in PRD treatments than in FI. Lower calcium concentration was found in PRD leaves but not in the fruit. PRD saved irrigation water by 50 %, but TDMF was reduced by 16 %. Saving water in areas where water is scarce and/or expensive may compensate for the reduction in TDMF by using PRD irrigation protocol.

## 9.1 Introduction

In Chapter 8, I reported that PRD alternated daily from the wet to the dry part of the rhizosphere did not negatively affect  $\Psi_{\text{leaf}}$ , A, and  $g_s$ . Therefore total fresh, dry mass of fruit and harvest index was the same between PRD and FI plants. Irrigation use efficiency was improved in PRD plants and fruit quality was the same in PRD and FI plants.

PRD has been studied by alternating irrigation in both sides of the row in maize (Kang et al., 2000), hot pepper (Kang et al., 2001) and pear (Kang et al., 2002), and the yield of these crops was not reduced. But the yield was negatively affected when PRD was given by irrigating only the same part of the root system for the entire growing season in maize (Kang et al., 2000) and hot pepper (Kang et al., 2001). In the latter PRD experiment, the reduction in yield was due to a poor root growth as a result of severe soil water deficit (Kang et al., 2000; Kang et al., 2001). However, other authors have indicated that roots exposed to water deficit lose their permeability therefore their ability to absorb water when re-watered due to suberization and lignification (Cantore et al., 2000; Steudle, 2000). In contrast, Vartanian (1981) observed that the root growth of *Sinapis alba* was enhanced as was the root hydraulic conductivity after a period of water deficit. I therefore became interested in knowing for how long a part of the rhizosphere could be kept unwatered in 'Petopride' tomato without deleterious effects on fruit yield and quality. I therefore did this research to compare the effect of three PRD irrigation shifting frequencies on plant water status, photosynthesis, plant growth, yield, irrigation use efficiency, and fruit quality. I hypothesised that shifting the irrigation frequently should not have any effect on plant performance because one part of the rhizosphere is always well wetted and according to Hsiao (1990) plant water status equilibrates with the wettest part of the soil.

## 9.2 Materials and methods

### 9.2.1 Experimental conditions and treatments

The general experimental conditions and plant material were the same as detailed in Chapter 8 (Section 8.2.1). The experiment was conducted from November 2001 to April 2002. Seeds were sown on 26 November 2001 and 40-day old individual seedlings were transplanted and spaced as detailed in Chapter 8 (Section 8.2.1).

Twenty days after transplanting, the following four irrigation treatments were randomly applied to a total of 48 plants. The irrigation treatments 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<sub>2</sub>), four (PRD<sub>4</sub>), and six (PRD<sub>6</sub>) consecutive days before the irrigation was shifted over to the dry side of the RS for the same period of time.

The experiment was conducted in a completely randomised design with four treatments replicated three times. There were four plants per treatment for each replication.

### 9.2.2 Measurements of soil water content

The plants were irrigated four times daily (at 7:00, 10:00, 13:00, and 16:00 hours) and at each time for 15 minutes 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<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub> treatments. This emitter was manually shifted over when needed. The PRD and FI plants were daily irrigated with a total of 4 and 8 L, respectively. A total of 202 and 400 L of water per plant was applied during the experiment to PRD and FI plants, respectively. Water losses by drainage and their implications on the irrigation use efficiency calculations were considered as mentioned in Chapter 8 (Section 8.2.2). Volumetric soil water content was monitored daily as detailed in Chapter 3 (Section 3.1).

### 9.2.3 Measurements of photosynthesis, stomatal conductance, and plant water status

Photosynthetic rate ( $A$ ), stomatal conductance ( $g_s$ ), and photosynthetic photon flux (PPF) were measured on two leaves per plant between 13:30 and 14:30 hours as described in Chapter 3 (Section 3.3). This was done on 94, 105, and 130 days after seeding (DAS). Diurnal changes of leaf water potential ( $\Psi_{\text{leaf}}$ ) were made on the same dates on two leaves as detailed in Chapter 3 (Section 3.2.2). Measurements were taken at 06:00, 09:00, 12:00, 15:00, and 18:00 hours.

### 9.2.4 Measurements of plant growth, yield, harvest index, irrigation use efficiency, and dry mass distribution

There was a single harvest during which the number of fruit (NF), total fresh mass of fruit (TFMF), and mean fresh mass per fruit (MFMF) were obtained as described in Chapter 3 (Section 3.5.2). Total dry mass of fruit (TDMF), total fresh mass of plant (TFMP), and total dry mass of plant (TDMP) were recorded as described in Chapter 3 (Section 3.6). Harvest index (HI) and irrigation use efficiency ( $IUE_{\text{TFMF}}$ ) were calculated as detailed in Chapter 3 (Sections 3.5.4 and 3.5.5). Destructive harvests were used to assess changes in TDMP (including fruit and roots) by collecting one plant per replication per treatment on 95, 105, and 130 DAS. Dry mass distribution was done as detailed in Chapter 3 (Section 3.6).

### 9.2.5 Fruit quality assessment

From the first trusses, 18 fruit per treatment (six per replication) were randomly chosen for quality measurements. They were weighed and considered for the assessment of TFMF and TDMF. Fruit were collected at the green stage and colour development was followed for 14 days. Fruit background skin colour, in terms of hue angle ( $HA^\circ$ ) and TSSC were measured as detailed in Chapter 3 (Sections 3.8.2 and 3.8.4). FWC was

calculated as described in Chapter 3 (Section 3.8.6). Blossom-end root (BER) incidence was expressed in percentage of NF affected per plant.

### **9.2.6 Measurement of $K^+$ , $Ca^{2+}$ , and $Mg^{2+}$ in leaf and fruit**

Ten leaflets were taken randomly from two plants per replication per treatment at harvest. The fruit described in the Section 9.2.5 were used to assess their mineral analysis concentration as detailed in Chapter 3 (Section 3.8.8).

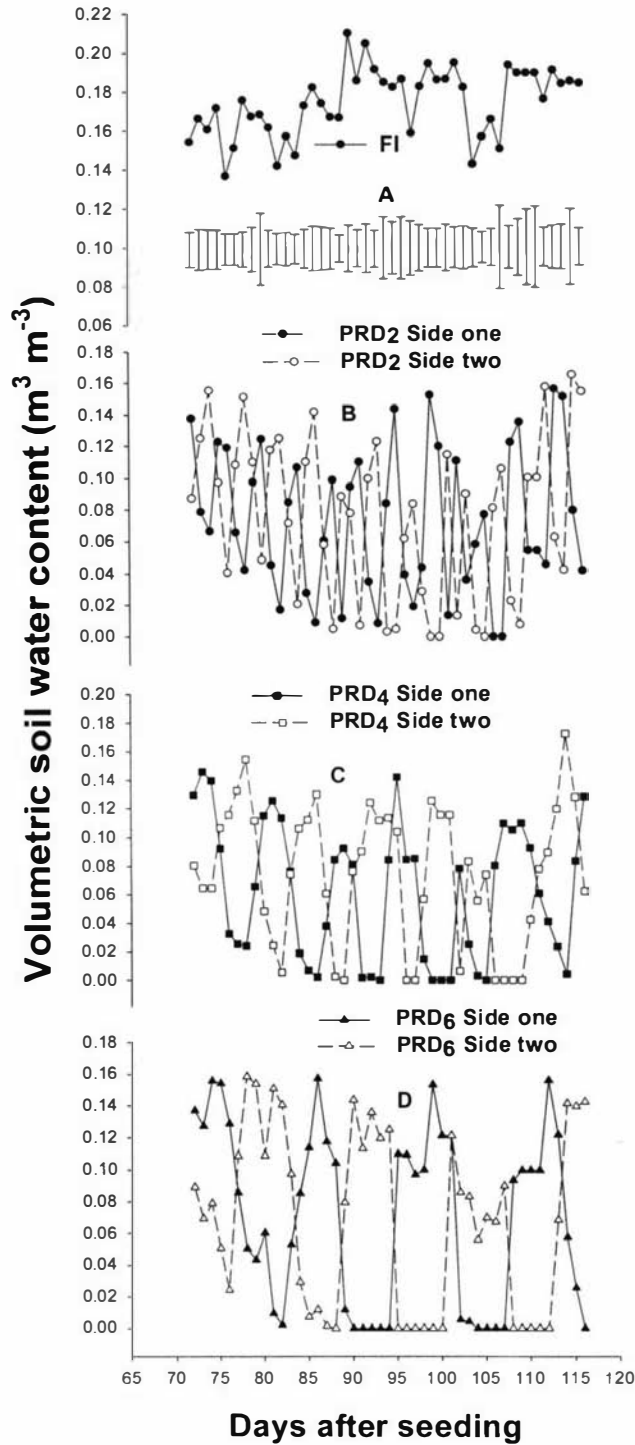
### **9.2.7 Statistical analysis**

The data were analysed as described in Chapter 8 (Section 8.2.7).

## **9.3 Results**

### **9.3.1 Volumetric soil water content**

Due to normally high evaporation demand throughout the season,  $\theta$  in FI treatment ranged from 0.15 to 0.21  $m^3 m^{-3}$  with on average of 0.18  $m^3 m^{-3}$  (Figure 9.1A).  $\theta$  was simultaneously and significantly increasing or decreasing in both sides of the root system of PRD<sub>2</sub> treatment (Figure 9.1B). But recovery of  $\theta$  with irrigation was not quick in PRD<sub>4</sub> and PRD<sub>6</sub> compared to PRD<sub>2</sub> (Figures 9.1C and 9.1D).

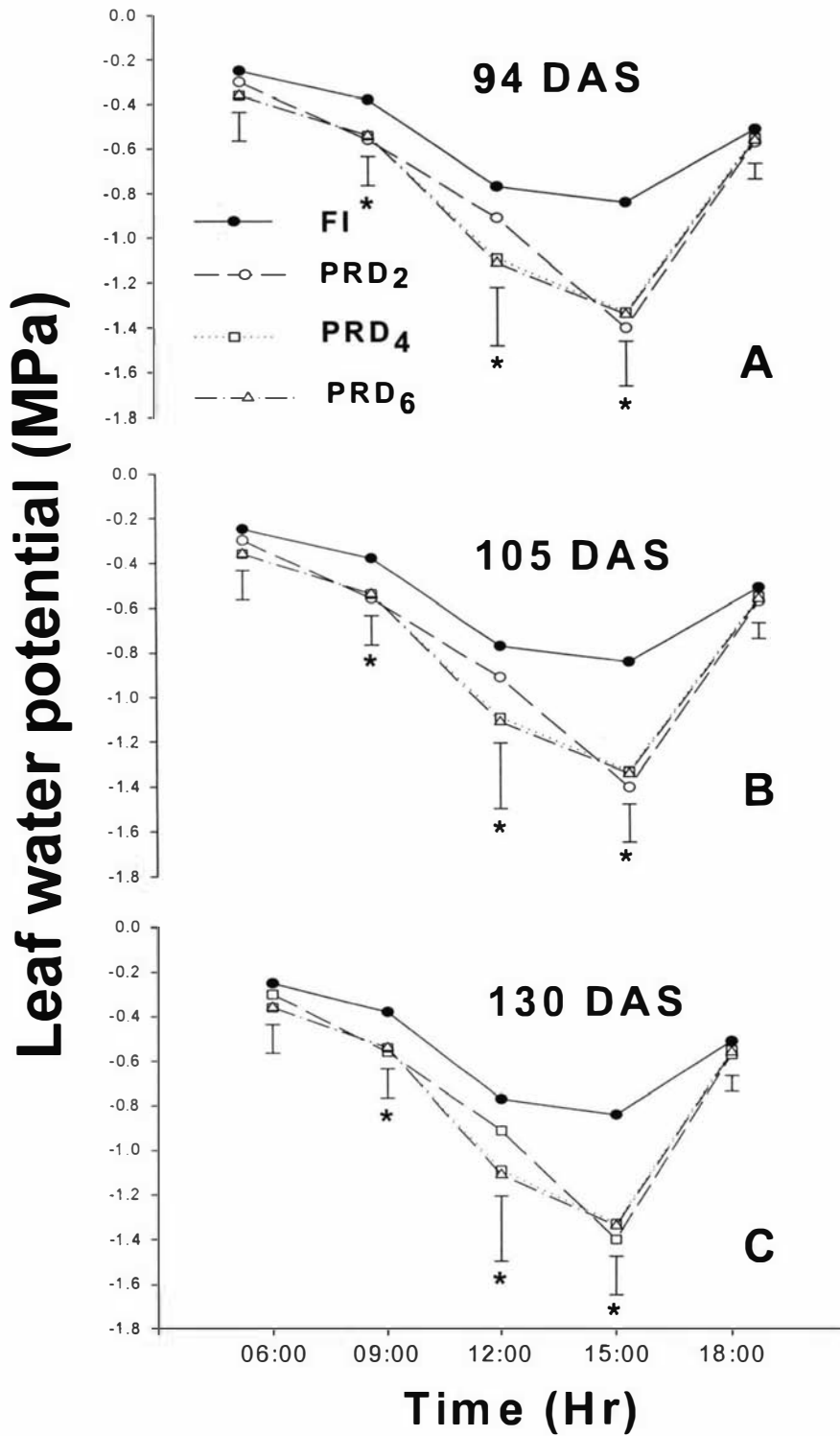


**Figure 9.1** Changes in soil water content in FI (A) and for the two sides of plant root system for PRD<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub> treatments. Vertical bars represent the minimum significant difference (MSD) by Tukey's test at  $P \leq 0.05$ .

### 9.3.2 Plant water status, photosynthesis, and stomatal conductance

$\Psi_{\text{leaf}}$  followed the typical diurnal pattern decreasing from early morning, reaching a minimum value after midday, and then starting to recover in late afternoon (Figure 9.2). The  $\Psi_{\text{leaf}}$  of PRD<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub> plants was significantly reduced relative to FI plants at 9:00, 12:00, and 15:00 hours in three occasions (Figures 9.2A-9.2D). The lowest  $\Psi_{\text{leaf}}$  value was observed at 15:00 hours and was approximately  $-1.4$  MPa in all PRD treatments suggesting a severe water deficit.

In general, A was significantly higher in FI plants relative to PRD plants in the first two occasions that A was measured (Table 9.1). The same was true for the first two occasions that stomatal conductance was measured (Table 9.1). On 130 DAS low solar radiation could have overridden the PRD effect on stomata closure.



**Figure 9.2** Diurnal changes of leaf water potential 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  $P \leq 0.05$ .

**Table 9.1** 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  $P \leq 0.05$ .

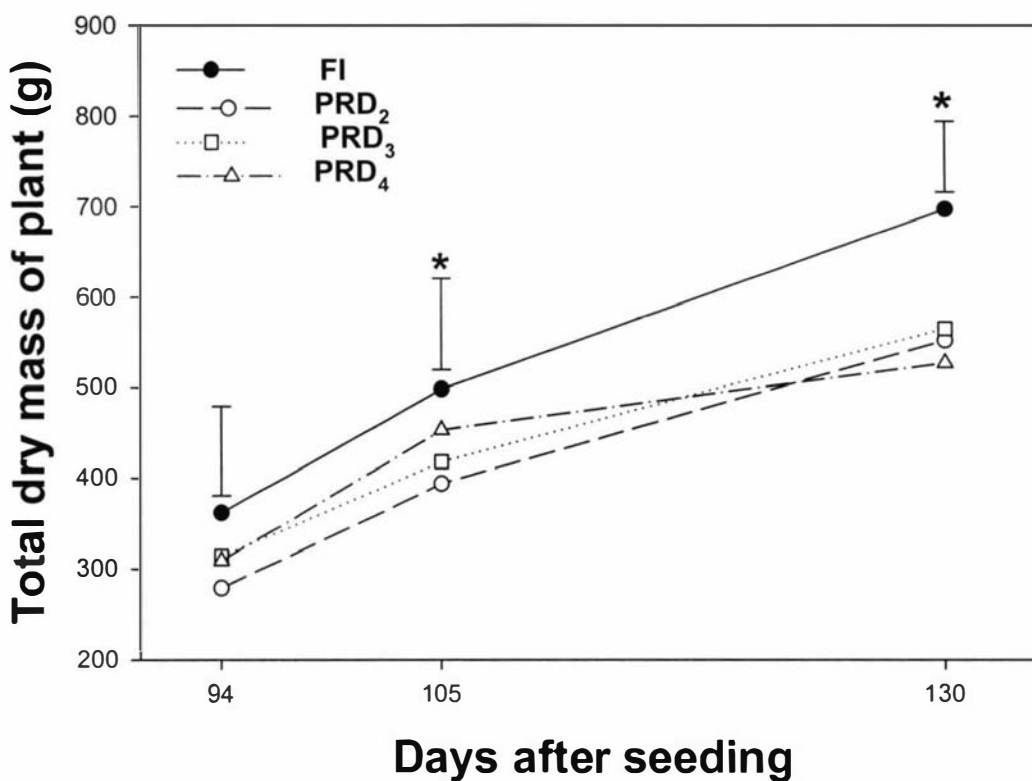
Parameter	ITs	Days after sowing			Mean
		94	105	130	
Photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	FI	19.2a	13.6a	8.0a	14.4a
	PRD <sub>2</sub>	9.2b	7.8b	7.5a	8.1b
	PRD <sub>4</sub>	7.2b	7.8b	6.3a	7.0b
	PRD <sub>6</sub>	8.7b	8.4ab	6.3a	7.8b
Stomatal conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ )	FI	3.5a	1.32a	1.9a	2.3a
	PRD <sub>2</sub>	0.9b	0.7b	2.0a	1.2b
	PRD <sub>4</sub>	0.5b	0.5b	1.8a	1.1b
	PRD <sub>6</sub>	0.5b	0.5b	1.7a	1.0b
PPF ( $\mu\text{mol m}^{-2} \text{s}^{-1} \pm \text{SD}$ )		1254 $\pm$ 235	836 $\pm$ 346	669 $\pm$ 289	

### 9.3.3 Plant growth, yield, harvest index, and irrigation use efficiency

Total fresh mass of plant (TFMP), total fresh mass of fruit (TFMF), and harvest index (HI) were lower in PRD plants than in FI plants (Table 9.2). However, the irrigation use efficiency ( $\text{IUE}_{\text{TFMF}}$ ) was improved by 40% in PRD plants relative to FI plants (Table 9.2). Total dry mass of plant (TDMP) was also reduced in PRD plants relative to FI plants (Figure 9.3).

**Table 9.2** Effect of irrigation treatments (ITs) on total fresh mass of plant (TFMP), total fresh mass of fruit (TFMF), irrigation use efficiency ( $IUE_{TFMF}$ ), and harvest index (HI) per plant. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	TFMP (kg plant <sup>-1</sup> )	TFMF (kg plant <sup>-1</sup> )	$IUE_{TFMF}$ (g L <sup>-1</sup> )	HI
FI	9.6a	7.4a	18.5b	0.66a
PRD <sub>2</sub>	6.8b	5.0b	24.7a	0.60b
PRD <sub>4</sub>	7.1b	5.3b	26.2a	0.62ab
PRD <sub>6</sub>	6.8b	5.0b	24.7a	0.60b



**Figure 9.3** 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 at  $P \leq 0.05$ .

### 9.3.4 Dry mass distribution

Dry mass allocation into roots, stems, and leaves was similar in all treatments (Table 9.3). However, there was a trend to increase the dry mass allocation into stems and leaves in PRD plants relative to FI plants. Apart of PRD<sub>4</sub>, dry mass allocation was significantly lower to PRD fruit relative to FI fruit (Table 9.3).

**Table 9.3** Effect of irrigation treatments (ITs) on dry mass distribution per plant. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	Dry mass distribution per plant (%)			
	Root	Stems	Leaves	Fruit
FI	1.5a	20.9a	11.6a	66.0a
PRD <sub>2</sub>	2.1a	23.7a	15.4a	58.8b
PRD <sub>4</sub>	1.8a	23.9a	12.6a	61.7ab
PRD <sub>6</sub>	1.8a	24.7a	13.6a	59.9b

### 9.3.5 Fruit quality

Apart from PRD<sub>4</sub>, number of fruit per plant was significantly lower in PRD treatments than in FI treatment (Table 9.4). 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, but they had the highest blossom-end rot incidence (Table 9.4). Fruit skin colour, in terms of HA°, was not significantly different among treatments. However, PRD fruit trended to be redder relative to FI fruit (Table 9.4).

**Table 9.4** 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), blossom-end rot (BER), and fruit colour in terms of hue angle (HA°) at green stage and 14 days after harvest (DAH). The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	NF	MFMF	TDMF	FWC	TSSC	BER	HA°	
	(g)	(g plant <sup>-1</sup> )	(%)	(%)	(%)	(%)	Green stage	14 DAH
FI	68a	110a	438a	94.1a	4.5b	5b	111.1a	39.3a
PRD <sub>2</sub>	49b	101ab	325b	93.4b	5.2a	21a	111.4a	37.5a
PRD <sub>4</sub>	57ab	93b	366b	93.0b	5.2a	21a	111.8a	38.1a
PRD <sub>6</sub>	51b	99ab	321b	93.5ab	5.3a	17a	111.5a	37.5a

### 9.3.6 Leaf mineral concentration

Leaf K<sup>+</sup> and Mg<sup>2+</sup> concentration, on a dry mass basis, was the same for all treatments, but Ca<sup>2+</sup> concentration was lower for most PRD treatments. Fruit K<sup>+</sup>, Ca<sup>2+</sup>, and Mg<sup>2+</sup> concentrations were not significantly affected by the treatments (Table 9.5).

**Table 9.5** Effect of irrigation treatments (ITs) on leaf and fruit mineral concentration (mg g<sup>-1</sup> of dry weight) at harvest of 'Petopride' processing tomato. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	Leaf			Fruit		
	K <sup>+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K	Ca <sup>2+</sup>	Mg <sup>2+</sup>
FI	3.4a	10.0a	1.9a	4.9a	0.19a	1.1a
PRD <sub>2</sub>	1.6a	4.9ab	1.4a	4.7a	0.19a	0.3a
PRD <sub>4</sub>	1.8a	1.8b	1.5a	5.2a	0.15a	0.4a
PRD <sub>6</sub>	2.6a	4.8b	1.9a	5.1a	0.14a	0.6a

## 9.4 Discussion

The significant decrease in leaf water potential ( $\Psi_{\text{leaf}}$ ) for the PRD plants indicates that their dry part of the rhizosphere did not contribute to the meeting of transpiration demand. This could be corroborated by their  $\Psi_{\text{leaf}}$  becoming the same as that of FI plants late in the afternoon (Figure 9.2). Although I lack data to corroborate it, based on the literature I could suggest that the rhizosphere should have had a lower hydraulic conductivity (Lafolie et al., 1999) and the lower hydraulic conductivity must have been in the dry part of the rhizosphere. However, root growth was not hampered by the PRD treatments. The root fresh weight ( $\text{g} \pm \text{SEM}$ ) for FI, PRD<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub> were  $78 \pm 8$ ,  $80.6 \pm 6.3$ ,  $73.7 \pm 5$ , and  $71.6 \pm 7$ , respectively. The corresponding root dry values were  $9.64 \pm 0.7$ ,  $11.5 \pm 0.8$ ,  $10.3 \pm 0.3$ , and  $9.6 \pm 0.8$ , respectively.

In general plant growth is inhibited by soil water deficit (Hsiao and Xu, 2000), but shoot growth is often more limited than the root growth (Sharp and Davis, 1989; Wu and Cosgrove, 2000). My data support this partially, because growth of shoot and leaves together was significantly reduced in PRD plants relative to FI plants in terms of fresh mass, but not in terms of dry mass. The fresh mass values ( $\text{kg per plant} \pm \text{SEM}$ ) were  $1.08 \pm 0.08$ ,  $1.7 \pm 0.04$ ,  $1.7 \pm 0.05$ , and  $2.1 \pm 0.06$  for PRD<sub>2</sub>, PRD<sub>4</sub>, PRD<sub>6</sub>, and FI, respectively. The dry mass values ( $\text{kg per plant} \pm \text{SEM}$ ) were  $0.22 \pm 0.01$ ,  $0.21 \pm 0.05$ ,  $0.20 \pm 0.06$ , and  $0.21 \pm 0.07$ , respectively. Therefore, the reduction on TFMP and TDMP in PRD plants here (Table 9.2 and Figure 9.3, respectively) was due to reproductive growth, simply because it is a more sensitive phenological stage to water deficit (Srinivasa et al., 2000).

The photosynthetic rate ( $A$ ) was reduced in PRD plants relative to FI plants. The stomate closure could be the sole reason for reduced  $A$  values in PRD plants because the ratios of leaf internal  $\text{CO}_2$  concentration to that of the air ( $P_i/P_a$ ) were the same for PRD plants and FI plants, indicating a normal  $\text{CO}_2$  transportation into the leaves. For example, on 105 DAS, which was a typical day,  $P_i/P_a$  ( $\pm \text{SEM}$ ) values for FI, PRD<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub> were  $0.9 \pm 0.01$ ,  $0.89 \pm 0.01$ ,  $0.87 \pm 0.01$ , and  $0.87 \pm 0.01$ , respectively. Their corresponding transpiration rates ( $E$ ,  $\text{mmol m}^{-2} \text{s}^{-1} \pm \text{SEM}$ ) in the

same order were  $18.5 \pm 1.3$ ,  $14.6 \pm 0.7$ ,  $14.6 \pm 0.4$ , and  $13.8 \pm 0.6$ . The PRD plants had significantly reduced  $E$ . Therefore the data suggest that  $g_s$  was regulating the gas exchange rates (Davis and Zhang, 1991) along with detectable changes in leaf water potential.

The reduced  $\Psi_{\text{leaf}}$ ,  $A$ , and  $g_s$  in PRD plants was accompanied, as expected, with a reduction in TFMP and TFMF, but  $IUE_{\text{TFMF}}$  was significantly improved (Table 9.2). This result agrees with those studies where only the part of the rhizosphere was irrigated for the entire growing season (Cantore et al., 2000; Kang et al., 2000; Kang et al., 2001). Because TDMF was more reduced than TDMP, a lower harvest index resulted (Hsiao, 1993) in PRD plants compared with FI plants (Table 9.2). However, TFMP, TFMF, and TDMF tended to be the same regardless of the soil dryness induced by PRD treatments. This experiment was conducted in relatively small containers so that the root was restricted to the volume of soil. In the field tomato responses to the PRD irrigation frequencies may be different due to soil type and soil depth (Lafolie et al., 1999), environmental conditions (Hartz, 1993), type of irrigation system, and water availability (Phene, 1999). Also the ability of the root system to explore the soil profile to satisfy the transpiration demand plays a central role (Tardieu et al., 1992).

When water supply is adequate, the tomato fruit is the strongest sink for assimilates compared with the rest of plant's organs (Ho, 1996b). But the reduction in fruit size under deficit irrigation is mainly attributed to reduction of water instead of reduced dry mass accumulation in the fruit (Ho, 1996b; Ho et al., 1987). In this study with greater water deficit, a lesser proportion of dry mass was partitioned into the PRD fruits than in FI fruits (Table 9.3). This was the case for the total dry mass of fruit and fruit water content (Table 9.4). These findings are in disagreement, in part, to those reported by Ho et al. (1987) and Ho (1996b). My data suggest that the reduction of fruit size under PRD treatments could be due to a suppression of both water and assimilate fluxes into the fruit. Tomato  $\Psi_{\text{leaf}}$  of  $-1.1$  MPa or lower at noon could reduce sap flux by 90% during the day and consequently will reduce fruit size (Johnson et al., 1992; Araki et al., 1998; Bussi eres, 2002). In my experiment  $\Psi_{\text{leaf}}$  dropped to  $-1.4$  MPa (Figure 9.2), hence water and dry mass imports into the fruit could be limited. But I also expect the PRD fruit to have lost more dry mass to respiration than the FI fruit as shown for

'Virosa' a tomato cultivar by Pulupol et al. (1996). As the photosynthesis was not totally inhibited in PRD plants (Table 9.1), the available assimilates were attracted by stems, leaves and roots, because they are stronger sink for assimilates than fruit under water deficit (Hsiao 2000) (Table 9.3). In a split-root experiment, a similar dry mass partitioning was found for *Capsicum annuum* (Cantore et al., 2000).

TSSC was higher in PRD fruit than in the FI fruit (Table 9.4). The reason could be that the water deficit induced a higher starch accumulation during the first stage of fruit growth (Mitchell et al., 1991a), followed by the subsequent conversion to sugars during the maturation (Davis and Cocking, 1965). The TSSC and FWC were moderately correlated ( $r = -0.60$  and  $P \leq 0.0001$ ) and therefore the increased TSSC in PRD fruit might have been due to a lower fruit water content. Therefore, sugars actively and/or passively concentrated could be a reason that postharvest fruit respiration could have been higher in water deficit fruit than well watered fruit (Pulupol et al., 1996). The number of fruit was reduced in PRD treatments (Table 9.4). Flower abortion could be a reason because tomato is very sensitive to water deficit during flower and fruit set (Pulupol et al., 1996), hence reduced number of fruit in PRD treatments.

The incidence of BER was higher in PRD fruit relative to FI fruit (Table 9.4). This was accompanied by a reduction of leaf  $\text{Ca}^{2+}$  concentration in PRD plants (Table 9.5). However, fruit  $\text{Ca}^{2+}$  concentration was similar in PRD fruit and FI fruit (Table 9.5). This finding may not support the idea that BER is induced by fruit  $\text{Ca}^{2+}$  deficiency *per se* (El-Gizawy and Adams, 1986; Adams and Ho, 1992). However, fruit  $\text{Ca}^{2+}$  was measured in the bulk fruit which might not represent the BER-affected area of the fruit. In this case BER incidence might be associated with reduced water transport via xylem to the fruit rather than transpiration rates as suggested by Stanghellini et al. (1998).

## 9.5 Conclusions

PRD reduced fresh yield and dry yield by 32% and 23%, respectively, but the fruit quality, in terms of fruit water content and total soluble solids, was improved. The irrigation use efficiency was improved 40%. However, the same advantages found for the PRD treatments here, in terms of improved irrigation use efficiency, could be

realised by the application of PRD<sub>1</sub> (daily irrigation) treatment described in Chapter 8. I therefore could not recommend any of the PRD treatments here for a commercial situation while PRD<sub>1</sub> of Chapter 8 could be applied as it saved water by 50%. The main purpose of the study in this chapter 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 the extent that a  $\Psi_{\text{leaf}}$  of less than  $-1$  MPa could be developed.

## Chapter 10

### Root water relations in processing tomatoes exposed to partial rootzone drying

#### Abstract

It has been suggested that for plants under split-root system, the roots in the dry soil may survive because there is water flow from wetted roots to dry roots. To explore this possibility, two glasshouse experiments were carried out to study the water potential in roots ( $\Psi_{\text{root}}$ ), in leaves ( $\Psi_{\text{leaf}}$ ), and the dry mass of plant organs of 'Petopride' processing tomato under partial rootzone drying (PRD). In the first experiment the treatments were: daily full irrigation (FI) on both sides of the root system (RS) considered as the control, daily irrigation on one side of the RS with half the volume of water given to the control (PRD<sub>1</sub>), full irrigation every other day of both sides of the RS (DI), and irrigation only on one side of the RS every other day with half the volume of water given to the control (PRD<sub>2</sub>). In the second experiment 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 consecutive days (PRD<sub>2</sub>), four consecutive days (PRD<sub>4</sub>), and six consecutive days (PRD<sub>6</sub>) before being shifted. In both experiments,  $\Psi_{\text{root}}$  was lower in the dry soil than in the wet soil. Decrease in  $\Psi_{\text{leaf}}$  and  $\Psi_{\text{root}}$  was dependent on the extent of soil drying. In both experiments the dry mass of roots, stems, and leaves were not negatively affected by DI and PRD treatments. In the first experiment, total dry mass of fruit (TDMF) from PRD<sub>1</sub> was the same as FI, while TDMF was lower in DI and PRD<sub>2</sub> plants than in FI and PRD<sub>1</sub> plants. In the second experiment, TDMF was reduced by 32% in all PRD treatments in comparison with FI treatment. In PRD plants, root osmotic adjustment seems to be the mechanisms for maintaining growth and survival of the roots rather than water flow from wetted roots to dry roots.

## 10.1 Introduction

The root system has a central importance for plants by providing anchorage, absorbing water and minerals, and synthesising growth regulators for the successful growth of above ground parts (Kramer, 1983, p. 121). The root water potential ( $\Psi_{\text{root}}$ ) plays a central role in uptaking water from the soil. In plant water relations studies the assessment of  $\Psi_{\text{root}}$  is often neglected because roots are less accessible than shoots (Steudle, 2000) and because of the difficulties involved in measuring  $\Psi_{\text{root}}$  (Gee et al., 1974). Nevertheless,  $\Psi_{\text{root}}$  has been measured by using the pressure bomb (Gee et al., 1974) in plants subjected to water deficit but not in split-root system (SRS) or PRD experiments. The root development of some deciduous trees subjected to SRS treatment was reported to be similar to fully irrigated trees (Poni et al., 1992; Dry et al., 2000b). These authors explained their results on the basis of water movement from wet roots to dry roots. There are, however, root anatomic changes (apoplast suberization) during water deficit that would impede water flow (Steudle, 2000). Under water deficit water movement across the root tissue is cell to cell towards the xylem vessels of the central cylinder (Steudle, 2000; Steudle, 2001). This would limit radial water movement to other sites of the root system. If water moves, however, then  $\Psi_{\text{root}}$  would be similar in both side of the root system. Therefore, it will be expected that that the growth of below- and above-ground parts of a PRD plant to be the same as that of fully irrigated plants. However, the impact of PRD will depend on the extent of the soil dryness. Consequently, a reduction in leaf water potential ( $\Psi_{\text{leaf}}$ ) is also expected without adverse effect on dry mass of fruit, because photosynthesis and assimilate transport to fruit are less affected under mild water deficit (Ho, 1999). The objective of this study was to characterise the response of 'Petopride' to different PRD treatments while monitoring  $\Psi_{\text{root}}$ ,  $\Psi_{\text{leaf}}$ , and dry mass distribution of the plants.

## 10.2 Materials and methods

### 10.2.1 Experimental conditions

The general experimental conditions, and plant material were the same for both experiments as detailed in Chapter 7 (Section 7.2.1) and Chapter 8 (Section 8.2.1).

#### 10.2.1.1 Experiment 1

The first experiment was conducted from July to December 2001. Seeds were sown on 31 July 2001 and forty-day-old individual tomato plants were transplanted and spaced as described in Chapter 8 (Section 8.2.1). The four irrigation treatments were: daily full irrigation (FI) on both sides of the root system (RS) considered as the control, daily irrigation on one side of the RS with half the volume of water given to the control (PRD<sub>1</sub>), full irrigation every other day of both sides of the RS (DI), and irrigation only on one side of the RS every other day with half the volume of water given to the control (PRD<sub>2</sub>). Treatments were randomly applied to a total of 48 plants as described in Chapter 8 (Section 8.2.1). There were two plants per treatment for each replication.

Irrigation design and management are detailed in Chapter 8 (Section 8.2.1). Volumetric soil water content ( $\theta$ ) was vertically monitored as detailed in Chapter 3 (Section 3.1).

#### 10.2.1.2 Experiment 2

The second experiment was conducted from November 2001 to April 2002. Seeds were sown on 26 November 2001 and forty-day-old individual tomato plants were transplanted and spaced as described in Chapter 9 (Section 9.2.1). The four irrigation treatments that 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<sub>2</sub>), four (PRD<sub>4</sub>), and six (PRD<sub>6</sub>) consecutive days before the irrigation was shifted over to the dry side of the RS for the same period of time. Treatments were randomly applied to a

total of 48 plants are described in Chapter 9 (Section 9.2.1). There were two plants per treatment for each replication.

Irrigation design and management are detailed in Chapter 9 (Section 9.2.2). Volumetric soil water content was vertically monitored as detailed in Chapter 3 (Section 3.1). The photosynthetic photon flux was measured as detailed in Chapter 3 (Section 3.3).

### **10.2.2 Measurements of root and leaf water status and dry mass distribution**

The  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  were evaluated by using three replicated plants per treatment on 119 and 137 DAS for the first experiment and on 105 and 130 DAS for the second experiment. The following procedure was used.  $\Psi_{\text{leaf}}$  was measured on two leaves as described in Chapter 3 (Section 3.2.2). It was done between 09:00 to 09:30 hours. For  $\Psi_{\text{root}}$  measurement, two root branches from two opposite sides (wet and dry sides for PRD treatments) were selected. They were excised and carefully removed from the soil minimising root damage and  $\Psi_{\text{root}}$  was measured as described in Chapter 3 (Section 3.2.2).  $\Psi_{\text{root}}$  was measured between 09:00 to 11:30 hours.

The plants used in the determinations of  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  were collected and dry mass distribution for each plant organ obtained for both experiments as detailed in Chapter 3 (Section 3.6). The number of fruit per plant was also recorded as described in Chapter 3 (Section 3.5.2).

### **10.2.3 Statistical analysis**

The data from both experiments were analysed as described in Chapter 8 (Section 8.2.7). Linear orthogonal contrasts were performed to assess the statistical difference in  $\Psi_{\text{root}}$  between the wet and dry sides of the root system of PRD plants.

### 10.3 Results

In the first experiment, on 119 DAS and 137 DAS, the volumetric soil water content ( $\theta$ ) was significantly higher in FI plants than either DI or PRD plants. The difference between the wet and dry sides of the root system for PRD<sub>1</sub> plants was also significant on both sampling dates.  $\theta$  was the same in the wet and dry side of the rhizosphere in PRD<sub>2</sub> plants and it was similar to  $\theta$  of DI plants (Table 10.1).

In the second experiment,  $\theta$  was higher in FI plants than in PRD plants on 105 DAS (Table 10.1).  $\theta$  was significantly lower in the dry side of the root system in all PRD plants (Table 10.1).

**Table 10.1** Changes in volumetric soil water content ( $\text{m}^3 \text{m}^{-3}$ ) for the control (FI), deficit irrigation (DI), and for the wet and dry sides of the root system for PRD treatments from two experiments. Irrigation treatments (ITs) are described in the text. Different letters within columns and rows indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	Experiment 1				ITs	Experiment 2	
	119 DAS		137 DAS			105 DAS	
	Row side		Row side			Row side	
	Wet	Dry	Wet	Dry		Wet	Dry
FI	0.15a		0.16a		FI	0.16a	
PRD <sub>1</sub>	0.12b	0.06c	0.17a	0.05b	PRD <sub>2</sub>	0.08b	0.0c
DI	0.02d		0.09c		PRD <sub>4</sub>	0.07b	0.0c
PRD <sub>2</sub>	0.06d	0.0d	0.04c	0.0c	PRD <sub>6</sub>	0.07b	0.0c

#### 10.3.1 Experiment 1

On 119 DAS,  $\Psi_{\text{root}}$  was lower in the wet and dry roots of PRD<sub>2</sub> plants than those of FI, PRD<sub>1</sub> and DI plants (Table 10.2). Although  $\Psi_{\text{root}}$  of PRD plants tended to be lower in the dry rhizosphere than in the wet rhizosphere, this difference was not significant using the orthogonal contrast analysis ( $P \leq 0.05$ ).  $\Psi_{\text{leaf}}$  were lower than those observed in  $\Psi_{\text{root}}$  for all treatments, but PRD<sub>2</sub> plants had the lowest  $\Psi_{\text{leaf}}$  (Table 10.2). The

average difference (MPa) between  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  was 0.39, 0.48, 0.55, and 0.57 for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub> plants, respectively. The values for  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  on 137 DAS were similar to those observed on 119 DAS. However, the difference between  $\Psi_{\text{root}}$ , and  $\Psi_{\text{leaf}}$  were smaller on 137 DAS than on 119 DAS. The differences (MPa) were: 0.49, 0.32, 0.26, and 0.35 for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub> plants, respectively.

**Table 10.2** Experiment 1. Effect of irrigation treatments (ITs) on root water potential ( $\Psi_{\text{root}}$ ) and leaf water potential ( $\Psi_{\text{leaf}}$ ) (all in MPa). Different letters within columns and rows indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	119 DAS			137 DAS		
	Row side $\Psi_{\text{root}}$		$\Psi_{\text{leaf}}$	Row side $\Psi_{\text{root}}$		$\Psi_{\text{leaf}}$
	Wet	Dry		Wet	Dry	
FI	-0.23a		-0.62a	-0.13a		-0.62a
PRD <sub>1</sub>	-0.18a	-0.29a	-0.72a	-0.26ab	-0.34ab	-0.62a
DI	-0.31a		-0.86a	-0.47bc		-0.73ab
PRD <sub>2</sub>	-0.59b	-0.61b	-1.17b	-0.48bc	-0.65c	-0.91b

On 119 DAS, the dry mass (DM) of root was higher in PRD<sub>1</sub> and DI plants than in FI and PRD<sub>2</sub> plants while DM of stems was the lowest in FI plants (Table 10.3). No significant differences among treatments were observed in DM of leaves, but there was a tendency to be increased in PRD plants. DM of fruit (Table 10.3) and total dry mass of plant were the lowest in PRD<sub>2</sub> plants. The values for total dry mass of plant (g, MSD = 96.42) were 520.0, 537.0, 531.0, and 409.5 for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub>, respectively. At harvest (on 137 DAS) DM of root, stems, and leaves was the same among treatments, but DM of fruit (Table 10.3) and total dry mass of plant were higher in FI and PRD<sub>1</sub> plants than in DI and PRD<sub>2</sub> plants. The values for total dry mass of plant (g, MSD = 87.5) were 820.9, 805.0, 698.2, and 574.0 for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub>, respectively.

**Table 10.3** Experiment 1. Effect of irrigation treatments (ITs) on dry mass of plant organs at different days after seeding (DAS). Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	Dry mass of organs (g)							
	119 DAS				137 DAS			
	Roots	Stems	Leaves	Fruit	Roots	Stems	Leaves	Fruit
FI	9.4bc	147.1b	91.0a	272.4a	12.9a	249.1a	145.6a	413.3a
PRD <sub>1</sub>	10.7ab	160.2ab	98.8a	267.4a	13.6a	237.6a	148.0a	405.9a
DI	11.7a	181a	108.4a	230.0a	14.3a	248.2a	145.3a	290.5b
PRD <sub>2</sub>	8.6c	151ab	99.9a	149.5b	10.8a	209.6a	136.4a	216.6b

### 10.3.2 Experiment 2

On 105 DAS,  $\Psi_{\text{root}}$  in the wet side was the lowest in PRD<sub>6</sub> plants, but  $\Psi_{\text{root}}$  in the dry side was the highest in PRD<sub>2</sub> plants (Table 10.4). The  $\Psi_{\text{root}}$  difference between dry side and wet side was lower in all PRD plants, but based on the orthogonal contrasts analysis, the difference was significant only for PRD<sub>4</sub> plants ( $P \leq 0.001$ ). The lowest  $\Psi_{\text{leaf}}$  was observed in PRD<sub>6</sub> plants. The average difference (MPa) between  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  was 0.27, 0.23, 0.0, and 0.15 for FI, PRD<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub>, respectively. The values of  $\Psi_{\text{root}}$  in the wet side of PRD plants were the same as in FI plants on 130 DAS (Table 10.4). But  $\Psi_{\text{root}}$  was significantly lower in the dry side than in the wet side in all PRD treatments ( $P \leq 0.0001$ ). On the other hand,  $\Psi_{\text{leaf}}$  was the same for all treatments, but there was a trend to be lower in PRD plants. Therefore the average difference between  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  was minimal on 130 DAS. The values (MPa) were 0.18, 0.09, 0.11, and 0.11 for FI, PRD<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub>, respectively. This could be influenced by a low radiation that might override water deficit effect as shown in Asian pear (*Pyrus serotina* Rehd.) by Behboudian et al. (1994), hence  $\Psi_{\text{leaf}}$  in PRD plants were similar to those of FI plants. The photosynthetic photon flux ( $\mu\text{mol m}^{-2} \text{s}^{-1} \pm \text{SD}$ ) for that day was  $350 \pm 150$ .

**Table 10.4** Experiment 2. Effect of irrigation treatments (ITs) on root water potential ( $\Psi_{\text{root}}$ ) and leaf water potential ( $\Psi_{\text{leaf}}$ ) (all in MPa). Different letters within columns and rows indicate significant differences by Tukey test at  $P \leq 0.05$ .

ITs	105 DAS			130 DAS		
	Row side $\Psi_{\text{root}}$			Row side $\Psi_{\text{root}}$		
	Wet	Dry	$\Psi_{\text{leaf}}$	Wet	Dry	$\Psi_{\text{leaf}}$
FI	-0.29a		-0.56a	-0.26a		-0.44a
PRD <sub>2</sub>	-0.44ab	-0.55bc	-0.65a	-0.27a	-0.49b	-0.47a
PRD <sub>4</sub>	-0.50abc	-0.84d	-0.67a	-0.33a	-0.54b	-0.54a
PRD <sub>6</sub>	-0.55bc	-0.71cd	-0.78b	-0.30a	-0.49b	-0.51a

The DM of root, stems, and leaves was the same among treatments on 105 DAS and also on 130 DAS. Dry mass of fruit was the highest in FI plants on 105 DAS and on 130 DAS (Table 10.5).

**Table 10.5** Experiment 2. Effect of irrigation treatments (ITs) on dry mass of plant organs at different days after seeding (DAS). Different letters within columns indicate significant differences by Tukey test at  $P \leq 0.05$ .

ITs	Dry mass of organs (g)							
	105 DAS				130 DAS			
	Roots	Stems	Leaves	Fruit	Roots	Stems	Leaves	Fruit
FI	7.5a	104.1a	57.8a	328.6a	10.0a	140.1a	78.1a	469.3a
PRD <sub>2</sub>	8.3a	93.4a	60.7a	231.6b	12.7a	149.3a	79.0a	311.0b
PRD <sub>4</sub>	7.5a	100.0a	52.7a	258.0b	10.7a	142.8a	73.2a	338.0b
PRD <sub>6</sub>	8.2a	112.0a	62.0a	271.5ab	10.3a	131.7a	71.5a	313.3b

## 10.4 Discussion

In Tables 10.2 and 10.4 the lower values of  $\Psi_{\text{root}}$  (compared to those of FI) in PRD and DI plants was due to a high evaporative demand during Experiment 1 and 2 as reflected in a low volumetric soil water content in Table 10.1. In both experiments, plants were grown during the summer and early autumn when evaporative demand was high. The average cumulative evaporation (mm) was 139, 155, 129, 99, and 57 for December,

January, February, March, and April, respectively. Although the difference between  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$  was not significant in PRD<sub>1</sub> and PRD<sub>2</sub> in Experiment 1 (Table 10.2),  $\Psi_{\text{Dry\_root}}$  tended to be lower than  $\Psi_{\text{Wet\_root}}$  in both treatments. This suggests that the water deficit developed was not severe enough for measurable differences between  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$ . In the second experiment, the extent of soil dryness accounted for a significant difference between  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$  among PRD plants on 105 and 130 DAS (Table 10.4). This shows that there was no water flow from wet roots to those growing in the dry soil to equilibrate  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$  as has been proposed for fruit trees by Poni et al. (1992) and re-iterated by Dry et al. (2000b) and Loveys et al. (2000). Studies of sap flow in apple and kiwifruit roots show that when water is supplied in part of the root system, water uptake is increased in almost 2-fold by the roots in wet soil with a corresponding decline in water uptake of those in the dry soil (Green and Clothier, 1995; Green et al., 1997; Green and Clothier, 1999). I did not measure root sap flow but higher  $\Psi_{\text{Wet\_root}} - \Psi_{\text{Dry\_root}}$  in PRD plants would be indicative that water flow might have declined in roots growing in dry soil which was reflected in lower transpiration rates ( $E$ ) in PRD plants than in FI plants. The  $E$  values ( $\text{mmol m}^{-2} \text{s}^{-1} \pm \text{SEM}$ ) were  $18.5 \pm 1.3$ ,  $14.6 \pm 0.7$ ,  $14.6 \pm 0.4$ , and  $13.8 \pm 0.6$  for FI, PRD<sub>2</sub>, PRD<sub>4</sub>, and PRD<sub>6</sub>, respectively.

Even though  $\Psi_{\text{root}}$  from the dry side of soil was lower than those in the wet side of the soil such difference was statistically the same in PRD<sub>1</sub> and PRD<sub>2</sub> plants. However, in the former case  $\Psi_{\text{leaf}}$  was unaffected and was similar to FI plants in two occasions that it was measured (Table 10.2). This suggests that water absorption was unaffected and therefore the water balance in PRD<sub>1</sub> plants was maintained to carry on normal functions because the total dry mass of fruit in FI and in PRD<sub>1</sub> was the same (Table 10.3). The opposite could occur in DI and PRD<sub>2</sub> plants on 137 DAS and in PRD<sub>6</sub> plants on 105 DAS (Tables 10.2 and 10.4, respectively), because the reduction in  $\Psi_{\text{root}}$  accounted for proportional reduction in  $\Psi_{\text{leaf}}$  (Tables 10.2 and 10.4). However, the measured values of both  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  did provide for the water flow between roots and leaves in PRD plants.

The study showed that the growth of roots, stems and leaves in the DI and PRD<sub>2</sub> plants were the same as the FI and PRD<sub>1</sub> plants. However, TDMF was reduced in DI and

PRD<sub>2</sub> plants compared to FI and PRD<sub>1</sub> plants. It is well documented that osmotic adjustment occurs in both tomato leaves and fruit (Johnson et al., 1992) and in the roots (Hsiao and Xu, 2000) under moderate water deficit. During osmotic adjustment turgor is maintained because the decrease in both  $\Psi_{\text{root}}$  and  $\Psi_{\text{leaf}}$  could be compensated for by a similar decline in their osmotic potential. I did not measure osmotic adjustment in these experiments, but it could occur, offering the mechanism by which the dry mass of roots, stems, and leaves became similar among the treatments at harvest (Tables 10.3 and 10.5). Also under moderate water deficit, photosynthesis is less limited than the plant growth (Kramer, 1983, p. 343). In this conditions roots and leaves compete as sinks for assimilates to maintain growth (Sharp and Davies, 1989; Hsiao, 2000). Also the assimilate influx to the tomato fruit might be significantly limited at low  $\Psi_{\text{leaf}}$  (Jonhson et al., 1992; Kitano et al., 1996) leaving large fractions of assimilates to be allocated not only to root and leaves, but also to stems (Table 10.3 and 10.5). Root osmotic adjustment and assimilate import to leaves occurs during water deficit (Hsiao, 2000; Hsiao and Xu, 2000). These two mechanisms might have been used by DI, PRD<sub>2</sub> and PRD plants to grow similarly to FI plants (Table 10.3 and 10.5) rather than simple water diffusion from wet to dry roots as suggested by Poni et al. (1992), Dry et al. (2000b), and Loveys et al. (2000). Another explanation for the root growth and root survival could be that the root pressure, which takes place late in the evening and during the night when transpiration is low (Steudle, 2001), might lower the difference between  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$ . The latter explanation could occur in PRD plants, in Experiment 2, because their roots were exposed to more severe soil drying (Table 10.1 and 10.5). Water absorption is enhanced in roots that had been exposed to water deficit for a short-time (Vartanian, 1981) similar here to shifting of irrigation from the wet to the dry soil. However, measurement of root density and sap flow in both roots and stem deserve research for getting a better understanding of PRD effects.

A significant reduction in TDMF was observed in the DI and PRD<sub>2</sub> plants compared with PRD<sub>1</sub> and FI plants (Table 10.3). The treatments were applied before the first truss appearance. Water deficit could have developed before and during the reproductive growth. Tomato plants are sensitive to water deficit during flowering and fruit set (Pulupol et al., 1996) so that flower abortion might have occurred. This caused reduction in the number of fruit, hence lower TDMF in DI and PRD<sub>2</sub> plants. The

number of fruit per plant (MSD = 16) was 76, 72, 50, and 47 for FI, PRD<sub>1</sub>, DI, and PRD<sub>2</sub> plants, respectively. A similar effect might have occurred in Experiment 2 because TDMF was also reduced in PRD plants (Table 10.5). The number of fruit per plant (MSD = 11) was 68, 56, 51, and 49 for FI, PRD<sub>2</sub>, PRD<sub>4</sub>, PRD<sub>6</sub> plants, respectively.

## 10.5 Conclusions

It was shown that PRD induces different pressure gradients within root system ( $\Psi_{\text{Wet\_root}} - \Psi_{\text{Dry\_root}}$ ) and between roots and leaves ( $\Psi_{\text{root}} - \Psi_{\text{leaf}}$ ) and yet meets the plant water requirements. However, if the difference between  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$ , depending on the extent of soil dryness, is significant then the water absorption might become reduced. This would lead to a decrease in  $\Psi_{\text{leaf}}$  causing a decline in TDMF. Therefore, it is important to characterise the diurnal variation of  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$  and  $\Psi_{\text{leaf}}$  to establish the minimum threshold value to maintain the acquisition of water from the soil. Dry mass of roots, stems and leaves, in DI treatment and in all PRD treatments was similar to those of fully irrigated plants. It is suggested to study sap flow in roots and stems, root osmotic adjustment, and root growth for better physiological understanding of PRD effects.

## Chapter 11

### Partial rootzone drying does not promote blossom-end rot in 'Petopride' processing tomato

#### Abstract

In previous experiments (Chapters 8 and 9) I found unacceptably high incidence of blossom-end rot (BER) in fruit and I hypothesised that this could be related to the irrigation system as there are suggestions in the literature to this effect. This study was therefore conducted with the objective of comparing furrow and drip irrigation effects both under PRD on the incidence of BER and some other fruit quality attributes. The irrigation treatments were: full irrigation by hand to both sides of the root system (RS) which mimicked furrow irrigation (FuI), and half of irrigation water in FuI given only to one side of the RS with each irrigation (PRD<sub>FuI</sub>), full drip irrigation (DrI) to both sides of the root system, and half of irrigation water in DrI given only to one side of the RS with each drip irrigation (PRD<sub>DrI</sub>). PRD<sub>FuI</sub> plants had the lowest midday  $\Psi_{leaf}$  in one sampling out of four. DrI and PRD<sub>DrI</sub> plants had the lowest photosynthetic rate (A) in one sampling out of four. PRD plants had reduced total fresh mass of plant and increased irrigation use efficiency compared with fully irrigated plants. Number of fruit, mean fresh mass per fruit, total fresh and dry mass of fruit, and harvest index were the same among treatments. There was no incidence of BER in this experiment. PRD<sub>DrI</sub> fruit had redder colour and higher total soluble solids concentration. These results suggest that the advancement in fruit maturity and fruit enhancement of quality can be achieved without detrimental effect on fresh and dry mass of 'Petopride' tomato fruit by application of PRD. Independently of the irrigation system, PRD treatments improved irrigation use efficiency by almost 2-fold. PRD has the potential to be used in limited and non-limited water environments.

## 11.1 Introduction

In Chapters 8 and 9, I reported a very high incidence of blossom-end rot (BER) in some of my PRD treatments which would have rendered them ineffective as a management tool. I therefore became interested in exploring the cause of the high BER incidence. This disorder is attributed to a local Ca deficiency in the distal part of the tomato fruit (Ho, 1999). BER has been controversially related to soil water deficit Saure (2001). Adams and Ho (1992) and Obreza et al. (1996) reported that it is associated with soil water deficit, while this cannot be confirmed by the results of Pulupol et al. (1996).

Irrigation method has also been implicated in the development of BER, although not conclusively. Pascual et al. (2000) did not find incidents of BER with drip and furrow irrigation, but Carrijo et al. (1983) did. I explored two irrigation methods, furrow and drip irrigation, for their possible effects on BER incidence. I expected this research to provide conclusive information on BER development as affected by water deficit, which could be realised through the application of PRD, and by irrigation method. Because the rootzone is uniformly wetted with furrow irrigation, I hypothesised that BER may be reduced with this method under PRD without yield reduction.

## 11.2 Materials and methods

### 11.2.1 Experimental conditions and treatments

The general experimental conditions and plant material were the same as detailed in Chapter 8 (Section 8.2.1). The experiment was conducted from March to August 2002. Seeds were sown on 18 March 2002 and thirty-eight-day old individual 'Petopride' processing tomato were transplanted and spaced as detailed in Chapter 8 (Section 8.2.1)

Eighteen days after transplanting, the following four irrigation treatments were randomly applied to a total of 48 plants. The first two were as follows: full irrigation by hand to both sides of the root system (RS) which mimicked furrow irrigation (FuI), and half of irrigation water in FuI given only to one side of the RS with each irrigation (PRD<sub>FuI</sub>). The next two irrigation treatments were full drip irrigation (DrI) to both sides of the root system, and half of irrigation water in DrI given only to one side of the RS with each drip irrigation (PRD<sub>DrI</sub>). Irrigation was reversed daily from the wet side to the dry side in PRD treatments. The experiment was conducted in a complete randomised design with four treatments replicated three times.

### 11.2.2 Measurements of soil water content

The plants under PRD<sub>FuI</sub> and FuI were irrigated once a day with 0.6 and 1.2 litres, respectively. Those under PRD<sub>DrI</sub> and DrI received, respectively, the same amounts of water given over two times (10:00 and 16:00 hours) by automated drip irrigation system. PRD<sub>DrI</sub> had one and DrI had two drippers per plant that emitted 4 L per hour. The drippers were placed 150 mm away from the main stem. The drippers were manually shifted over when needed in PRD<sub>DrI</sub> treatment. A total of 65 and 130 L of water (gross irrigation) per plant was applied to PRD and FuI and DrI plants, respectively. Water losses by drainage and their implication on the irrigation use efficiency calculations were considered as mentioned in Chapter 8 (Section 8.2.2). Volumetric soil water content ( $\theta$ ) was daily recorded as detailed in Chapter 3 (Section 3.1). Field capacity was reached at a  $\theta$  of  $0.25 \text{ m}^3 \text{ m}^{-3}$  for the medium and this was established before setting up the experiment according to Parchomchuk et al. (1997).

### 11.2.3 Measurements of photosynthesis, stomatal conductance, and plant water status

Photosynthetic rate ( $A$ ), stomatal conductance ( $g_s$ ), and photosynthetic photon flux (PPF) were measured between 13:30 and 14:30 hours as described in Chapter 3 (Section 3.3). The measurements were taken on 73, 117, 141, and 161 days after seeding (DAS). Diurnal leaf water potential ( $\Psi_{\text{leaf}}$ ) changes were measured as

described in Chapter 3 (Section 3.2.2). Measurements were taken at 6:00, 09:00, 12:00, 15:00, and 18:00 hours.

#### **11.2.4 Measurements of plant growth, yield, harvest index, and irrigation use efficiency**

There was a single harvest during which fruit yield and dry mass of each plant organ, except for the roots, were obtained as described in Chapter 3 (Sections 3.5.2 and 3.6). Harvest index (HI) and irrigation use efficiency ( $IUE_{TFMF}$ ) were calculated as detailed in Chapter 3 (Section 3.5.4 and 3.5.5). Fruit size, in terms of mean fresh mass per fruit, was obtained by dividing fresh mass of fruit by number of fruit.

#### **11.2.5 Advancement in fruit maturity**

The reddest fruit from each plant were used to evaluate the advancement in fruit maturity by collecting 18 fruit per treatment (six per replication). This was done on two occasions on 152 and 163 DAS. Fruit background skin colour, in terms of hue angle ( $HA^\circ$ ), total soluble solids concentration (TSSC), and dry mass concentration of fruit (DMCF) were measured as detailed in Chapter 3 (Sections 3.8.2, 3.8.4, 3.8.5). Additionally, 18 fruit per treatment (six per replication) were collected at green stage and colour development was followed for 16 days. Fruit used for colour and dry mass concentration measurements were included for measurement of total fresh and dry yields.

#### **11.2.6 Fruit quality assessment**

Twelve fruit per treatment (four per replication), from the first trusses over two harvests, were randomly chosen at the firm red stage for quality measurements.  $HA^\circ$  and TSSC were assessed as described in Chapter 3 (Sections 3.8.2 and 3.8.4). After sampling for TSSC, the fruit were oven-dried at 85 °C to a constant mass for

measuring dry mass of fruit and fruit water content was calculated as described in Chapter 3 (Section 3.8.6). All fruit were examined for presence of BER.

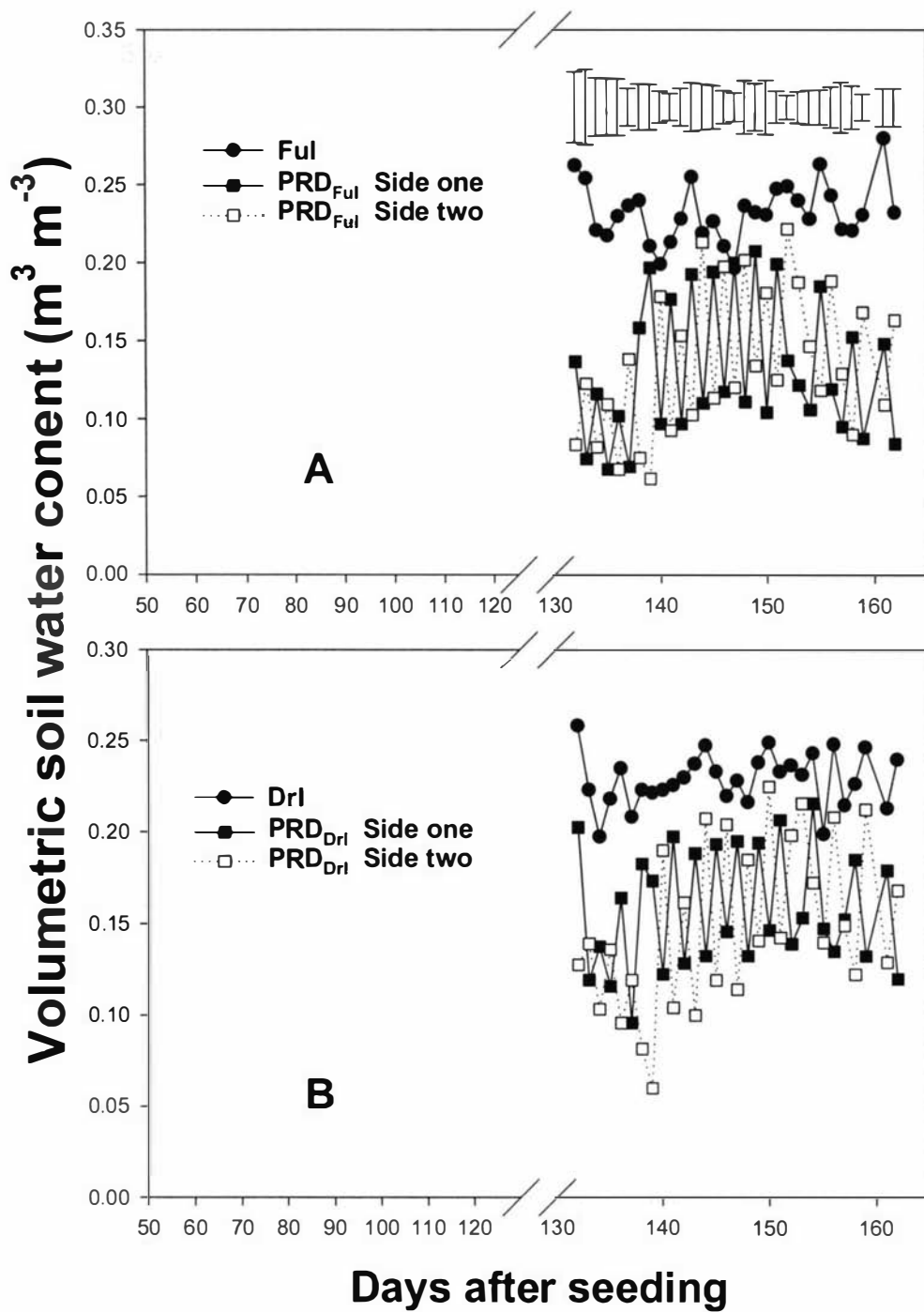
### 11.2.7 Statistical analysis

The data were analysed by complete randomised model using GLM procedure of SAS software. To stabilise the variance, the variables expressed in percentage and in discrete unit were arcsine- and square-root transformed, respectively, as mentioned in Chapter 4 (Section 4.3). Means are reported after back transforming. Treatment means were separated by Tukey's test at  $P \leq 0.05$ .

## 11.3 Results

### 11.3.1 Volumetric soil water content

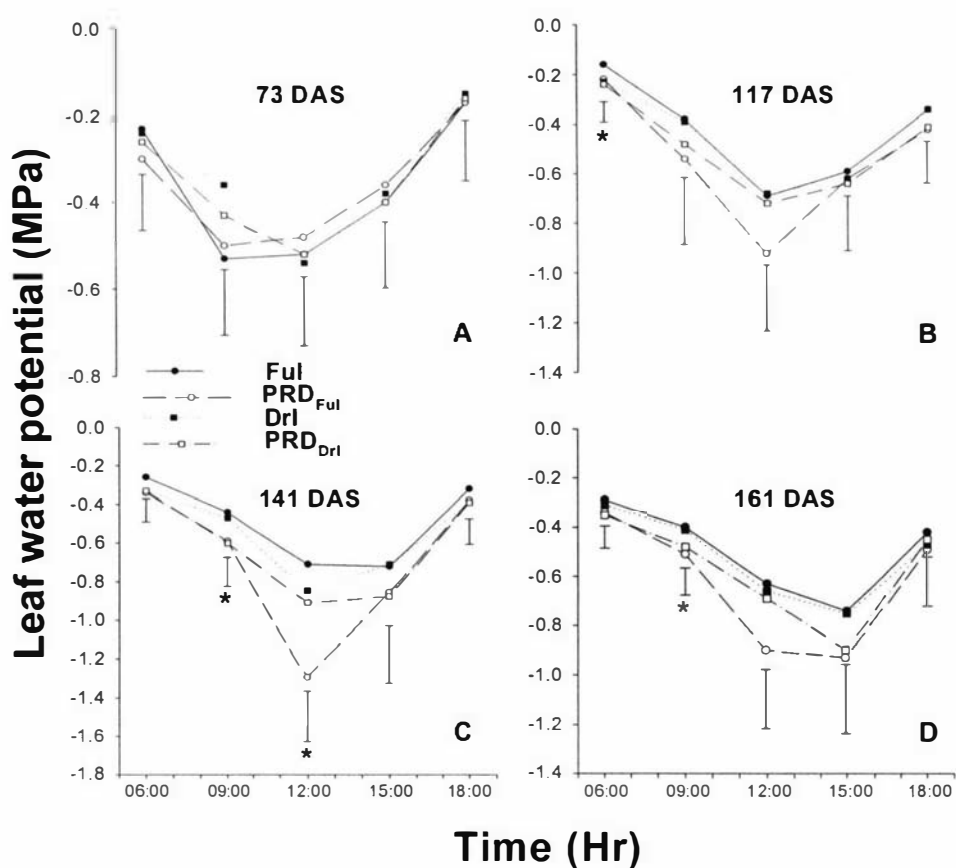
The volumetric soil water content ( $\theta$ ) in FuI and DrI plants ranged between 0.2 and  $0.28 \text{ m}^3 \text{ m}^{-3}$ , while  $\theta$  in the two sides of the root system of PRD<sub>FuI</sub> and PRD<sub>DrI</sub> plants simultaneously increased and decreased during the growing season (Figure 11.1A and B). The  $\theta$  gap between 50 DAS and 130 DAS was due to a malfunctioning of the equipment and therefore impeded data collection.



**Figure 11.1** Changes in soil water content for furrow irrigation (A) and drip irrigation (B) treatments applied either to both sides of plant row (FuI in A and DrI in B) or only to one side at a time. Vertical bars, which apply to A and B, represent the minimum significant difference (MSD) by Tukey's test at  $P \leq 0.05$ .

### 11.3.2 Plant water status, photosynthesis, and stomatal conductance

Diurnal changes in  $\Psi_{\text{leaf}}$  followed a parabolic pattern on all dates of measurement reaching a minimum value at midday and starting to recover early afternoon (Figure 11.2). On 73 DAS,  $\Psi_{\text{leaf}}$  was the same among treatments at all times of the day (Figure 11.2A). On 117 DAS, FuI plants had the highest  $\Psi_{\text{leaf}}$  at 6:00 hr (Figure 11.2B). On 141 DAS, PRD<sub>FuI</sub> and PRD<sub>DrI</sub> plants had lower  $\Psi_{\text{leaf}}$  than FuI and DrI plants at 09:00 hours (Figure 11.2C), but PRD<sub>FuI</sub> plants showed the lowest  $\Psi_{\text{leaf}}$  at midday (Figure 11.2C). Similarly trend for PRD<sub>FuI</sub> plants occurred on 161 DAS (Figure 11.2D).



**Figure 11.2** Diurnal changes in leaf water potential at four 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  $P \leq 0.05$ . Abbreviations are explained in Materials and methods of this Chapter.

A was unaffected by the irrigation treatments for three of four measurements performed (Table 11.1). A reduction in photosynthetic rate in DrI and PRD<sub>DrI</sub> relative to FuI and PRD<sub>FuI</sub> plants was observed on 73 DAS, but  $g_s$  remained unaffected by the treatments in all four measurements conducted (Table 11.1).

**Table 11.1** 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  $P \leq 0.05$ . Abbreviations are explained in Materials and methods of this Chapter.

Parameter	Days after seeding				
	ITs	73	117	141	161
Photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	FuI	7.1a	5.2a	6.0a	9.4a
	PRD <sub>FuI</sub>	7.6a	5.6a	4.5a	7.0a
	DrI	3.6b	6.8a	9.1a	9.6a
	PRD <sub>DrI</sub>	4.7b	7.2a	6.8a	8.3a
Stomatal conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ )	FuI	1.7a	1.1a	1.7a	0.8a
	PRD <sub>FuI</sub>	1.3a	1.2a	1.3a	0.8a
	DrI	1.5a	1.1a	1.6a	0.9a
	PRD <sub>DrI</sub>	1.5a	1.0a	1.5a	0.9a
PPF ( $\mu\text{mol m}^{-2} \text{s}^{-1} \pm \text{SD}$ )		166 $\pm$ 66	461 $\pm$ 130	548 $\pm$ 213	778 $\pm$ 187

### 11.3.3 Plant growth, yield, harvest index, and irrigation use efficiency

Total fresh mass of plant was significantly reduced in PRD<sub>FuI</sub> and PRD<sub>DrI</sub> plants compared with FuI and DrI plants (Table 11.2). However, number of fruit, mean fresh mass per fruit, total fresh mass of fruit, total dry mass of fruit, and harvest index were not affected by the treatments. But there was a trend to reduce total dry mass of fruit in PRD treatments. Irrigation use efficiency was higher in PRD<sub>FuI</sub> and PRD<sub>DrI</sub> plants than in FuI and DrI plants (Table 11.2).

**Table 11.2** Effect of irrigation treatments (ITs) on total fresh mass of plant (TFMP), number of fruit per plant (NF), mean fresh mass per fruit (MFMF), total fresh mass of fruit (TFMF), total dry mass of fruit (TDMF), irrigation use efficiency ( $IUE_{TFMF}$ ), and harvest index (HI) per plant. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

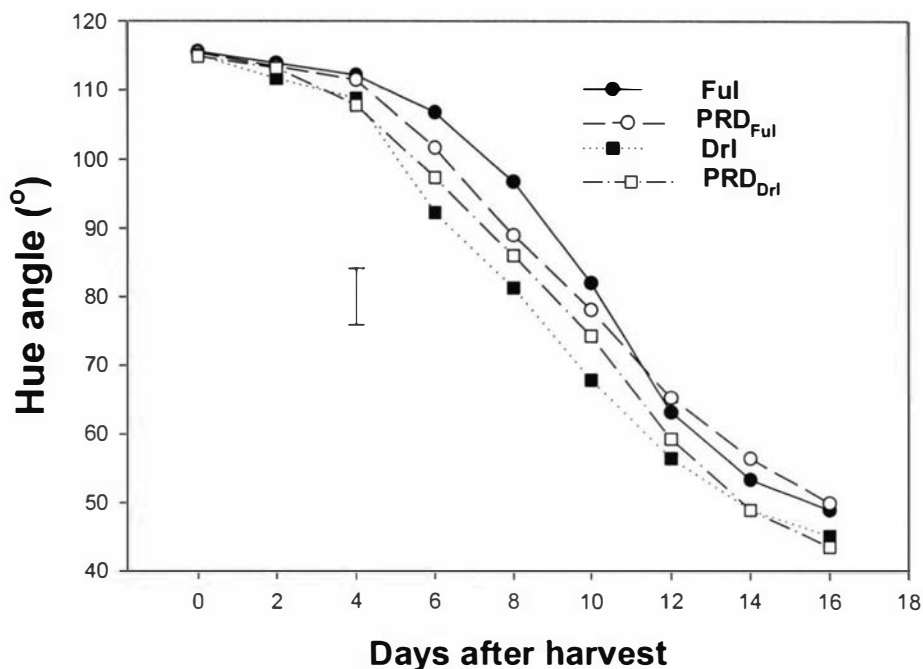
ITs	TFMP (kg plant <sup>-1</sup> )	NF	MFMF (g)	TFMF (kg plant <sup>-1</sup> )	TDMF (g plant <sup>-1</sup> )	$IUE_{TFMF}$ (g L <sup>-1</sup> )	HI
FuI	4.5a	30a	87a	2.7a	162a	20.5b	0.48a
PRD <sub>FuI</sub>	3.6b	29a	84a	2.6a	157a	34.9a	0.53a
Drl	4.7a	33a	88a	2.6a	166a	23.3b	0.53a
PRD <sub>Drl</sub>	3.8b	30a	86a	2.6a	158a	38.0a	0.53a

#### 11.3.4 Advancement in fruit maturity

Fruit maturity advancement was evaluated in terms of dry mass concentration of fruit (DMCF), total soluble solids concentration (TSSC), and skin colour in terms of hue angle ( $HA^\circ$ ) (Table 11.3). On 152 DAS, DMCF and TSSC were statistically the same among treatments. However, the lowest  $HA^\circ$  was observed in PRD<sub>Drl</sub> fruit while the highest was in FuI fruit, thus the former fruit were redder than the latter. On 163 DAS, PRD<sub>FuI</sub> and PRD<sub>Drl</sub> plants had higher DMCF and TSSC relative to FuI and plants, but Drl and PRD<sub>Drl</sub> were more advanced in redness of fruit skin colour relative to FuI and PRD<sub>FuI</sub> (Table 11.3). The last finding was confirmed by following the changes in fruit skin colour ( $HA^\circ$ ) over 16 days (Figure 11.3).

**Table 11.3** Effect of irrigation treatments (ITs) on dry mass concentration of fruit (DMCF), total soluble solids concentration (TSSC), and fruit colour in terms of hue angle (HA°) at two harvest dates. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

Harvest dates	ITs	DMCF	TSSC	HA°
		(mg g <sup>-1</sup> fresh mass)		
152 DAS	FuI	56.1a	4.7a	94.8a
	PRD <sub>FuI</sub>	56.0a	4.9a	88.3a
	DrI	54.5a	4.9a	88.2a
	PRD <sub>DrI</sub>	54.3a	5.1a	63.8b
163 DAS	FuI	55.6b	4.5c	80.4a
	PRD <sub>FuI</sub>	58.4a	5.0ab	79.4ab
	DrI	53.9b	4.7bc	63.1b
	PRD <sub>DrI</sub>	57.7a	5.2a	50.2c



**Figure 11.3** Changes of skin colour of 'Petopride' processing tomato fruit. The treatments are described in the text. Separate bar represents the MSD by Tukey's test at  $P \leq 0.05$ .

### 11.3.5 Fruit quality evaluation at firm red stage

The evaluation of fruit quality at firm red stage showed that PRD<sub>FuI</sub> had the lowest fruit water content. The values (% MSD = 0.37) were 93.9, 93.3, 94.0, and 93.9, for FuI, PRD<sub>FuI</sub>, DrI, and PRD<sub>DrI</sub>, respectively. TSSC was higher in PRD<sub>FuI</sub> and PRD<sub>DrI</sub> fruit than in FuI and DrI fruit. The values (% MSD = 0.48) were 4.5, 5.0, 4.7, and 5.0, for FuI, PRD<sub>FuI</sub>, DrI, and PRD<sub>DrI</sub>, respectively. Redness in skin colour was higher in PRD<sub>DrI</sub> fruit than in FuI, PRD<sub>FuI</sub>, and DrI fruit. The values (HA°, MSD = 4.0) were 45.4, 44.0, 45.1, and 41.1, for FuI, PRD<sub>FuI</sub>, DrI, and PRD<sub>DrI</sub>, respectively.

## 11.4 Discussion

A main purpose of this experiment was to study the development of BER in the fruit. But there was no incidence of this physiological disorder in any of the treatments. While this could be disappointing in some respects, it is heartening to learn that PRD treatments do not cause BER incidence *per se*. BER development has been the subject of intensive research exploring various environmental and plant factors and it is not a drive of my research to try to elaborate on it any further. In this experiment I concentrated on collecting data on other physiological and postharvest quality factors which are discussed below.

The maintenance of leaf water potential in PRD plants depended on the irrigation method used. PRD<sub>FuI</sub> plants tended to have lower leaf water potential than PRD<sub>DrI</sub> plants (Figure 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 (Hartz, 1993), 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 11.1). 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 and Figure 11.2). 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<sub>Ful</sub> plants on 141 DAS, no significant changes in stomatal conductance were noticed. In PRD<sub>Ful</sub>, the stomatal conductance values might have been at their maximum when taken between 13:30 and 14:30 hours.

Total fresh mass of plant was higher in fully irrigated plants than in PRD plants, but number of fruit, mean fresh mass per fruit, and total fresh and dry masses of fruit were the same among treatments (Table 11.2). Tomato fruit, as the strongest sink for photoassimilates (Ho, 1996b), could compete for assimilates in the PRD<sub>Ful</sub> and PRD<sub>DrI</sub> 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 ( $g \pm$  one standard error) were:  $172 \pm 11$ ,  $130 \pm 4$ ,  $162 \pm 7$ , and  $135 \pm 6$  for Ful, PRD<sub>Ful</sub>, DrI, and PRD<sub>DrI</sub> plants, respectively. The maintenance of total dry mass of fruit in PRD<sub>Ful</sub> and PRD<sub>DrI</sub> plants was in agreement with those observed in a split-root experiment (Davis et al., 2000) and in a PRD experiment which was watered mimicking furrow irrigation (Zegbe-Domínguez et al., 2003b). 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. (2003b) did the shifting when volumetric soil water content fell to between  $0.02$  and  $0.1 \text{ m}^3 \text{ m}^{-3}$ . Davis et al. (2000) alternated the irrigation initially between 10-14 days and the alternating frequency was increased according 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 by 70% and 63% in the irrigation use

efficiency. The harvest index therefore became similar among treatments (Table 11.2).

In processing tomatoes, four fruit quality attributes are important for the industry. Fruit colour, in particular lycopene concentration due to its human health benefits is one. Reduced FWC, and therefore higher DMCF and TSSC into the fruit (Ho, 1996a; 1996b), is important because less energy would be needed to dry the fruit (Zegbe et al., 2003a). Advancement in fruit maturity would reduce production cost and it is important in terms of early marketing (May and Gonzales, 1999). The fruit were harvested on 152 (H1) and 163 DAS (H2). Fruit maturity was more advanced, in terms of development of fruit skin colour, in PRD<sub>Dr1</sub> than any other treatment at H1 (Table 11.3, Figure 11.3). This result was consistent not only for PRD<sub>Dr1</sub> fruit, but also for PRD<sub>Ful</sub> fruit at H2 (Table 11.3). 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. A decrease in root cytokinins concentration could be induced in PRD plants (Pillay and Beyl, 1990), hence ethylene production could start the transformation of chloroplasts into chromoplasts in the fruit (Giovannoni, 2001). The ethylene production may have been higher in PRD fruit because they were redder to those of fully irrigated plants (Table 11.3), and the fruit redness is an indicative of higher lycopene concentration (Pulupol et al., 1996). Both treatments also had higher DMCF and TSSC than their respective fully irrigated plants (Table 11.3). This could be presumably due to lower respiration rate and less dilution of TSSC 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  $\Psi_{leaf}$  is associated with reduced assimilates flux rate into the tomato fruit during the daylight, in particular at midday when  $\Psi_{leaf}$  is lower, as observed here in PRD<sub>Ful</sub> and in PRD<sub>Dr1</sub> plants (Figure 11.2C and D). They also observed that when  $\Psi_{leaf}$  started to recover early in the afternoon, the assimilate flux into the fruit not only recovered but also enhanced. This would explain DMCF and TSSC in PRD<sub>Ful</sub> and PRD<sub>Dr1</sub> 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).

## 11.5 Conclusions

The study indicates that PRD did not induce BER incidence *per se*. Also, in general, PRD can maintain the fresh and dry mass of fruit and save water by 50% and therefore increase the irrigation use efficiency by 70 or 63% by using, respectively, PRD<sub>Ful</sub> or PRD<sub>DrI</sub>, in comparison with their respective fully irrigated plants. PRD<sub>DrI</sub> not only increased the irrigation use efficiency by 85% over furrow irrigated plants, but also kept higher photosynthetic rate and leaf water potential comparable to DrI. Fruit maturity was more advanced in PRD<sub>DrI</sub> in terms of redness of fruit with an increase in TSSC and DMCF compared with any other treatment, which is important for processing and for marketing. Either PRD<sub>Ful</sub> or PRD<sub>DrI</sub> has a great potential to be adopted as a water saving practice for limited and non-limited water environments. However, field research needs to be done because processing tomatoes are normally grown in the field rather than in a glasshouse. I conducted this trial in glasshouse conditions to avoid the rain interference. Finally, a wide range of processing tomato varieties should be screened for their ability to respond to PRD, because their genetic potential might produce different results as those presented in this study.

## Chapter 12

### Processing tomato response to partial rootzone drying at different phenological stages

#### Abstract

In the previous research (Chapters 8 and 9), it was observed that PRD maintained the yield and improved quality except for higher incidence of blossom-end rot (BER). The objective of this study was to assess the effects of PRD applied at three phenological stages on yield, yield components, plant efficiency, fruit quality, and especially BER incidence of 'Petopride' processing tomato. The treatments were daily full irrigation (FI) on both sides of the root system (RS) considered as the control and PRD which was applied at three phenological stages: during the first vegetative stage until the first truss was observed ( $PRD_{FVS-FT}$ ), from the first truss to fruit-set ( $PRD_{FT-FS}$ ), and from fruit-set to harvest ( $PRD_{FS-H}$ ).  $\Psi_{leaf}$  was lower in all PRD treatments than in FI. Total fresh mass of plant (TFMP), number of fruit (NF), total fresh mass of fruit (TFMF), total dry mass of fruit (TDMF), irrigation use efficiency in terms of TFMF ( $IUE_{TFMF}$ ), harvest index (HI), and fruit growth were significantly lower in  $PRD_{FT-FS}$  and  $PRD_{FS-H}$  plants compared with FI and  $PRD_{FVS-FT}$  plants. However, irrigation use efficiency in terms of TDMF ( $IUE_{TDMF}$ ) was the same among treatments.  $PRD_{FT-FS}$  and  $PRD_{FS-H}$  plants reduced mean fresh mass per fruit and fruit water content and increased dry mass concentration of fruit and total soluble solids compared with FI and  $PRD_{FVS-FT}$ .  $PRD_{FT-FS}$  plants had the highest BER incidence. Fruit skin colour ( $HA^\circ$ ) was the same among treatments. TDM per plant decreased by 20% for  $PRD_{FS-H}$  plants and by 23% for  $PRD_{FT-FS}$  plants relative to FI plants. Fruit quality improvement in  $PRD_{FS-H}$  could compensate for the reduction in TDMF where water is expensive for tomato production but an economical analysis is needed here.

## 12.1 Introduction

In Chapter 8 two PRD treatments were tested against FI and DI. PRD (daily irrigation of only one side of the root system) produced the same TFMF and TDMF as in FI, but fruit quality was not improved and higher BER was observed. In Chapter 9, irrespective of the extent of soil drying, the reduction in TFMF and TDMF was similar among PRD treatments which all had lower values than FI treatment. Although fruit quality was improved in all PRD treatments, higher BER incidence was observed. In both experiments, PRD treatments saved water by 50% relative to FI. In this experiment, I studied the responses of 'Petopride' processing tomato to PRD at three phenological stages in terms of yield, plant efficiency, and fruit quality. However, I especially focussed the present experiment on identifying which of the plant phenological stages are more sensitive to BER incidence.

Tomato is sensitive to water deficit (Waister and Hudson, 1970) depending on the growth stage of the plant. Flowering, fruit-set (Helyes and Varga, 1994; Pulupol et al., 1996), and fruit growth stages (Johnson et al., 1992) are highly sensitive to water deficit. The main objective of this experiment was to identify a growth stage at which 'Petopride' would be least sensitive to application of PRD. This would be with respect to maintenance of yield and possible improvement of fruit quality. In view of BER development in the previous experiments, I was especially interested in identifying a phenological stage at which development of BER be either minimised or eliminated. This information would be an important decision tool to establish a suitable PRD irrigation program for processing tomatoes. This experiment was carried out in a glasshouse to avoid rain interference.

## 12.2 Materials and methods

### 12.2.1 Experimental conditions and treatments

The general experimental conditions and plant material were the same as detailed in Chapter 8 (Section 8.2.1). The experiment was conducted from November 2002 to

February 2003. Seeds were sown on 12 November 2002 and twenty-day-old individual plants were transplanted and spaced as detailed in Chapter 8 (Section 8.2.1)

Fourteen days after transplanting, the following four irrigation treatments were randomly applied to a total of 48 plants. The treatments were: daily full irrigation (FI) on both sides of the root system (RS) considered as the control and PRD treatments. The latter were applied at three phenological stages: during the first vegetative stage until the first truss was observed ( $PRD_{FVS-FT}$ ), from the first truss to fruit-set ( $PRD_{FT-FS}$ ), and from fruit-set to harvest ( $PRD_{FS-H}$ ). Fruit-set was defined either 95% of the fruit started to grow or when flowers were not seen in four trusses described in Section 12.2.5. However, an overlapping between flowering and fruit-set occurred. During each phenological phase only one side of the RS was watered and the other side allowed to dry for two consecutive days, and then the irrigation was reversed to the dry side of the RS.

### 12.2.2 Measurements of soil water content

With each irrigation  $PRD_{FS-H}$ ,  $PRD_{FT-FS}$ ,  $PRD_{FVS-FT}$ , and FI were given 3.8, 4.1, 4.8, and 5.0 L of water, respectively. This amount of water was daily applied in four irrigation turns (07:00, 10:00, 13:00, and 18:00 hours) by an automated drip irrigation system. A total of 245, 272, 319, and 334 L of water (gross irrigation) per plant were applied to  $PRD_{FS-H}$ ,  $PRD_{FT-FS}$ ,  $PRD_{FVS-FT}$ , and FI plants, respectively. Water losses by drainage and their implication on the irrigation use efficiency calculations were considered as mentioned in Chapter 8 (Section 8.2.2). Volumetric soil water content ( $\theta$ ) was daily recorded as detailed in Chapter 3 (Section 3.1). Field capacity was reached at a  $\theta$  of  $0.30 \text{ m}^3 \text{ m}^{-3}$  for the medium and this was established according to Parchomchuk et al. (1997) before setting up the experiment.

### 12.2.3 Measurements of plant water status

Diurnal leaf water potential ( $\Psi_{\text{leaf}}$ ) changes were measured on two leaves per plant as described in Chapter 3 (Section 3.2.2). The measurements were taken on 45, 57, 65,

85, and 93 days after seeding (DAS). Measurements were taken at 6:00, 09:00, 12:00, 15:00, and 18:00 hours.

#### **12.2.4 Measurements of plant growth, yield, harvest index, and irrigation use efficiency**

There was a single harvest during which data on fruit yield and dry mass of each plant organ were obtained as described in Chapter 3 (Sections 3.5.2 and 3.6). Fruit with a diameter larger than 5.5 cm were included as marketable fruit (Obreza et al., 1996). The incidence of blossom-end rot (BER) was also recorded. Harvest index (HI) and irrigation use efficiency (IUE) were calculated as detailed in Chapter 3 (Section 3.5.4 and 3.5.5). Fruit size, in terms of mean fresh mass per fruit, was obtained by dividing fresh mass of fruit by the number of fruit. Fruit growth was obtained as described in Chapter 3 (Section 3.4.3). This was done on the first two fruit from the first truss from each plant. Measurements started nine days after anthesis and on 7-day intervals prior to harvest.

#### **12.2.5 Flower abortion and fruit growth inhibition**

The first four trusses from the main stem of each plant (four plants per replication per treatment) were tagged as soon as they had clearly developed. Pollination was assisted during anthesis with a truss vibrator to minimise flower abortion and maximise similar number of fruit among treatments. This was done in all trusses and all plants including the tagged ones.

#### **12.2.6 Fruit quality assessment**

Twenty-four fruit per treatment (eight per replication), from the first trusses were randomly chosen at mature-green stage for quality measurements. The fruit background skin colour in terms of hue angle ( $HA^\circ$ ) was assessed at harvest and at the

firm red stage as detailed in Chapter 3 (Section 3.8.2). TSSC, DMCF, and FWC were assessed as described in Chapter 3 (Sections 3.8.4, 3.8.5, and 3.8.6).

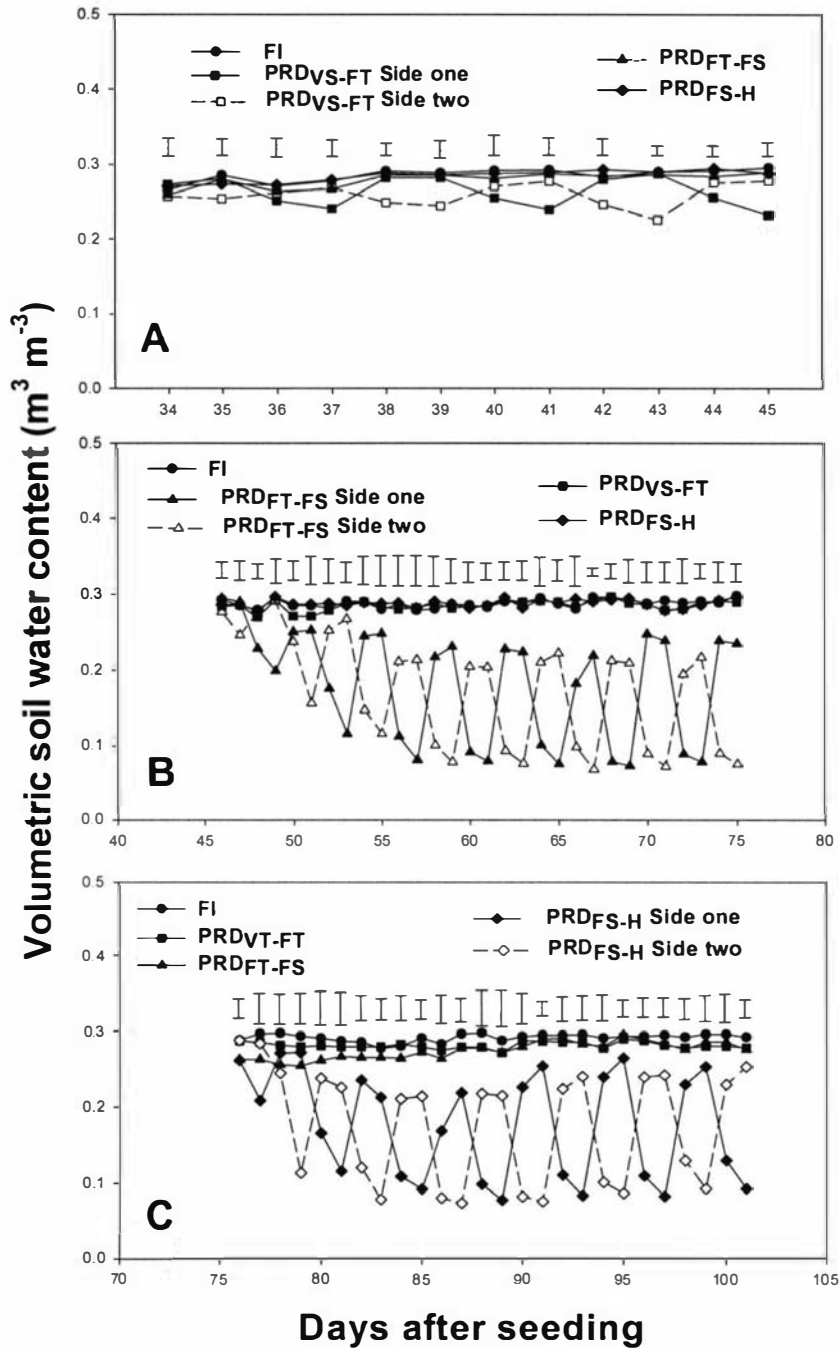
### 12.2.7 Statistical analysis

Data were analysed by a complete randomised model using the GLM procedure of SAS software. To stabilise the variance, the variables expressed in percentage were arcsine-transformed and those expressed in discrete units were square-root transformed, respectively, as mentioned in Chapter 4 (Section 4.3). Means are reported after back transforming. Treatment means were separated by Tukey's test at  $P \leq 0.05$ . Data were further studied by canonical discriminant analysis as detailed in Chapter 5 (Section 5.3).

## 12.3 Results

### 12.3.1 Volumetric soil water content

A, B, and C of Figure 12.1 correspond, respectively, to the phenological stages of PRD<sub>FVS-FT</sub>, PRD<sub>FT-FS</sub>, and PRD<sub>FS-H</sub> plants. The volumetric soil water content ( $\theta$ ) on both sides of the root system of PRD<sub>FVS-FT</sub> plants simultaneously increased and decreased during that phenological stage, while  $\theta$  of the remaining treatments was kept close to field capacity (Figure 12.1A). Similar  $\theta$  changes were observed in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants (Figures 12.1B and C).

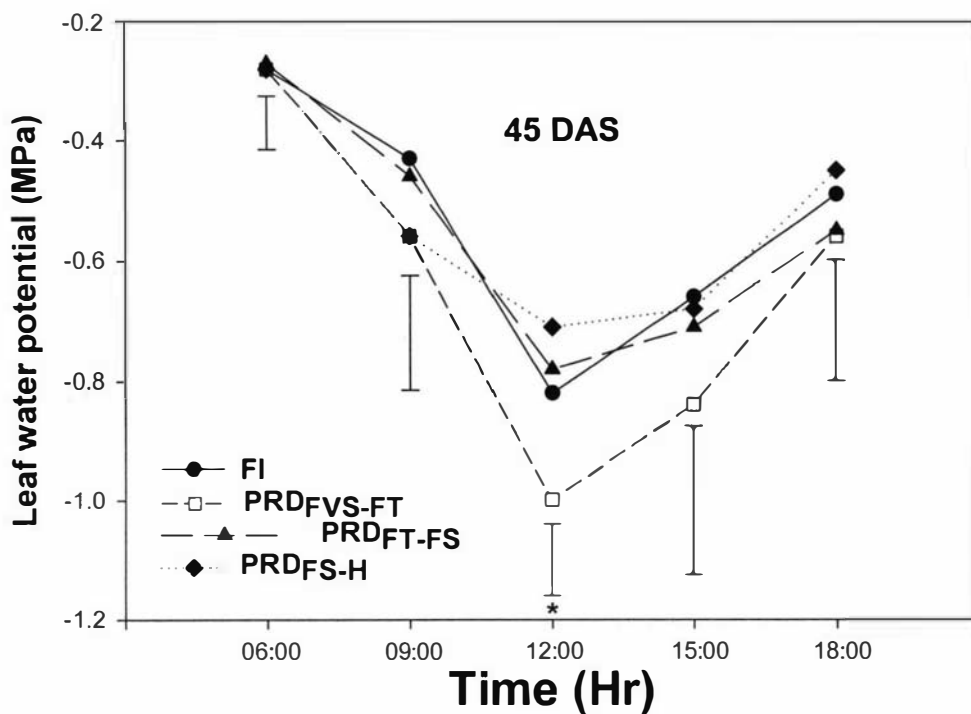


**Figure 12.1** Changes in volumetric soil water content for fully irrigated (FI) plants and PRD treatments in ‘Petopride’ processing tomato. Vertical bars represent the minimum significant difference (MSD) by Tukey’s test at  $P \leq 0.05$ .

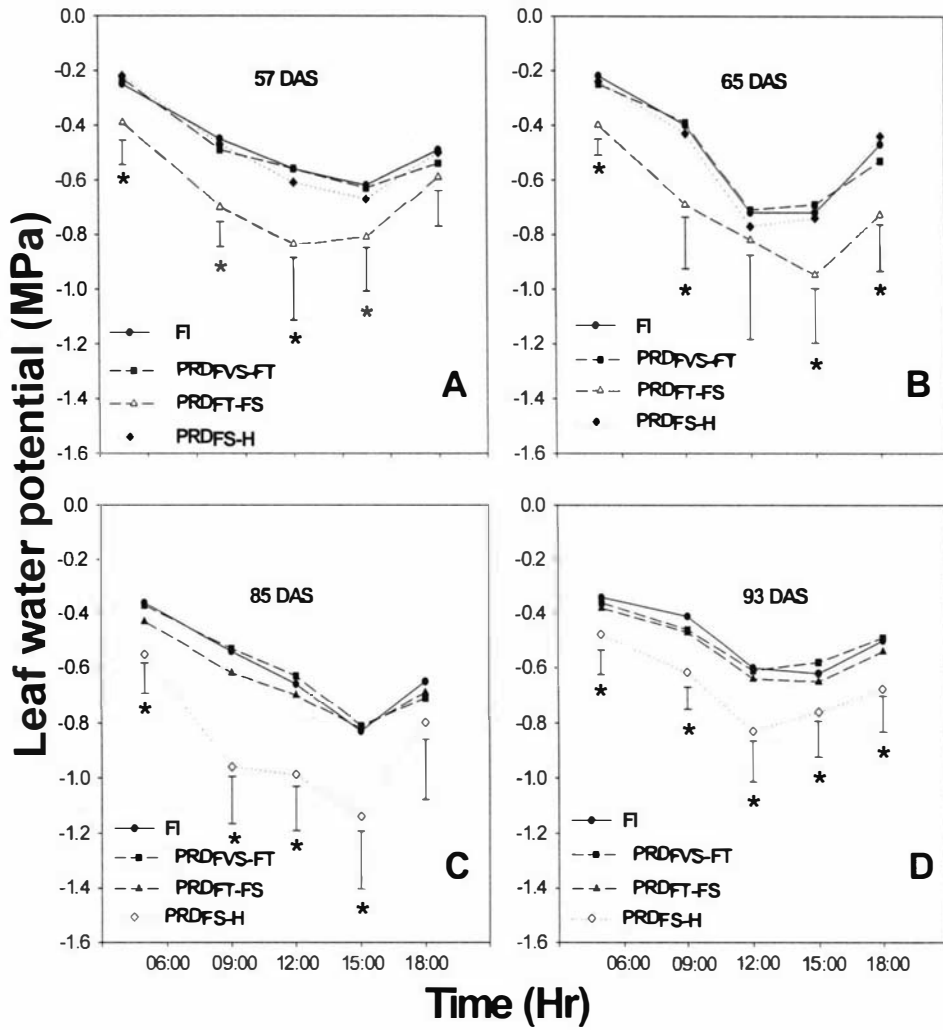
### 12.3.2 Plant water status

Diurnal changes in  $\Psi_{\text{leaf}}$  followed a parabolic pattern on all dates of measurement reaching a minimum value at midday and starting to recover early afternoon (Figures 12.2 and 12.3). Except for PRD<sub>FVS-FT</sub> plants,  $\Psi_{\text{leaf}}$  was the same among treatments at all times of the day on 45 DAS (Figure 12.2).  $\Psi_{\text{leaf}}$  was significantly lower in PRD<sub>FVS-FT</sub> plants at 12:00 hours.

Plants exposed to PRD<sub>FT-FS</sub> had the lowest  $\Psi_{\text{leaf}}$  on 57 DAS and 65 DAS (Figures 12.3 A and B). The same occurred in plants under PRD<sub>FS-H</sub> on 85 DAS and 93 DAS (Figures 12.3C and D).



**Figure 12.2** Diurnal changes in leaf water potential of different treatments which are described in the text. Vertical bars represent the MSD by Tukey's test and the asterisk shows significant differences at  $P \leq 0.05$ .



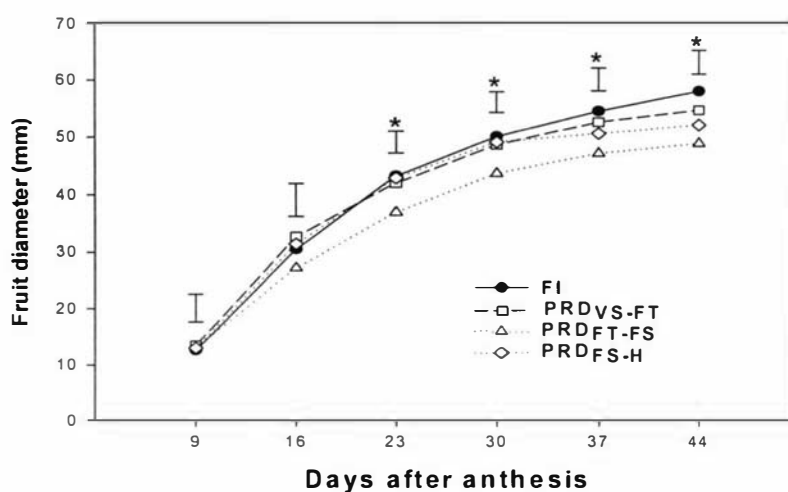
**Figure 12.3** Diurnal changes in leaf water potential at four occasions under four irrigation treatments. The treatments are described in the text. Vertical bars represent the MSD by Tukey's test and the asterisks show significant differences at  $P \leq 0.05$ .

### 12.3.3 Plant growth, yield, harvest index, and irrigation use efficiency

Total fresh mass of plant was significantly reduced in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants compared with FI and PRD<sub>FVS-FT</sub> plants (Table 12.1). The same was true for NF, TFMF, TDMF, IUE<sub>TFMF</sub>, and HI (Table 12.1), however IUE<sub>TDMF</sub> was the same among treatments (Table 12.1). Fruit growth was lower in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants compared with FI and PRD<sub>FVS-FT</sub> plants (Figure 12.4).

**Table 12.1** Effect of irrigation treatments (ITs) on total fresh mass of plant (TFMP), number of fruit per plant (NF), total fresh mass of fruit (TFMF), total dry mass of fruit (TDMF), irrigation use efficiency in terms of TFMF (IUE<sub>TFMF</sub>) and TDMF (IUE<sub>TDMF</sub>), and harvest index (HI) per plant. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	TFMP (kg plant <sup>-1</sup> )	NF (per plant)	TFMF (kg plant <sup>-1</sup> )	TDMF (g plant <sup>-1</sup> )	IUE <sub>TFMF</sub> (g L <sup>-1</sup> H <sub>2</sub> O)	IUE <sub>TDMF</sub> (g L <sup>-1</sup> H <sub>2</sub> O)	HI
FI	8.8a	52ab	5.3a	523ab	16ab	1.6a	0.57a
PRD <sub>FVS-FT</sub>	9.5a	60a	5.9a	588a	18a	1.8a	0.56ab
PRD <sub>FT-FS</sub>	7.2b	46bc	3.5b	404b	13b	1.5a	0.47bc
PRD <sub>FS-H</sub>	7.4b	40c	3.4b	416b	13b	1.6a	0.46c



**Figure 12.4** Cumulative fruit growth, in terms of fruit diameter of 'Petopride' processing tomato 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  $P \leq 0.05$

### 12.3.4 Fruit quality

PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants had lower MFMF and FWC and higher DMCF and TSSC than FI and PRD<sub>FVS-FT</sub> plants (Table 12.2). However, PRD<sub>FT-FS</sub> plants had the highest BER incidence (Table 12.2). HA° was statistically the same among treatments, nevertheless there was a trend to increase redness in skin colour (HA°) in PRD<sub>FS-H</sub> (Table 12.2).

**Table 12.2** Effect of irrigation treatments (ITs) on mean fresh mass per fruit (MFMF), dry mass concentration of fruit (DMCF), fruit water content (FWC), total soluble solids concentration (TSSC), blossom-end rot (BER), and fruit colour in terms of hue angle (HA°) at green and firm red stages. The treatments are described in the text. Different letters within columns indicate significant differences by Tukey's test at  $P \leq 0.05$ .

ITs	MFMF	DMCF	FWC	TSSC	BER	HA°	
	(g)	(mg g <sup>-1</sup> fresh wt)	(%)	(%)	(%)	Green	Red
FI	99.0a	53.1b	95.0a	4.6b	4b	84a	46a
PRD <sub>FVS-FT</sub>	97.8a	55.0b	94.9a	4.8b	8b	84a	46a
PRD <sub>FT-FS</sub>	73.8b	64.3a	94.2b	5.4a	48a	79a	45a
PRD <sub>FS-H</sub>	83.3b	61.9a	94.2b	5.5a	8b	76a	42a

### 12.3.5 Multivariate analysis

Yield, yield components, plant efficiency and fruit quality attributes were further examined by canonical discriminant analysis (CDA). This multivariate analysis was performed using the following thirteen response variables: TFMP, NF, TFMF, TDMF, IUE<sub>TFMF</sub>, IUE<sub>TDMF</sub>, HI, MFMF, DMCF, FWC, TSSC, BER, and HA°. The square Mahalanobis distance and the multivariate statistics and F approximation suggested a clear difference among treatments (Table 12.3). To corroborate the multivariate results, the standardised canonical scores (SCS) from the first canonical discriminant function (CDF) were subjected to a univariate analysis and mean separation by Tukey's test at  $P \leq 0.05$ . The latter statistical analysis supported the multivariate test where the 13 variables were considered collectively. Using SCS of the first CDF indicated that the horticultural attributes collectively were significantly different in FI and PRD<sub>FVS-FT</sub> plants than those of PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants. The values (SCS, MSD = 1.4) were

13.6, 7.4, -8.3, and -12.6 for FI,  $PRD_{FVS-FT}$ ,  $PRD_{FT-FS}$ , and  $PRD_{FS-H}$  plants, respectively. Although the first CDF accounted for 94% of the variation and explanation among treatments, the second CDF was kept only for plotting the SCS for each treatment (Figure 12.5).

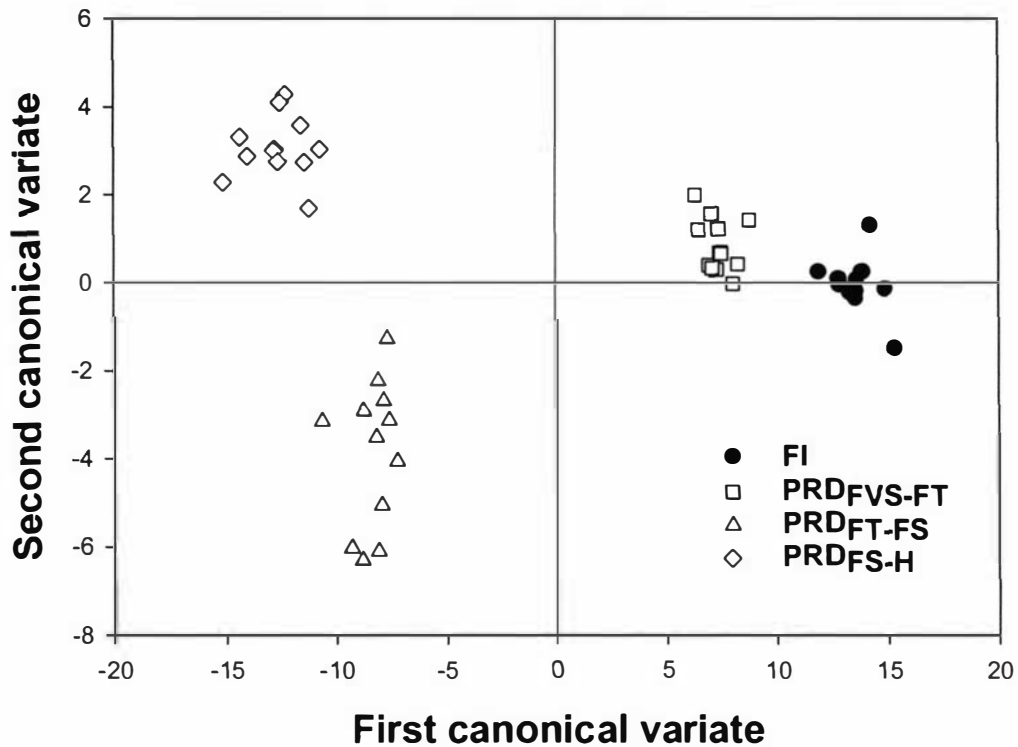
**Table 12.3** Mahalanobis squared distance and significance ( $P \leq 0.0001$ , \*\*\*\*) from irrigation treatments to irrigation treatments (ITs).

ITs	FI	$PRD_{FVS-FT}$	$PRD_{FT-FS}$	$PRD_{FS-H}$
FI	0	15.9 ***	166.2 ***	233.1 ***
$PRD_{FVS-FT}$		0	90.9 ***	136.9 ***
$PRD_{FT-FS}$			0	22.3 ***
$PRD_{FS-H}$				0

The first CDF accounted for 94% of the separation among treatments and the standardised canonical coefficients (SCC) were positively weighed toward NF, MFMF, TDMF, and HI, but negatively weighed toward  $IUE_{TFMF}$ ,  $IUE_{TDMF}$ , BER, and TSSC (Table 12.4). NF, MFMF, TDMF, and HI were moderately and highly correlated with CDF, while BER and TSSC showed comparatively low and moderate negative correlation with CDF. Discrimination between FI and  $PRD_{FVS-FT}$  plants and  $PRD_{FT-FS}$  and  $PRD_{FS-H}$  plants can be based on higher NF, MFMF, TDMF, and HI, and lower  $IUE_{TFMF}$ ,  $IUE_{TDMF}$ , and TSSC (Figure 12.5).

**Table 12.4** Standardised canonical coefficients (SCC) and correlation coefficients (r) for the first canonical discriminant function (CDF) and thirteen horticultural attributes of 'Petopride' processing tomato.

Variable	CDF	
	SCC	r
Total fresh mass of plant	0.3	0.8
Number of fruit	4.7	0.6
Mean fresh mass per fruit	2.7	0.8
Total fresh mass of fruit (TFMF)	-0.1	0.8
Total dry mass of fruit (TDMF)	7.0	0.7
Irrigation use efficiency <sub>(TFMF)</sub>	-7.2	0.5
Irrigation use efficiency <sub>(TDMF)</sub>	-7.2	0.2
Harvest index	1.2	0.6
Blossom-end rot	-0.3	-0.5
Total soluble solids concentration	-0.5	-0.8
Dry mass concentration of fruit	0.3	-0.7
Fruit water content	-0.0	0.8
Hue angle	-0.4	0.3
Canonical correlation	0.99	
Eigenvalue	128	
Variance explained (%)	94	
Significance	0.0001	



**Figure 12.5** Canonical scores of the first two canonical discriminant functions and thirteen horticultural attributes of 'Petopride' processing tomato (variables in Table 12.4) under four irrigation treatments. The treatments are described in the text.

## 12.4 Discussion

Leaf water potential was reduced in PRD treatments at all three phenological stages (Figure 12.2 and 12.3). The decrease in leaf water potential was more noticeable in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants (Figure 12.3A-D). This could be, in part, due to the extent of soil dryness reached at each phenological stage (Figure 12.1). Besides, the root system was confined to a relatively small container, which may also limit water availability to the plants. Field-grown tomato with a dense canopy, where evaporation from the soil will be low, it is expected that leaf water potential for PRD treatments might be maintained because the roots could take up sufficient water from deeper parts of the soil profile.

The duration of PRD<sub>FVS-FT</sub> of just 11 days might not have been long enough to induce adverse effects on yield parameters and therefore all yield attributes became similar to the FI plants (Table 12.1). Compared to the other treatments, PRD<sub>FVS-FT</sub> had enhanced root growth in terms of dry mass and the difference was significant with FI. The values (g, MSD = 4.3) were 14.3, 20.3, 19.0, and 18.5 for FI, PRD<sub>FVS-FT</sub>, PRD<sub>FT-FS</sub>, and PRD<sub>FS-H</sub>, respectively. The higher root growth for the PRD treatments might have been stimulated by the frequent alternation of the irrigation from one side of the root system to the other and exposure of root to water deficit which encourages their growth (Vartanian, 1981; Steudle, 2000). This may have implications for the enhancement of water uptake (Vartanian, 1981; Steudle, 2000) and yield under field conditions. Yield reduction in tomato is attributed to floral abortion when water deficit is applied during flowering and fruit set (Helyes and Varga, 1994; Pulupol et al., 1996). However, in this study flower abortion and the number of undeveloped fruit were not responsible for the reduced yield in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants (Table 12.1). The percentage of floral abortion (MSD = 3.9) was 1.1, 1.1, 3.6, and 2.4 for FI, PRD<sub>FVS-FT</sub>, PRD<sub>FT-FS</sub>, and PRD<sub>FS-H</sub>, respectively. While the percentage of undeveloped fruit ( $\pm$  one SE) was  $44 \pm 2.5$ ,  $46 \pm 2.3$ ,  $44 \pm 2.9$ , and  $44 \pm 2.8$  for FI, PRD<sub>FVS-FT</sub>, PRD<sub>FT-FS</sub>, and PRD<sub>FS-H</sub>, respectively. However, the number of undersized fruit (fruit diameter less than 55 mm) was higher in PRD<sub>FT-FS</sub>, and PRD<sub>FS-H</sub> compared with FI and PRD<sub>FVS-FT</sub> which would explain better the reduction in yield attributes in the former two treatments. The mean number of undersized fruit (MSD = 20) was 21, 15, 36, and 31 for FI, PRD<sub>FVS-FT</sub>, PRD<sub>FT-FS</sub>, and PRD<sub>FS-H</sub>, respectively.

The duration of each PRD treatment, the amount of water supplied, and possibly the water lost by drainage during each phenological stage may have contributed to the similarity of irrigation use efficiency among treatments. However, the water lost by drainage was minimised by adjusting irrigation with the development of the crop. Nevertheless, compared to FI, water was saved by 6%, 20%, and 25% for PRD<sub>FVS-FT</sub>, PRD<sub>FT-FS</sub>, and PRD<sub>FS-H</sub>, respectively. This is particularly useful if PRD<sub>FS-H</sub> were applied in horticultural systems where water is a limiting factor for processing tomato production.

Lower fruit growth, in terms of fruit diameter and therefore lower fresh mass of fruit (Figure 12.4 and Table 12.2), in PRD<sub>FT-FS</sub> is indicative that fewer cell number and reduced cell size might have been induced by an interaction between an imbalance of non-hydraulic mechanisms (Mapelli et al., 1978; Ho, 1984) and water deficit as reflected in the lower leaf water potential developed (Figure 12.3A and B). This conclusion was reached because when PRD<sub>FT-FS</sub> plants were fully rewatered, compensatory fruit growth did not occur thereafter (Figure 12.4). Low fruit water content in PRD<sub>FT-FS</sub> may be due to smaller cell size and thus a reduced capacity to store water within cells. Reduction of fruit growth and fruit water content (Table 12.2 and Figure 12.4) in PRD<sub>FS-H</sub> may be more related to a reduction in water transport to fruit and competition among fruit (Ho, 1996a; 1996b).

Reduced fruit water content, and therefore higher dry mass concentration of fruit and increased total soluble solids concentration (Ho, 1996a; 1996b) are important for the processing industry because less energy would be needed to dry the fruit. These parameters were higher in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants than in FI and PRD<sub>FVS-FT</sub> plants (Table 12.2 and Figure 12.4). Water transport through the xylem to the fruit might have been reduced. This may explain the lower fruit water content in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub>. However, assimilate imports must have continued and this accounted for the increase in dry mass concentration of fruit in the latter two treatments. Kitano et al. (1996) found that lower diurnal leaf water potential (as observed here in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> plants (Figure 12.3A-D) enhanced the assimilate flux into the tomato fruit. This may have occurred in the latter treatments. Higher total soluble solids concentration in tomato fruit under low leaf water potential has been attributed to lower respiration rates and a lower dilution in the fruit resulting from reduced water level within the fruit (Young et al., 1993). Additionally, under water deficit, there is a higher conversion of starch into sugars (Kramer, 1983, p. 364).

PRD<sub>FT-FS</sub> was the most susceptible phenological stage to blossom-end rot incidence (Table 12.2). Blossom-end rot is associated with local calcium deficiency in the distal fruit tissue (Ho, 1999). This arises due to low levels of water transport across the plant and may also be associated with hormonal imbalance (Saure, 2001). Lower fruit water content in PRD<sub>FT-FS</sub> plants is indicative that water transport through xylem to fruit was also low, leading a higher incidence of blossom-end rot in this treatment. Higher

blossom-end rot presence in PRD<sub>FT-FS</sub> fruit suggests that a combination of water deficit (Ho, 1999) and hormonal imbalance (Bangerth, 1979) might have occurred in PRD<sub>FT-FS</sub> fruit. However, for PRD applied either before or after this phenological stage, blossom-end rot incidence was similar to FI plants (Table 12.2). This would obviate the need for Ca<sup>2+</sup> sprays on young fruit, a method suggested by Ho (1999). The avoidance of Ca<sup>2+</sup> sprays would reduce production cost on processing cultivars susceptible to blossom-end rot. Fruit colour, in terms of hue angle, was the same among treatments (Table 12.2). This suggests that PRD applied at different phenological stages does not delay red colour development as observed in tomatoes under deficit irrigation (Vittum et al., 1962; May and Gonzales, 1999).

## 12.5 Conclusions

This study showed that PRD<sub>FVS-FT</sub> plants could produce fruit similar in yield and quality to FI plants, for a saving of 5% in irrigation water. Greater water savings were achieved in PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub>, but they produced significantly more undersized fruit and therefore reduced yield in terms of both fresh and dry mass. These treatments showed increases in dry mass concentration of fruit and total soluble solids concentration with a corresponding reduction in fruit water content. The multivariate analysis discriminated to PRD<sub>FT-FS</sub> and PRD<sub>FS-H</sub> as the best treatments for fruit quality. PRD<sub>FT-FS</sub> realized water saving of 20%, but induced higher blossom-end rot incidence and therefore cannot be recommended as a PRD option. Fruit quality improvement in PRD<sub>FS-H</sub> plants could compensate for the reduction in total fresh and dry masses of fruit where water is expensive for tomato production in view of 25% of water saved for this treatment compared to FI.

## Chapter 13

### General discussion, conclusions, and recommendations

#### 13.1 General discussion and conclusions

Water, to irrigate agricultural lands, is scarce and expensive in different horticultural systems (Csizinszky, 1993). New irrigation strategies are now essential to manage and to save water (van Schilfgaarde, 1994). Minimising water use would not only reduce the contamination of the land and water resources, but also production costs, and might also increase net farm income (English and Raja, 1996). However, before adopting a reduced irrigation strategy to save water, it is essential to understand its effects on crop production. So far, deficit irrigation has been an option in minimising water usage in fruit tree production (Behboudian and Mills, 1997) and vegetable production as showed for tomatoes by Waister and Hudson (1970), Rudich et al. (1977), Mitchell et al. (1991a), Obreza et al. (1996), and Pulupol et al. (1996). Partial rootzone drying (PRD), which is defined in Chapter 1 (Section 1.2), could be another option for saving water for irrigation. Much research information on split-root experiments has been referred to as PRD for different horticultural crops (Kang et al., 1998; Cantore et al., 2000; Davis et al., 2000; Loveys et al., 2000; Stoll et al., 2000; Kang et al., 2001; Yao et al., 2001). Before my research, only three field experiments had been conducted under the PRD definition given in this dissertation and on a field scale. These were conducted for maize (Kang et al., 2000), grape (Loveys et al., 2000), and pear (Kang et al., 2002). However, information on the physiology of plant, yield, plant efficiency, and fruit quality were still limited and inconclusive.

I decided to conduct field experiments in apple trees because this fruit crop is grown in many countries and therefore in a wide range of environmental conditions (Westwood, 1993, p. 50-53) and require irrigation to achieve high yields. Under the same criteria, 'Petopride' processing tomato was selected. All tomato experiments were conducted

under glasshouse to avoid interference by rain. However, my studies were performed mimicking field conditions and without splitting the root system. To achieve this, I designed and built twelve wooden boxes each housing four containers described in Chapters 7 and 8 (Sections 7.2.1 and 8.2.1).

Three field experiments were conducted in apple: one with 'Royal Gala' and two with 'Pacific Rose™'. Experiments 1 and 3 on 'Pacific Rose™' were conducted at Fruit Crops Unit in Manawatu region during the 2000/01 and 2001/02 growing seasons (Chapters 4 and 6, respectively). Experiment 2 for 'Royal Gala' apple was conducted in a commercial orchard in Hawke's Bay during 2001/02 growing season (Chapter 5).

For Experiment 1 two treatments were applied, commercial irrigation (CI) and PRD. Trees were irrigated using microsprinkler irrigation. One side of the tree row was irrigated and the other side left to dry for the whole growing season in PRD trees. The same treatments were explored in Experiment 3 using drip irrigation. In the latter experiment PRD irrigation was shifted from the wet side to the dry side of the tree row when the volumetric soil water content ( $\theta$ ) ranged between 18% and 22%. In both experiments, in general, the rate of photosynthesis ( $A$ ), stomatal conductance ( $g_s$ ), transpiration rate ( $E$ ), and leaf water potential ( $\Psi_{\text{leaf}}$ ) were the same between treatments. The  $\Psi_{\text{leaf}}$  maintenance in PRD could be explained by the increase in rate of water acquisition by the roots in the wetted soil and enhancement of water absorption by the previously dried root when re-watered (Green and Clothier, 1995; Green et al., 1997). Other possibility to maintain  $\Psi_{\text{leaf}}$  could be related with the ability of apple root system to explore large volume of soil and to extract water from other sites where it is more freely available (Hsiao, 1990; Green and Clothier, 1999). However, it has been suggested that for plants under split-root system, the roots in the dry soil may survive because there is water flow from wetted roots to dry roots (Poni et al., 1992; Dry et al., 2000b; Loveys et al., 2000). The study of tomato  $\Psi_{\text{root}}$ , described in Chapter 10, showed that there were different pressure gradients within root system ( $\Psi_{\text{Wet\_root}} - \Psi_{\text{Dry\_root}}$ ) and between roots and leaves ( $\Psi_{\text{root}} - \Psi_{\text{leaf}}$ ). This depended on the extent of soil dryness. The difference between  $\Psi_{\text{Wet\_root}}$  and  $\Psi_{\text{Dry\_root}}$  is indicative that there was no water movement from the wet roots to the dry roots. Sap flow studies in roots and

stems would provide important information on water movement and mineral transport across the soil-plant-atmosphere-continuum.

The maintenance  $\Psi_{\text{leaf}}$  in PRD trees (Chapters 4 and 5) allowed that yield, fruit mass, yield efficiency, trunk growth, and final shoot growth were the same as the CI trees. In the three apple experiments, 50% of the water was saved and the yield was the same between CI and PRD trees. Although more research in a dry environment is required to be conducted, PRD could be seen as a water saving practice for apple production. Nevertheless, this irrigation strategy could be recommended for New Zealand apple growing areas of Hawke's Bay and Marlborough. The commercial orchard that I used for my research in Hawke's Bay had fast-draining gravelly soil near a river bed. I covered the soil for the duration of my experiment and as I reported in Chapter 5 there was no water deficit effect on the tree performance. In New Zealand commercial orchards using the PRD system, there would be the strong possibility of rainfall during the growing season insuring that PRD will not impose undue water deficit on the trees. But irrigation water, which is increasingly becoming a precious commodity, could be still saved by 50%.

In processing tomato,  $\Psi_{\text{leaf}}$  in PRD, DI, and fully irrigated plants were the same in the experiment described in Chapter 7. However, fruit fresh mass was lower in PRD and DI plants than in the control plants. But fruit dry mass was the same among treatments. An important conclusion from this experiment was that fruit fresh mass was affected by the quantity of irrigation water applied, but not by the volume of soil wetted. The same conclusion was reached for apple by Caspari et al. (2002). To conduct the other tomato experiments, three important changes were done in the design of containers. Firstly, a small piece of wood was placed centrally in the bottom of each compartment to avoid lateral water movement. Secondly, compartments were lined with polyethylene and laterally perforated at the bottom to allow drainage. Finally, automated drip irrigation was set up. Thereafter, a series of experiments were conducted for different situations. The experiment described in Chapter 8 showed that  $\Psi_{\text{leaf}}$  was the same in PRD and control plants. This was achieved only if the irrigation is reversed daily from the wet side to the dry side of the root system in PRD plants. Therefore plant and fruit size parameters were the same between PRD and control plants. Although the same amount

of water was given to PRD and DI plants, the latter plants had significantly lower plant and fruit size parameters. Experiments described in Chapters 7 and 8 showed that PRD has more advantages over DI.

The  $\Psi_{\text{leaf}}$  maintenance has been one of the most interesting findings in split-root experiments (SRE) in bell pepper (Yao et al., 2001) and young fruit trees (Gowing et al., 1990; Poni et al., 1992; Stoll et al., 2000). These experiments were conducted for short-term and maybe the time was not long enough to develop measurable changes in plant water status. The latter statement was corroborated with the experiment described in Chapter 9. Plants were exposed to three different extents of soil drying under PRD during the growing season. Lower  $\Psi_{\text{leaf}}$  was observed in all PRD plants than in control plants and various growth parameters were significantly reduced in the former plants. The same was observed in pepper under split-root experiment (Cantore et al., 2000). In all PRD treatments described in Chapters 7, 8, and 9, irrigation use efficiency was improved and irrigation water was saved by 50%.

The improvement in tomato fruit quality by PRD was more related with the extent of soil drying, lower  $\Psi_{\text{leaf}}$ , and plant growth stage (Chapters 7, 8, 9, 11, and 12). Fruit quality improvement and advancement in fruit maturity, in terms of total soluble solids concentration, fruit water content, fruit colour, and maintenance of fruit mass was achieved using drip irrigation and  $\Psi_{\text{leaf}}$  around  $-1.0$  MPa (Chapter 11). But research with deficit irrigation in processing tomato (e.g. May and Gonzales, 1999) has shown that fruit quality improvement might be at the expense of compromising yield. Research under field conditions is needed to corroborate my findings with the application of PRD. Fruit quality improvement and advancement in fruit maturity of apple deserves also research in dry environments because the Experiment 3 described in Chapter 5 suggested that FF and TSSC of 'Royal Gala' apple were improved in PRD fruit over CI fruit. In the same experiment, lower starch pattern index (SPI), observed in PRD fruit than in CI, is indicative of advancement in fruit maturity. Higher IEC was observed in 'Pacific Rose™' (Chapter 6). This is also indicative of fruit maturity advancement, but this needs more investigation.

Development of blossom-end rot (BER) should be one of the considerations in introducing any new management system for tomatoes, especially irrigation and fertilisation. Although studying BER was not one of the objectives of this study, in various experiments I noticed higher-than-acceptable incidence of this disorder for some of the PRD treatments. I therefore designed a special experiment to assess the effect of PRD, and the way it is applied, on the development of BER (Chapter 11). However, in this experiment there was no incidence of BER in any of the PRD treatments I applied using both drip and furrow irrigation methods. I therefore concluded that PRD *per se* is not a cause of BER development. It was in Chapters 8 and 9 that I reported a higher incidence of BER in the PRD treatments than the control. This was minimised by applying PRD before flowering and after fruit set. It was concluded that for 'Petopride' the most sensitive phenological stages for BER incidence is from the first truss development to fruit set. More details about BER are given in Chapter 12 (Section 12.4).

In Experiment 1 (Chapter 4), fruit water loss of 'Pacific Rose™' was lower after storage at 1 °C for 12 weeks and at 20 °C for 18 days. In Experiment 3 (Chapter 6) where irrigation was reversed from the wet side to the dry side of the PRD trees, fruit water loss was the same between control and PRD trees. This suggests that PRD (in Experiment 1) might have modified fruit skin permeance. But this needs to be investigated. Fruit with lower water loss are highly preferred by the industry for either distant markets or for long-term storage.

I think one of the major findings of this dissertation is that although tomato fruit is a strong sink under normal circumstances, it becomes a weaker sink than vegetative organs during water deficit. This is suggested by the relative distribution of dry mass in roots, stems, leaves and fruit under some PRD treatments and all DI treatments tested in this dissertation (Chapters 7, 8, and 9). This has not been explored in woody plants under PRD in a dry environment. However, for 7 year-old almond trees dry mass partitioning into roots, trunk, scaffolds, branches, spurs, and stems was studied (Esparza-Frausto, 1999, p. 110.), but yield was not included. Dry mass of the organs tended to decrease in DI trees compared with control trees. However, total non-structural carbohydrates on each organ were significantly lower in DI than in control

trees. The latter finding is indicative that the allocation of photoassimilates to each tree organ could be modified somehow which deserves investigation under PRD in dry environments.

### 13.2 Recommendations for future research

This study suggests the following topics for future research.

1. Field PRD studies in dry regions are recommended for apple and processing tomato.
2. Sap flow measurements in root and in stem for apple and tomatoes will provide better understanding of the plant water balance under PRD.
3. Although the study of roots is extremely difficult, measurements of diurnal  $\Psi_{\text{root}}$  and  $\Psi_{\text{soil}}$  are important to establish the minimum threshold value between  $\Psi_{\text{root}}$  and  $\Psi_{\text{soil}}$  and above-ground plant water balance in tomato under PRD.
4. Studies on root distribution and/or root pattern changes in both apple and tomato are needed to understand the acquisition of water by the roots and the maintenance of  $\Psi_{\text{leaf}}$ .
5. The study of PRD in a wide range of processing tomato cultivars for their sensitivity to BER
6. Fruit quality improvement for tomato deserves further investigation in measurement of sugars and their relation with the climacteric process and fruit maturity advancement.
7. Studies on fruit quality, fruit advancement, and storage potential are suggested for apple grown in dry environments.

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