IMPROVING THE WATER USE EFFICIENCY OF HORTICULTURAL CROPS

FINAL REPORT

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CONDENSED REPORT

Partial rootzone drying (PRD) is one of a number of irrigation techniques which deliberately expose the plant to water deficits to bring about physiological changes that can improve the efficiency of water use. The application of PRD to horticultural crops was first suggested by Loveys (1991). Since that time a large amount of evidence has accumulated to show that application of PRD can significantly improve water use efficiency (Loveys et al 2000; Stoll et al 2000; Dry et al 2000; Düring et al 1996; Kang et al 2000; Kang et al 2002).

There are many pressures on irrigators to improve the water use efficiency of their crops. These include increases in the cost of water, reduced availability of water, the need to return water to river systems for the maintenance of environmental flows, and, in the case of winegrape production, responding to the recognition that there is a link between irrigation management and fruit quality. Further pressures will develop in the future as it is increasingly recognised that climate change will result in reduced water availability for agriculture and natural ecosystems.

An NPIRD project (CDH1) demonstrated that by using PRD techniques it was possible to grow a commercial crop of pears, with no effect on yield or quality, with an irrigation input of approximately 50% of the district average. Similar water savings were demonstrated for Valencia and Navel orange. The project also provided important basic information about the physiological mechanisms involved in PRD responses and drew attention to the important role played by plant hormones in controlling plant water use. The current project (CDH2) seeks to develop further the PRD concept for irrigation of a range of woody horticultural crops and to define more accurately the minimum water requirements for these crops.

Project objectives

- *Undertake additional PRD trials on the existing experimental sites to further investigate potential longer terms effects of PRD, including biennial bearing and poor fruit set.*
- *Incorporate more extensive groundwater monitoring to clarify the extent of groundwater utilisation by plants under a PRD regime.*
- *Incorporate sapflow measurement techniques to better understand the compensatory movement of water around the plants in response to PRD regimes.*
- *For a range of horticultural crops:*

    demonstrate best management practices for the use of Partial Rootzone Drying (PRD)

    redefine minimum crop water requirements for successful crop maturation

    prepare guidelines for the maintenance of productivity in years of low water availability.

General materials and methods

Experiments were carried out at four sites; University of Adelaide Alverstoke orchard, Waikerie in the SA Riverland, New South Wales Agriculture experiment station Yanco, and Agriculture Victoria, Institute of Sustainable Irrigated Agriculture, Tatura.

Experiments were aimed at defining lower limits of water application to a range of woody perennial horticultural crops and assessing the improvements that could be achieved by implementation of PRD principles. Attention was given in a number of experiments to the differentiation of responses to changes in the amount of available water and true PRD responses that improve the efficiency of water use.

Results

At the Yanco site the irrigation treatments were applied for five consecutive years to mature Navel orange trees. The treatments compared standard industry practice of flood irrigation, flood irrigation where only half the ground area was wetted, drip irrigation where both sides of the tree were wetted and half drip (PRD) where the trees were irrigated on one side only at any one time and the side was alternated at each irrigation. Water application rates (including rainfall) were conservative and varied from 51% ETo (calculated from pan evaporation data), for the full flood treatment, to 28% ETo for the PRD drip treatment. There was no evidence of induction of biennial bearing or poor return fruitset over and above that seen in the control trees. There was no significant difference between fruit numbers in any "on" year ($P>0.05$), nor was there any significant difference between fruit numbers in the "off years" ($P>0.05$). Mean fruit size did not vary between treatments within any year ($P>0.05$) but varied significantly ($P<0.05$) between years with bigger fruit being associated with the lower fruit numbers in the "off years". The irrigation treatments thus had no effect on fruit yield.

There was a tendency for these trees to be over-cropped as evidenced by relatively small mean fruit size across all treatments. Fruit from the 1999 harvest were predominantly classed as *Very Small* (less than 63 mm diameter) although there were no significant differences between treatments ($P>0.05$). Fruit from the 2002 harvest were similarly distributed, but again there were no significant differences between treatments. There was a strong tendency, however, for the alternate drip treatment to produce smaller fruit.

Irrigation applied in all years was low by district standards.

None of the irrigation treatments caused the appearance at any time of symptoms of water stress. The trees were able to retain a heavy crop load despite the low water application rates in the alternate drip treatment. It was not considered possible for the trees to have accessed water from other sources. There was no watertable within 3 m of the surface as assessed by a number of piezometer tubes in the orchard.

A reduction in water input, applied by flood or by drip, resulted in a small but significant reduction in juice % and an increase in % acid in both the 1999 and 2002 harvests.

However, there was no treatment effect on sugars in either year. Sugar/acid ratios changed accordingly.

Sap flow sensors were installed in the drip irrigated trees to assess transpiration over a whole season. On average, transpiration was reduced by about 15% in the PRD trees, but the magnitude of the effect depended on prevailing weather conditions. The correlation between daily sap flow and VPD was stronger in control trees than in PRD trees. This suggests that higher VPD had a reduced effect in stimulating transpiration in PRD trees than it did in control trees. Experiments with potted pear trees in Adelaide supported this interpretation (see below).
Experiments were also conducted in a 1.2 ha pear orchard at Tatura. Irrigation treatments (6 replicates) were control (1.0C) and two PRD treatments (0.5PRD and 1.0PRD) which received 50 and 100% of control water. Irrigation was applied with microjets to one side (PRD treatments) of the tree on a 14-day alternating cycle compared to the control treatment, which received water on both sides. Irrigation was applied daily based on estimated crop water requirement calculated from FAO procedures and using a basal crop coefficient (K_{cb}) of 1.15 and a soil evaporation coefficient (K_e) of 0.1. Reference crop evapotranspiration (ET_o) was computed from pan evaporation data using a pan (class A) coefficient (K_p) of 0.8. Thus, derived ET_{pear} adjusted for effective canopy cover (ECC) and soil evaporation was: (ET_o* K_{cb}* ECC) + (ET_o* K_e).

Shoot and fruit growth were reduced by the 0.5PRD treatment. The average fruit size for 0.5PRD failed to meet size requirements for processing (60.3 to 73.0 mm diameter), whereas both fully watered treatments produced fruit within the size range required for canning. For 0.5PRD, yield tended (P=0.14) to be below the fully watered treatments. Fruit size was reduced and juice total soluble solids increased under 0.5PRD, but flesh firmness was similar between treatments. Pruning weights were less under 0.5PRD. Significant reductions were also found for leaf stomatal conductance and midday leaf water potential throughout the irrigation season and signs of water-stress were evident from the amount of preharvest fruit drop under 0.5PRD (P=0.14). Water inputs and yield were less under 0.5PRD and WUE was calculated to be 17 t/ML for the fully watered treatments 1.0C and 1.0PRD, and 28 t/ML for 0.5PRD.

It was clear from these experiments that the 0.5PRD treatment resulted in a degree of water stress. A combination of low stomatal conductance, low leaf water potential and reduction in fruit size is suggestive water supply below optimum. We therefore have to recognise that there is a lower limit, below which trees will show signs of water stress, whatever the irrigation regime applied. However, the control treatments that received 170 mm irrigation were still well below the district average of from 500 to 600 mm for pears. Given that the trees used in this experiment were relatively small (ECC approximately 0.33) a value close to 270 to 300 mm irrigation may more closely match ET_{pear} to irrigation for orchards with greater canopy cover. There were no clear indicators from these experiments that the trees had shown a PRD response. However, given that the PRD0.5 trees received only 85 mm irrigation it is likely that stress responses dictated the trees' performance.

To differentiate between a real PRD effect and a simple response to water volume application it was decided to apply irrigation water at the high end of what had been used in previous experiments and to make frequent irrigation to reduce the possibility of transient water stress effects at the end of an irrigation cycle. Accordingly, the aim was to apply water at a rate which would result in a yearly total of about 700 mm.

These experiments were carried out on Valencia orange trees at Waikerie. Water was scheduled to be applied every four days and in the case of the PRD trees the side irrigated was switched every fourth irrigation. Stomatal conductance was measured on east and west side of the trees during morning (9 to 11 am) and afternoon (2 to 4 pm) periods. During the morning stomatal conductance on the east sides of the trees was always lower in the PRD trees when compared with the controls. On the shaded (west) side of the trees conductance was low and there was no difference between PRD and controls. The extent of the inhibition depended on the prevailing VPD during the measurement period. When mean VPD was 0.9, 1.3 and 1.9 kPa the conductance was reduced by 27, 44 and 60% respectively. During the afternoon conductance fell to very low values and there was no difference between PRD and control trees. VPD during this period was high at 3.7 kPa. The results show that Valencia orange trees respond dramatically to prevailing evaporative conditions.

Despite the abundant availability of water stomatal conductance fell during periods of high VPD and this effect was accentuated by the PRD treatment and would have had the effect of increasing the efficiency of water use of these trees. It could be argued that this degree of stomatal closure may have limited photosynthesis and therefore the ability of the trees to successfully mature their crop. However, previous work with these same trees had shown that there was no effect of the PRD treatment on fruit number, size or quality.

Sap flow sensors were used to describe the relationship between environmental changes and transpiration of container-grown pear trees. Six sap flow sensors were inserted in the trunk of the trees between 300 and 400 mm above soil level. The sensors were equally spaced around the trunk circumference and transpiration was assessed as a mean value from all six sensors. This was done to reduce any sectorial effects resulting from changes in soil water distribution. During the first phase of the experiment both pots were irrigated. The early part of this period was characterised by days of greatly varying VPD. Transpiration changed accordingly and the correlation coefficient between daily sap flow and VPD was high.

During the PRD period, drip emitters from one pot were transferred to the other, giving this pot double the water. A significant proportion of this water drained from the pot, however. The high irrigation frequency (three times per day) ensured that no water deficits developed during the experiment. The first 4 or 5 days of this PRD period were characterised by low VPD and there was no effect of the treatment on sap flow. Later in the PRD period the weather was hot and dry resulting in VPD values between 4 and 6 kPa but sap flow changed little, resulting in a significant reduction in correlation coefficient between daily sap flow and VPD.

When water was restored to both pots the relationship between VPD and sap flow again was tighter as shown by a rise in correlation coefficient. These data show clearly that by exposing part of the root system to water deficit the ability of the whole tree to respond to stressful ambient conditions is changed. This is the same response seen in the Valencia orange trees where the intensity of stomatal response to VPD was increased by PRD.

Minimum water requirements and relationships to management practices

Trials carried out in this project, in a previous NPIRD project (CDH1) and in a HAL project (Adem et al., HAL FR00007) have consistently shown that it is possible to produce commercially viable crops of pears, Navel oranges, Valencia oranges and canning peaches with water inputs significantly less than what is current industry practice in the respective regions. Water use efficiency in these cases was then greatly improved. However, it has not always been possible to differentiate between a simple effect of response to water volume *per se* and a true PRD effect where tree transpiration is influenced independently of water volume effects.

Experiments at Tatura with pears showed that by carefully estimating crop water requirements from pan evaporation data and by taking into account effective canopy cover and making allowances for soil evaporation, a commercially acceptable crop was grown with an irrigation input of just 1.7 ML/ha. By reducing this already low water input further to 0.87 ML/ha and applying PRD the trees were clearly water stressed as judged by crop response and by a range of physiological measures. There is obviously a lower limit below which water stress will be encountered, no matter how the water is applied.

In contrast to these data, a true PRD response was demonstrated with Valencia orange where, even when both control and PRD trees received the same amount of water, the PRD trees had lower stomatal conductance and, critically, these trees showed an accentuated response to varying VPD. Even without a demonstrable effect of PRD on stomatal conductance the technique can be an advantage as it promotes a more efficient use of stored soil water. In a previous trial at Tatura flood irrigated pears were successfully grown with an irrigation input of 1.8 ML/ha by applying PRD to alternate sides of the trees or to a fixed side of the trees. In this case it was concluded that the use of stored soil water was increased by the treatment.

It is clear from these results that in all crops we have studied significant reductions in water input, compared with current industry practice, are possible with no penalty in terms of yield or fruit quality. However, where fruit size is an important measure of crop quality, in Navel orange and pears for example, the possibility of reduced fruit size, induced at the lowest rates of water input, may act as a disincentive for growers to embrace the idea of PRD.

PRD irrigation will confer an advantage when it produces specific physiological responses that allow a plant to better cope with potentially stressful environmental conditions. Evidence that this does occur came from experiments with Valencia oranges in an orchard and with potted pear trees. In both cases the PRD treatment received the same amount of water as the normally irrigated control plants but stomatal conductance was reduced and the effect was accentuated on days when environmental conditions became more stressful (higher VPD).

The present project has taken an empirical approach to assess the effectiveness of PRD in a range of crops because this would bring the practical application of the process one step nearer. It is clear from the discussion above that the effectiveness of PRD varies greatly from crop to crop and the reason for this may be that different crops use different mechanisms to deal with water stress. Nevertheless, PRD is unlikely to have a negative impact on plant performance and the balance of evidence suggests that there will be positive outcomes. This project has shown that many perennial horticultural crops can be successfully grown with far less water than has traditionally been used and that PRD adds another dimension to crop response to stressful environmental conditions.

Based on our experiments described above, the following points encapsulate our present knowledge of PRD responses and best management practice for PRD implementation:

- Best PRD responses occur in soils with high values of readily available water (RAW). Shallow soils with low RAW can allow rapid depletion of water in the relatively small soil volume wetted by PRD. To some extent this could be overcome by more frequent irrigation.
- Use of PRD in soils with poor infiltration characteristics may similarly be problematic if sufficient water cannot be supplied through what is effectively 50% of the normal soil surface area.
- When soil moisture monitoring is available the irrigated side of the plant should be switched when water extraction from the "dry" side becomes negligible. In sandy soils and under hot dry conditions this may be only a few days, while in soils with a higher water retention characteristic and under less stressful conditions the cycle time may become several weeks.
- Use of PRD should not result in significant reduction in midday leaf water potential when compared with standard irrigation practice.
- When PRD is being implemented in an existing orchard total soil area wetted by the irrigation system (wet plus dry sides) should not vary significantly from that wetted by the original irrigation system. For example, conversion from flood to drip may wet only a small fraction of the available roots. The PRD irrigation system should aim to wet approximately half the roots at any one time.
- Correctly implemented PRD should not result in major effects on fruit quality. In some of our experiments with Navel orange PRD at very low water application rates there was a reduction in fruit size of heavily cropped trees but this problem was not evident at higher water inputs. A reduction in water input, applied by flood or by drip, may result in a small but significant reduction in % juice and an increase in % acid. There should be no effect on sugars and sugar/acid ratios may change accordingly.
- In pear very low water inputs resulted in an increase in total soluble solids and a small reduction in fruit size, but at a higher level of water input (1.7 ML/ha) these effects were not evident.
- Response to PRD will depend on species.

Reference

Adem, H. H., D.G. Williams, B. R. Loveys and J. Selman. (2002), Final Report to Horticultural Australia Project Number FR00007, *Water Use Efficiency in Fruit Trees Through Partial Rootzone Drying*

COMPREHENSIVE REPORT

Partial rootzone drying (PRD) is one of a number of irrigation techniques that deliberately expose the plant to water deficits to bring about physiological changes that can improve the efficiency of water use. The current project (CDH2) seeks to develop further the PRD concept for irrigation of a range of woody horticultural crops and to define more accurately the minimum water requirements for these crops.

Experiments were carried out at four sites; University of Adelaide Alverstoke orchard, Waikerie in the SA Riverland, New South Wales Agriculture experiment station Yanco, and Agriculture Victoria, Institute of Sustainable Irrigated Agriculture, Tatura and were aimed at defining lower limits of water application to a range of woody perennial horticultural crops and assessing the improvements that could be achieved by implementation of PRD principles. Attention was given in a number of experiments to the differentiation of responses to changes in the amount of available water and true PRD responses that improve the efficiency of water use.

At the Yanco site the irrigation treatments were applied for five consecutive years to mature Navel orange trees. The treatments compared standard industry practice of flood irrigation, flood irrigation where only half the ground area was wetted, drip irrigation where both sides of the tree were wetted and half drip (PRD) where the trees were irrigated on one side only at any one time and the side was alternated at each irrigation. Water application rates (including rainfall) were conservative and varied from 51% ETo (calculated from pan evaporation data, averaging 1519mm per year over the 5 year experimental period), for the full flood treatment, to 28% ETo for the PRD drip treatment.

There was no significant difference between fruit numbers in any year. Mean fruit size did not vary between treatments within any year but varied significantly between years with bigger fruit being associated with the lower fruit numbers in the "off years" of the biennial bearing cycle. The irrigation treatments thus had no effect on fruit yield. All fruit from this site tended to be classed as small although there were no significant differences between treatments. There was a strong tendency however, for the alternate drip treatment to produce smaller fruit. Irrigation applied in all years was low by district standards. None of the irrigation treatments caused the appearance at any time of symptoms of water stress.

At Tatura, experiments were conducted in a 1.2 ha pear orchard. Irrigation was scheduled according to pan evaporation and amounted to 170 mm and 85 mm for the control and 0.5PRD treatments respectively. Shoot and fruit growth were reduced by the 0.5PRD treatment, whereas both fully watered treatments produced fruit within the size range required for canning. For 0.5PRD, yield tended (P=0.14) to be below the fully watered treatments. Fruit size was reduced and juice total soluble solids increased under 0.5PRD, but flesh firmness was similar between treatments. Pruning weights were less under 0.5PRD. Significant reductions were also found for leaf stomatal conductance and midday leaf water potential throughout the irrigation season and signs of water-stress were evident from the amount of preharvest fruit drop under 0.5PRD (P=0.14). Water inputs and yield were less under 0.5PRD and WUE was calculated to be 17 t/ML for the fully watered treatments 1.0C and 1.0PRD, and 28 t/ML for 0.5PRD.

It was clear from these experiments that the 0.5PRD treatment resulted in a degree of water stress. A combination of low stomatal conductance, low leaf water potential and reduction in fruit size suggests water supply below optimum. We therefore have to recognise that there is a lower limit, below which trees will show signs of water stress, whatever the irrigation regime applied. However, the control treatments that received 170 mm irrigation were still well below the district average of 500 to 600 mm for pears. There were no clear indicators from these experiments that the trees had shown a PRD response. However, given that the PRD0.5 trees received only 85mm irrigation it is likely that stress responses dictated the trees performance.

To differentiate between a real PRD effect and a simple response to water volume application, irrigation water was applied at the high end of what had been used in previous experiments to a Valencia orange orchard at Waikerie and the same amount was applied to both control and PRD trees. During the morning stomatal conductance on the east sides of the trees was always lower in the PRD trees when compared with the controls. On the shaded, (west), side of the trees conductance was low and there was no difference between PRD and controls. The extent of the inhibition depended on the prevailing VPD during the measurement period. During the afternoon conductance fell to very low values and there was no difference between PRD and control trees.

The results show that Valencia orange trees respond dramatically to prevailing evaporative conditions. Despite the abundant availability of water stomatal conductance fell during periods of high VPD and this effect was accentuated by the PRD treatment and would have had the effect of increasing the efficiency of water use of these trees.

Sap flow sensors were used to describe the relationship between environmental changes and transpiration of container-grown pear trees while they experienced PRD cycles. The data show clearly that by exposing part of the root system to water deficit the ability of the whole tree to respond to stressful ambient conditions is changed.

It was concluded that many perennial horticultural crops can be successfully grown with far less water than has traditionally been used and that PRD enables changes to crop response to stressful environmental conditions that improve water use efficiency.

Introduction

Irrigated horticultural crops occupy about 248,000 ha in Australia (ABS 1993) and major problems are now being encountered in sustaining water supply to some of these crops. In the grape industry, for example, even current water use is considered to be unsustainable in some areas. These issues are, to a large extent generic, applying to most irrigated horticultural crops. Furthermore, some irrigation practices can be extremely inefficient and environmentally damaging through over-use of water resources leading to depletion of groundwater reserves, elevation and contamination of watertables, eutrophication and salinisation of drainage water. However, supply of water through irrigation is an essential component of intensive horticultural practice. Water is required for canopy growth, supply of nutrients to roots, changing soil characteristics to encourage root growth and maintaining leaves in a healthy condition to allow photosynthesis and the acquisition of carbon and water into structural and reproductive elements of the plant.

Most plants, from which our current horticultural crops have been derived, evolved under conditions where water availability and evaporative demand could change quite dramatically according to seasonal influences. As a consequence they have complex physiological responses that allow them to cope with reduced water availability and harsh environmental conditions. These responses take their cues from environmental variables such as irradiance, ambient humidity, ambient temperature, atmospheric CO_2 concentration and, most importantly, soil water availability. It is the existence of these mechanisms that allow the manipulation of plants, with consequent changes in water use efficiency, through irrigation management.

PRD is one of a number of irrigation techniques which deliberately expose the plant to water deficits to bring about physiological changes that can improve the efficiency of water use. Applying PRD to horticultural crops was first suggested by Loveys (1991). Since that time a large amount of evidence has accumulated to show that application of PRD can significantly improve water use efficiency (Loveys *et al* 2000; Stoll *et al* 2000; Dry *et al* 2000; During *et al* 1996; Kang *et al* 2000; Kang *et al* 2002).

There are many pressures on irrigators to improve the water use efficiency of their crops. These include increases in the cost of water, reduced availability of water, the need to return water to river systems for the maintenance of environmental flows, and, in the case of winegrape production, responding to the recognition that there is a link between irrigation management and fruit quality. Further pressures will develop in the future as it is increasingly recognised that climate change will result in reduced water availability for agriculture and natural ecosystems.

An NPIRD project (CDH1) demonstrated that by using PRD techniques it was possible to grow a commercial crop of pears, with no effect on yield or quality, with an irrigation input of approximately 50% of the district average. Similar water savings were possible with both Valencia and Navel orange. The project also provided important basic information about the physiological mechanisms involved in PRD responses and drew attention to the important role played by plant hormones in controlling plant water use. The current project (CDH2) seeks to develop further the PRD concept for irrigation of a range of woody horticultural crops and to define more accurately the minimum water requirements for these crops. These aims are closely allied with those of a Horticulture Australia project (FR00007, Water Use Efficiency in Fruit Trees through Partial Rootzone Drying).

Project objectives

- *Undertake additional PRD trials on the existing experimental sites to further investigate potential longer terms effects of PRD, including biennial bearing and poor fruit set.*

- *Incorporate more extensive groundwater monitoring to clarify the extent of groundwater utilisation by plants under a PRD regime.*

- *Incorporate sapflow measurement techniques to better understand the compensatory movement of water around the plants in response to PRD regimes.*

- *For a range of horticultural crops :-*

  demonstrate best management practices for the use of Partial Rootzone Drying (PRD)

  redefine minimum crop water requirements for successful crop maturation

  prepare guidelines for the maintenance of productivity in years of low water availability.

General materials and methods

Experiments were carried out at four sites; University of Adelaide Alverstoke orchard, Waikerie in the SA Riverland, New South Wales Agriculture's Yanco Agricultural Institute and Agriculture Victoria, Institute of Sustainable Irrigated Agriculture, Tatura.

Adelaide. Pear trees (WBC/ Callereyana D6) were grown with their roots divided between two 75 L containers. These trees were used for sap flow and transpiration studies. Each root container was watered independently up to three times daily to maintain the soil close to field capacity at all times. Sap flow sensors (Greenspan Technologies, model SF 100) were inserted in the tree trunk 300 to 400mm above soil level. Six sensor sets were installed in a tree at any one time to allow for the effects of uneven radial and circumferential sap flow to be accounted for.

Waikerie. The trial site consisted of eight rows of mature Valencia orange trees on rough lemon rootstock. Rows ran north-south and consisted of 25 trees. Treatments were applied to blocks of five trees buffered on either side by at least five trees whose irrigation was controlled by the orchard manager. Treated trees were irrigated by an independent system that could be controlled by telemetry from Adelaide. Irrigation was applied with under-tree microsprinklers that delivered approximately 50 L/h. There were four sprinklers per tree disposed two either side of the tree line. The sprinklers were arranged so that the wetted zone did not extend beyond the centre line or beyond the centre of the inter-row. This arrangement resulted in wetting of the whole orchard floor, as had been the case previously.

Control trees were irrigated with all sprinklers on together and PRD trees had sprinklers on one side only on at any one time. Each treatment was replicated four times. Flow meters were installed in each irrigation line to determine water application per irrigation. Soil moisture at 100, 400 and 700 mm was monitored by TDR probes (Delta-T Theta probes) in control and treatment blocks and a weather station was located within 50 m of the experimental trees. Both weather station and soil moisture probes were accessed by telemetry.

Sap flow in roots was measured with heat dissipation probes (Granier). A set of probes was specially constructed for these experiments. These consisted of a heated reference probe and two additional probes instead of the usual two probe system. This arrangement allowed for more accurate assessment of bi-directional sap flow in roots. The probes were installed in roots approximately 25 mm in diameter on either side of a PRD treated tree. The heated reference probe was installed centrally with the two measurement probes spaced 100 mm on each side.

Yanco. A block of Bellamy nucellar Navel orange trees (*Citrus sinensis* [L.] *Osbeck*) propagated on *P. trifoliata*, Troyer and Carrizo citrange rootstock growing at the Yanco Agricultural Institute (34^{o} 36′ S, 146^{o} 25′ E; elevation 138 m) was selected for use in this trial. The trees were planted in 1963 at a spacing of 6.7 x 6.7 m in rows of twenty one trees (standard plant density of 222 trees/ha.). They received standard fertilisation and were irrigated on the basis of weather based scheduling (ET) and soil moisture monitoring.

The soil at this site is a medium clay Merungle Loam (Taylor *et al.*, 1979). It is classified under the Northcote Principal Profile Form: Dr 2.23 in the Red-brown earth Great Soil Group. The water content at field capacity[1] of the top 100 cm is 170 mm of which 40 to 60 mm is readily available for plant growth in the top 50 cm (rootzone). Most roots occurred in the top 40 cm and analysis of soil water data was restricted to that layer in this study.

The average annual rainfall of this semi-arid environment is 400 mm and the climate is described as mediterranean, with a mainly winter rainfall, cool winters and hot, dry summers. Maximum temperatures in summer often reach 40^{o}C. Mean daily minimum/maximum air temperatures are 15.6/31.4 C^{o} in January/February and 2.7/15.6 C^{o} in June/July (Australian Bureau of Meteorology, National Climate Centre). Mean daily potential evapotranspiration for the same periods are 9.5 mm and 1.67 mm respectively.

The irrigation water supplied from the Murrumbidgee River is of good quality with average salinity levels of 100 μS cm^{-1} total dissolved salts. Drip irrigation was applied

[1] The classical definition of field capacity is the amount of water held in the soil when drainage under the influence of gravity has ceased. The modern reference point is usually taken as the amount of water held by the soil against a suction of 0.01 MPa. This is the reference point used here

using in-line drippers spaced at 0.5 m and delivering 2 L/hr at an operating pressure of 150 kPa. The drip tube was placed 0.2 m under the tree skirt on each side of the tree row to provide a wetted band of 0.75 m. All trees were irrigated on a 2-day watering cycle with Control trees receiving water from both irrigation laterals and treated trees (PRD) alternately receiving their water from one side only at any one time. Irrigation was alternately cycled every 14 days from the wet to the dry side of PRD treated trees.

Tree growth, yield and fruit quality were recorded on all measurement trees from 1997 until 2002. The study of water relations and crop phenological response to the changed water delivery treatments commenced with the onset of the 1999 irrigation season. Yield and fruit quality parameters were measured on all trees in each row and blocks of three trees, located within each row, were intensively sampled and instrumented. The growth of 10 fruits on each of these trees within each treatment sub-plot was monitored weekly from the time of fruit set (early December) until harvest in all years of the study

Soil moisture sensors were located close to these intensively sampled trees. Soil moisture was monitored on either side of PRD trees with both Theta probes (Delta T, England) and Enviroscan sensors located at 10, 20, 30, 50, 70 cm depth. Soil wetting-front sensors (Full Stop®) were also installed at a depth of 40 cm and in years 2000 and 2001 these were used to control irrigation. Six sensors were installed in a control (double drip line) row. Irrigation was terminated when four of the six sensors had sensed the wetting front. Water application rates were measured with flow meters in each lateral pipe.

Moisture stress monitoring was undertaken each year throughout the irrigation season from early October until the end of May. Diurnal measurements of leaf water potential (ψ_l), stomatal conductance (g_s) and sap flow were made at varying intervals throughout the irrigation season at critical growth stages in the annual phenological cycle. Leaf water potential was measured on five fully expanded sunlit leaves with a pressure chamber, following procedures recommended by Turner (1981). Stomatal conductance was measured on five similar leaves using a dynamic diffusion type porometer[2].

Estimates of transpiration were made using sap flux measurements (heat pulse techniques) to assist in field analysis of water use efficiency. Tree water use measurements were made with Greenspan® Sapflow Sensors (Model SF100. Two pairs of sensors were installed 30 cm above the bud union on a straight and uniformly cylindrical part of the trunk on three of the measurement trees in each of the irrigation treatments. At different stages of the annual growth cycle these were removed and re-installed into other measurement trees to collect long-term water use data throughout the growing season. They were installed in accord with recommended procedures.

Meteorological data were recorded at the experimental site with an NRI Electronics automatic weather station, OptiMiser® model (Northern Rivers Industrial Electronics). Parameters measured were maximum and minimum temperatures, %RH, solar radiation, Rainfall, wind run and wind speed. These data were compared to regional climatic data collected at a registered Bureau of Meteorology site (CSIRO, Griffith) and

[2] Delta-T MK3 model AP3; Delta Devices, Cambridge, UK. Mention of the product name does not constitute endorsement

used to calculate daily reference crop evaporation (Et) using a locally calibrated form of the Penman-Monteith combination equation with site specific adjustments for wind (Myer, 1994).

Tatura. Experiments were conducted in a 1.2 ha pear orchard at Tatura ($36^{o}26$'S, $146^{o}15$E). Trees were 47-year-old 'William's Bon Chretien' planted at 6 x 6 m spacing in an open vase structure on a brown chromosol soil. The orchard is typical in terms of tree density, vigour, soil type, fertiliser and pest and disease management. Irrigation treatments (6 replicates) were control (1.0C) and two PRD treatments (0.5PRD and 1.0PRD) which received 50 and 100% of control. Plots (3 trees) were allocated using a complete randomised block design. Irrigation was applied with mirojets (flow rate: 37.3 L/h, 360^{o}, 2 m radius) to one side (PRD treatments) of the tree on a 14-day alternating cycle compared to the control treatment, which received water on both sides.

Irrigation was applied daily based on estimated crop water requirement (ET_{pear}) calculated from FAO procedures (Allen *et al.* 1998) and using a basal crop coefficient (K_{cb}) of 1.15 and a soil evaporation coefficient (K_e) of 0.1. Reference crop evapotranspiration (ET_o) was computed from pan evaporation data using a pan (class A) coefficient (K_p) of 0.8. Thus, derived ET_{pear} adjusted for effective canopy cover (ECC) and soil evaporation was: (ET_o* K_{cb}* ECC) + (ET_o* K_e). Fruit diameter (6 tagged fruit/tree) and shoot length (6 tagged shoots/tree) were measured weekly. ECC was determined from fractional photosynthetically active radiation interception using a ceptometer at solar noon at approximately 20-day intervals. Stomatal conductance was measured with a porometer (Delta-T Devices AP4) and leaf water potential was measured at midday with a Scholander pressure bomb on fully sunlit leaves. At harvest flesh firmness and juice total soluble solids (TSS) were recorded. Fruit drop and pruning weights were also measured. Analysis of variance was conducted on data using GENSTAT 5.4.1. The significant differences between treatments were determined using Fisher's unrestricted Least Significant Difference at $P<0.05$.

Results

Objective 1: *Undertake additional PRD trials on the existing experimental sites to further investigate potential longer terms effects of PRD, including biennial bearing and poor fruit set.*

Objective 2: *Incorporate more extensive groundwater monitoring to clarify the extent of groundwater utilisation by plants under a PRD regime.*

Objective 3: Incorporate sap flow measurement techniques to better understand the compensatory movement of water around the plants in response to PRD regimes

Yanco. The irrigation intervals used for citrus growing in the MIA are generally arbitrarily determined, very often being influenced more by grower convenience than scientific criteria. Growers tend to be conservative and err on the side of applying too much water rather than risk applying too little. The normal application method is flood irrigation, with enough water applied to saturate the soil. The aim of the study reported here was to establish the effects on citrus production of reducing the amount of water applied to Navel orange trees by converting from flood to drip irrigation and further by imposing a PRD regime on the drip irrigated trees. The consequences of the treatments applied were assessed in terms of soil moisture depletion, plant water relations, tree growth, yield and fruit quality, as well as some physiological measures of plant water relations.

At the Yanco site the irrigation treatments have been applied for five consecutive years and there has been no evidence of induction of biennial bearing or poor fruit set over and above that seen in the control trees (Table 1). The trees had a normal biennial cycle with 1998-99 and 2000-01 being "off years" and 1997-98, 1999-00 and 2001-02 being "on years".

There was no significant difference between fruit numbers in any "on" year ($P>0.05$), nor was there any significant difference between fruit numbers in the "off years" ($P>0.05$). Mean fruit size did not vary between treatments within any year ($P>0.05$) but varied significantly ($P<0.05$) between years with bigger fruit being associated with the lower fruit numbers of the "off years" (Table 2). The irrigation treatments thus had no effect on fruit yield. There was a tendency for these trees to be over-cropped as evidenced by the relatively small mean fruit size across all treatments. An analysis of fruit size distribution in all years confirmed this. Fruit from the 1999 harvest were predominantly classed as *Very Small* (less than 63 mm diameter) although there were no significant differences between treatments ($P>0.05$) (Figure 1). Fruit from the 2002 harvest were similarly distributed, but again there were no significant differences between treatments. There was a strong tendency however, for the alternate drip treatment to produce smaller fruit. In the 2002 harvest 22.6% of the fruit from full drip treatments would have been considered packable but only 4.1% of the fruit from alternate drip.

Irrigation applied in all years was low by district standards. The highest water input (irrigation plus rainfall) was 791 mm for the full flood treatment. The alternate drip treatment consistently received between 232 and 273 mm between 1997 and 1999 (Table 3). Higher water application was difficult with conventional drip because of the poor infiltration characteristics of the soil and the relatively small area to which water was applied. This problem of poor infiltration means that higher water application rates, even with flood irrigation, may not be possible as they are associated with increased run-off and water ponding. Water availability to roots may not be increased over the relatively modest application rates used in these experiments with the alternate drip treatment because of the relatively small area to which the water was applied.

In the 2000-01 season the conventional driplines were replaced with pulsating sprinklers on two rows of trees to identify the effect that increasing the wetted area and reducing the wetted depth had on tree performance using similar volumetric water allocations to drip. The pulsators were made by Irridelco. They were 4 L/hr with a throw of ~2 m, giving an application rate of ~0.3 mm/hr. No surface ponding was observed when these sprinklers were used for up to 12 hours.

We also observed deep wetting to 40 cm from the Envisoscan data. The sprinklers were placed under the canopy with dual lines positioned along the tree centres in one row and individual lines each placed along the row at a 1 m offset from the tree centre in the other. This allowed investigation of alternate wetting and drying cycles across and along the tree rows respectively.

In 2001 an automated system was installed that irrigated every two days until 4 out of 6 FullStop detectors had detected the wetting front. This system put water on at a rate of about ETo*0.32. This pulsator irrigation system was considered superior to the conventional dip system since it distributed the water evenly over the soil surface, allowing better penetration to depth without surface ponding. However, no tree response in terms of yield or fruit size could be distinguished between any of the alternate wetting treatments. Therefore conventional drip irrigation delivery systems are considered the best option because of their significantly lower installation cost. In soil situations where wetted soil volume is insufficient (less than 50%) to support optimal tree and fruit growth or where it is desirable to maintain an actively growing mid-row cover crop, the pulsating sprinklers would be a real option. The FullStops sensors also performed well, limiting the water to the soil layers associated with high root density in the top 40 cm of the soil profile.

None of the irrigation treatments caused symptoms of severe water stress to appear at any time. The trees were able to retain a heavy crop load despite the low water application rates in the alternate drip treatment. It was not considered possible for the trees to have accessed water from other sources. There was no water table within 3 m of the surface as assessed by a number of piezometer tubes in the orchard (Figure 2).

A reduction in water input, applied by flood or by drip, resulted in a small but significant reduction in juice % and an increase in % acid in both the 1999 and 2002 harvests (tables 4 and 5). However, there was no treatment effect on sugars in either year. Sugar-acid ratios changed accordingly.

Sap flow sensors were installed in the drip irrigated trees to assess transpiration over a whole season. On average, transpiration was reduced by about 15% in the PRD trees, but the magnitude of the effect depended on prevailing weather conditions. The correlation between daily sap flow and VPD was stronger in control trees than in PRD trees. During the period 1 September 1999 to 1 January 2000, the daily correlation coefficients between sap flow and VPD were 0.79 and 0.57 (P=0.058) for control and PRD trees respectively. This suggests that PRD made the trees less responsive to VPD changes than it was in control trees. Experiments with potted pear trees in Adelaide supported this interpretation (see below).

Tatura. Shoot and fruit growth were reduced by the 0.5PRD treatment. The average fruit size for 0.5PRD failed to meet size requirements for processing (60.3 - 73.0 mm diameter), whereas both fully watered treatments produced fruit within the size range required for canning. For 0.5PRD, yield tended (P=0.14) to be below the fully watered treatments (Table 6). Fruit size was reduced and juice total soluble solids increased under 0.5PRD, but flesh firmness was similar between treatments. Pruning weights were less under 0.5PRD. Significant reductions were also found for leaf stomatal conductance and midday leaf water potential throughout the irrigation season and signs of water-stress were evident from the amount of preharvest fruit drop under 0.5PRD (P=0.14).

Water inputs and yield were less under 0.5PRD and water use efficiency was calculated to be 17 t/ML for the fully watered treatments 1.0C and 1.0PRD, and 28 t/ML for 0.5PRD.

It was clear from these experiments that the 0.5PRD treatment resulted in a degree of water stress. A combination of low stomatal conductance, low leaf water potential and reduction in fruit size suggests that supply was below optimum. We therefore have to recognise that there is a lower limit, below which trees will show signs of water stress, whatever the irrigation regime applied. However, the control treatments that received 170 mm irrigation were still well below the district average of 500 to 600 mm for pears (Boland *et al*, 2001). Given that the trees in this experiment were relatively small (ECC approximately 0.33) a value close to 270 to 300 mm irrigation may more closely match ET_{pear} to irrigation for orchards with greater canopy cover.

There were no clear indicators from these experiments that the trees had shown a PRD response. Physiological indicators such as stomatal conductance and leaf water potential suggested that the trees were responding in a simple manner to changes in soil available water. During the
2002-2003 season stem water potentials were, on average, about 0.4MPa lower in the 0.5PRD treatment than either the control or 1.0PRD treatments, providing further evidence that the 0.5PRD treatment trees were more water stressed that the control or 1.0PRD treatments. There was no difference in stem water potential between the control and 1.0PRD treatments.

There is interest in developing non-invasive measures of plant performance with which to assess crop performance. One such measure was assessed at Tatura during the 2002-03 season. Leaf temperatures were measured by a simple handheld infrared thermometer and compared to ambient air temperature. During each measurement leaf temperature, as measured by infrared thermometry, was significantly higher that ambient temperature, and during the latter part of the season, when other measures suggested that the 0.5PRD trees were more water stressed, the leaf temperatures of these trees was much higher than either the control or 1.0PRD treatment leaves. These data accord with differences in stomatal conductance that suggest lower transpiration in the 0.5PRD treatment trees compared with the control or 1.0PRD treatments.

The trees in this experiment were grown in an orchard where there was no water table within 3 m of the surface. Furthermore, soil moisture data showed that water extraction from the 800 to 1200 mm depth was small and did not vary greatly over the course of the season (Figure 3), suggesting that root development in this region of soil was poor. By contrast, work carried out in CDH1 in a flood irrigated pear orchard with a shallow groundwater table showed that PRD irrigation, applied to alternate side of the trees or to one side of the trees for the entire experimental period, caused the trees to make more use of soil-stored water. The PRD treatments reduced daily water consumption by an average of 14% but the total irrigation applied was reduced by 44% compared to the conventional flood irrigation treatment that received 2.8 ML/ha irrigation during the experimental period. Total yield and fruit number per tree were unaffected by the treatments, meaning that water use efficiency was substantially improved. Conventional measures of tree performance such as stomatal conductance and leaf water potential were unaffected by the treatments, suggesting that the trees were not stressed.

Waikerie. To differentiate between a real PRD effect and a simple response to water volume application it was decided to apply irrigation water at the high end of what had been used in previous experiments and to make frequent irrigation to reduce the possibility of transient water stress effects at the end of an irrigation cycle. Accordingly, the aim was to apply water at a rate that would result in a yearly total of about 700 mm. Water was scheduled to be applied every four days and, in the case of the PRD trees, the side irrigated was switched every fourth irrigation.

Water application rates were assessed from water meters in each irrigation line. Water application rates varied a little from time to time because of pressure differences in the supply but over the course of the experiment the mean application rate was 14.8, 14.2 and 14.8mm per irrigation for the control, east side of the PRD trees and west side of the PRD trees respectively. To further eliminate the possibility that any apparent changes in transpiration were due to the stage of the irrigation cycle or to the side of the tree that was measured relative to the side that was being irrigated, sample times were chosen to coincide with strategic times of the cycle.

Stomatal conductance was measured on east and west side of the trees during morning (9 am to 11am) and afternoon (2 pm to 4 pm) periods. During the morning stomatal conductance on the east sides of the trees was always lower in the PRD trees when compared with the controls (tables 8, 9 and 10). On the shaded, west side of the trees conductance was low and there was no difference between PRD and controls. The extent of the inhibition depended on the prevailing VPD during the measurement period. When mean VPD was 0.9, 1.3 and 1.9 kPa the conductance of PRD trees was reduced by 27, 44 and 60% respectively relative to controls.

During the afternoon, conductance fell to very low values and there was no difference between PRD and control trees (Table 10). VPD during this period was high at 3.7kPa. If this pattern of gas exchange response to VPD occurs over normal irrigation cycles, and the frequent stomatal conductance measurements made on these Valencia orange trees suggests that it is a normal occurrence, then it may be expected that foliage on the western side of trees will experience lower potential for photosynthesis than foliage that is eastern-facing. A consequence of this may be that less assimilate is available to fruit on western aspects of trees. Analysis of some data from the Yanco site does indeed suggest that this is so. Fruit numbers and fruit weight were significantly reduced on the western side compared to the eastern side (Figure 6).

Conversations with contractors installing irrigation pipes in the orchard suggested that root densities under the trees irrigated in this experiment were greater than under trees in the same block irrigated by the orchard manager. Accordingly, root samples were taken from the top 250 mm of soil with a steel coring tool. Dry weights of roots included in the soil core are shown in Table 11. There were no differences between treatments. Anecdotal evidence should always be treated with some caution!

In the 2001-2002 irrigation season sap flow sensors were installed in the roots of Valencia orange trees to investigate the redistribution of water that may occur as the result of water potential gradients induced by the PRD irrigation. Figure 4 shows the relative movement of water in a root during one PRD cycle.

When irrigation was applied to the side of the tree containing the sap flow sensors there was an immediate increase in sap flow during the day (day 0). No further water was applied to this side of the tree for the following 38 days. Sap flow continued during the day for the following 13 days. This pattern of diurnal sap flow was then replaced by a pattern where low flow rates occurred during the night and, on several days, also during the day.

These data suggest that the roots on the non-irrigated side of the trees are able to continue to extract water from the soil for about two weeks. The soil is by then so dry that water movement takes place in the reverse direction, stimulated by gradients in water potential. The source of this water could be the wetted roots on the alternate side of the tree or the aerial parts of the tree, the water potential of which had been restored by water uptake during late afternoon or evening. There was some evidence for sap flow in these dry roots during the day (days 16 to 20, for example) which could represent transpiration of water accumulated during the previous night. This ability of roots on the non-irrigated side of the tree to gain water from other parts of the hydraulic system may be a significant aspect of PRD since it would allow the roots on the dry side to maintain sufficient water content to prevent injury. Furthermore, the apparent remobilisation of some of this water during the day may allow the movement of abscisic acid, known to be present in these dry roots at high concentration, into the aerial parts of the tree where it would induce partial stomatal closure.

Adelaide. Sap flow sensors were used to describe the relationship between environmental changes and transpiration of container-grown pear trees. Six sap flow sensors were inserted in the trunk of the trees between 300 and 400 mm above soil level. The sensors were equally spaced around the trunk circumference and transpiration was assessed as a mean value from all six sensors. This was done to reduce any sectorial effects resulting from changes in soil water distribution.

During the first phase of the experiment both pots were irrigated. The early part of this period was characterised by days of greatly varying VPD. Transpiration changed accordingly (Figure 5) and the correlation coefficient between daily sap flow and VPD was high (Table 12). During the PRD period, drip emitters from one pot were transferred to the other, giving this pot double the water. A significant proportion of this water drained from the pot, however. The high irrigation frequency (three times per day) ensured that no water deficits developed during the experiment. The first 4 or 5 days of this PRD period were characterised by low VPD and there was no effect of the treatment on sap flow. Later in the PRD period the weather was hot and dry resulting in VPD values between 4 and 6 kPa but sap flow changed little, resulting in a significant reduction in correlation coefficient for the period (Table 12). When water was restored to both pots the relationship between VPD and sap flow again was tighter as shown by a rise in correlation coefficient (Table 12).

After these experiments the trees were planted out in the field as it was felt that they had become too large to be supported for an additional season in the 75 L bags. Accordingly, the cherry, apple, apricot and pear trees were planted in the University of Adelaide Alverstoke orchard to be used as a student resource in coming years. A large hole was excavated for each tree and the two root masses planted with a plastic membrane to separate them. A plastic sheet barrier was also placed above ground to confine irrigation from irrigation sprinklers if it was desired to keep irrigation restricted to one or the other of the root masses. An experiment was set up with the pear, apple, cherry and apricot trees to investigate the possibility that PRD could stimulate osmotic adjustment. This is on-going and results are not available for this report.

Objective 4*: For a range of horticultural crops:*

> *demonstrate best management practices for the use of Partial Rootzone Drying (PRD)*
>
> *redefine minimum crop water requirements for successful crop maturation*

Objective 5*: prepare guidelines for the maintenance of productivity in years of low water availability*

Trials carried out in this project, in a previous NPIRD project (CDH1) and in a HAL project (Adem *et al*., HAL FR00007) have consistently shown that it is possible to produce commercially viable crops of pears, Navel oranges, Valencia oranges and canning peaches with water inputs significantly less than what is current industry practice in the respective regions. The water use efficiency in these cases was then greatly improved. However, it has not always been possible to differentiate between a simple effect of response to water volume *per se* and a true PRD effect where tree transpiration is influenced independently of water volume effects.

Experiments at Tatura with pears showed that by carefully estimating crop water requirements from pan evaporation data and by taking into account effective canopy cover and making allowances for soil evaporation, a commercially acceptable crop was grown with an irrigation input of just 1.7 ML/ha. There was no evidence for accelerated use of water from deeper soil layers, nor was there any detectable water table on this site. It can therefore be concluded that all the crop water requirements were being satisfied by the irrigation plus rainfall.

There appeared to be no advantage in applying this amount of water as PRD. By reducing this already low water input further to 0.87 ML/ha and applying PRD the trees were clearly water stressed as judged by crop response and by a range of physiological measures. There is obviously a lower limit below which water stress will be encountered, no matter how the water is applied. In a previous trial at Tatura (CDH1) flood irrigated pears were successfully grown with an irrigation input of 1.8 ML/ha by applying PRD to alternate sides of the trees or to a fixed side of the trees. In this case it was concluded that the use of stored soil water was increased by the PRD treatment.

Also at Tatura, Adem *et al*. (2002) showed that by applying PRD irrigation to high density canning peaches irrigation input could be reduced by over 40% from the grower practice of 4.8 ML/ha with no penalty in terms of fruit yield or quality. Similar reductions were possible by applying PRD to Valencia oranges in the Riverland of South Australia when 4.9 ML/ha was applied compared with a district average of from 7 to 8 ML/ha. There was no effect on fruit yield or size distribution. However, some reduction in fruit size was seen when reducing water application rates further in a Navel orange crop at Yanco.

It is clear from these results that in all crops we have studied significant reductions in water input, compared with current industry practice, are possible with no penalty in terms of yield or fruit quality. However, where fruit size is an important measure of crop quality, in Navel orange and pears for example, the possibility of reduced fruit size would act as a real disincentive for growers. This is in contrast to the winegrape industry where a reduction in berry size may be seen as a positive attribute because of the change in the skin to pulp ratio in smaller berries.

PRD may offer an advantage over conventional irrigation at low level of water input because of the continued water availability to some of the root system which may favour the normal development of fruit over vegetative growth. This was the case in grapevine where PRD caused a reduction in vegetative growth, especially the lateral shoots, but did not influence berry growth. Furthermore, the changed relationship between stomatal conductance and ambient evaporative conditions that we have shown to be part of the PRD response, would help reduce water use during periods of extreme evaporative demand while maintaining high levels of photosynthesis during periods of lower evaporative demand.

PRD irrigation will confer an advantage when it produces specific physiological responses that allow a plant to better cope with potentially stressful environmental conditions. Evidence that this does occur came from experiments with Valencia oranges in an orchard and with potted pear trees. In both cases the PRD treatment received the same amount of water as the normally irrigated control plants but stomatal conductance was reduced and the effect was accentuated on days when environmental conditions became more stressful (higher temperatures and lower humidity). This response would tend to make the water requirements less than anticipated through calculations based on weather station or pan evaporation data. Yunusa *et al*. (2000) have noted that the transpiration of grapevines is remarkably constant over a range of environmental conditions and not tightly coupled to current temperature or humidity. It would be anticipated that the transpiration rate of the PRD Valencia orange trees used in our experiments would also be less affected by stressful conditions than the control trees, despite the fact that both received the same amount of water.

Since PRD depends on the stimulation of physiological responses to water stress, for example the production of the stress hormone abscisic acid (ABA) in the drying roots and reductions in the production of other growth-controlling hormones (cytokinins) in roots (Stoll *et al*., 2000), it is likely that the magnitude of response will depend on the degree to which these changes occur in the crop plant in question. These responses are aimed at maintaining the water status of the plant as near as possible to an ideal figure and are achieved through changing the gas exchange characteristics of the leaves. It is therefore likely that PRD will work best in crops where a reduction in water loss is the first line of defence against mild water stress. Grapevine is a good example of this type of plant.

The grapevine operates within a fairly narrow range of leaf water potentials, from typical predawn values of 0 to –0.2 MPa to minimum values at midday of approximately –1.2 to –1.6 MPa for well watered vines to perhaps –1.8 MPa at midday for stressed vines. A crop like apricot, however, may well exhibit leaf water potentials as low as –2.5 to –3.0 MPa at midday with no apparent ill effect. The key to these differences is that the plants are using different strategies to deal with water stress. Grapevine tends to maintain a relatively constant water status through mechanisms that respond in the short term to prevailing environmental conditions.

Apricot is different in that it allows its water status to fluctuate with prevailing conditions as a result of the diversion of resources derived from photosynthesis into osmotically-active substances that allow gas exchange to occur at low leaf water potentials (Loveys *et al* 1987). It is not known at this stage whether PRD will stimulate these responses. The relative importance of these mechanisms may also vary in different plants. We have shown in this project that PRD will induce gas exchange responses in both pear and orange (Valencia and Navel) but low leaf water potentials may also be encountered in these plants, suggesting that there may be some reliance on changes in osmotic balance to maintain their water status.

The present project has taken an experimental approach to assess the effectiveness of PRD in a range of crops because this would bring the practical application of the process one step nearer. It is clear from the discussion above that the effectiveness of PRD varies greatly from crop to crop and the reason for this may be that different crops employ different mechanisms to deal with water stress. For this reason it is difficult to make generalised recommendation for its implementation. Nevertheless, PRD is unlikely to have a negative impact on plant performance and the balance of evidence suggests that there will be positive outcomes. Negative aspects may relate more to any additional costs associated with its implementation. Although, as pointed out by Adem *et al.* (2002), these are likely to be small. A positive outcome from the implementation of PRD may be that it encourages experimentation with irrigation water application rates, and as this project has shown, many perennial horticultural crops can be successfully grown with far less water than has traditionally been used.

Summary of present knowledge

Based on our experiments described above, the following points encapsulate our present knowledge of PRD responses and best management practice for PRD implementation:

- Best PRD responses occur in soils with high values of readily available water (RAW). Shallow soils with low RAW can allow rapid depletion of water in the relatively small soil volume wetted by PRD. To some extent this can be overcome by more frequent irrigation.

- Use of PRD in soils with poor infiltration characteristics may similarly be problematic if sufficient water cannot be supplied through what is effectively 50% of the normal soil surface area.
- The amount and timing of irrigation applied to the 'wet' side should be sufficient to prevent the development of significant water deficits (soil moisture tension should remain higher than 50kPa)
- When soil moisture monitoring is available the irrigated side of the plant should be switched when water extraction from the "dry" side becomes negligible. In sandy soils and under hot dry conditions this may be only a few days, while in soils with a higher water retention characteristic and under less stressful conditions the cycle time may become several weeks.
- Use of PRD should not result in significant reduction in midday leaf water potential (however, see the discussion above about osmotic adjustment) when compared with standard irrigation practice.
- When PRD is being implemented in an existing orchard total soil area wetted by the irrigation system (wet plus dry sides) should not vary significantly from that wetted by the original irrigation system. For example, conversion from flood to drip may wet only a small fraction of the available roots. The PRD irrigation system should aim to wet approximately half the roots at any one time.
- Correctly implemented PRD should not result in major effects on fruit quality. In some of our experiments with Navel orange PRD at very low water application rates there was a reduction in fruit size of heavily cropped trees but this problem was not evident at higher water inputs. A reduction in water input, applied by flood or by drip, may result in a small but significant reduction in % juice and an increase in % acid. There should be no effect on sugars and sugar/acid ratios may change accordingly.
- In pear very low water inputs resulted in an increase in total soluble solids and a small reduction in fruit size, but at a higher level of water input (1.7 ML/ha) these effects were not evident
- Response to PRD will be dependent on species and we do not know how some plants will respond.

The approach taken in the experiments with pears at Tatura appears to offer a model for determining minimum crop water requirements. Here, a fairly traditional approach was adopted, based on class A pan evaporation to estimate water requirements. However, inclusion of canopy cover and soil evaporation components resulted in a conservative water use estimate which must have been close to the minimum acceptable since further reduction resulted in water stress as assessed by a range of methods and some detrimental effects on crop yield and quality.

During times of critical water shortage some reduction in yield may become acceptable. Data from the experiments with Navel orange and PRD at Yanco showed that water application rates (irrigation plus rain) could be reduced to about 30% of calculated reference evapotranspiration (ETo) with no detrimental effect on return crop or apparent health of the trees, but in this case there was a tendency for the fruit size to be adversely affected. Similarly at Waikerie with Valencia orange significant reductions in irrigation amount could be achieved with PRD. In this case some problems were sometimes encountered with fruit firmness, although there were no detrimental effects on fruit size. This problem was overcome with more frequent irrigations without changing the irrigation amount. Thus, many of our experiments have explored the minimum water input required for the maintenance of productivity. PRD offers advantages over conventional irrigation such as reduction of evaporative losses due to a smaller wetted soil surface area and stimulation of physiological mechanisms that reduce tree water use during times of high evaporative demand.

Publications, adoption and publicity

Work undertaken in this project has been incorporated in numerous publications and presentations to conferences and grower groups. Some of these are listed below.

Refereed journals

Davies, W.J., Wilkinson, S. and Loveys, B.R. (2001) Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. *New Phytologist* 153, 449-460

Dry, P.R., Loveys, B.R., McCarthy, M.G. and Stoll., M. (2001). Strategic irrigation management in Australian vineyards. *Jnl. Int. Sci. Vigne Vin*, 35, 129-139

Kang, S., Hu, X., Goodwin, I and Jerie, P. (2002). Soil water distribution, water use, and yield response to partial root zone drying under a shallow groundwater table condition in a pear orchard. *Scientia Horticulturae* 92: 277-291.

Loveys, B.R., Dry, P.R., Stoll, M. and McCarthy, M. (2000)
Using plant physiology to improve the water use efficiency of horticultural crops.
Acta Horticulturae 537, 187-199

Stoll, M., Loveys, B.R. and Dry, P.R. (2000) Improving the Water Use Efficiency of Irrigated Horticultural Crops, *Journal of Experimental Botany* 51, 1627 1634

Refereed conference proceedings

Dry, P.R, Loveys, B.R, Stoll, M. and McCarthy, M.G. (2001). Partial Rootzone Drying – a strategic irrigation technique. Paper presented to the Australian Society of Horticultural Science annual conference, Sydney, September 2002

Goodwin, I. (2002). Water management – a tool for vineyard managers. In: *Managing Water. Proceedings of Australian Society of Viticulture and Oenology Seminar*, Mildura 12 July 2002.

Loveys BR and Lu P, 2002. Plant Response to Water – New Tools for Irrigators, Paper presented at Australian Society of Viticulture and Oenology seminar

Loveys, BR and Soar CJ, 2002. Mechanisms of Transpiration Control in Horticultural Crops.
Paper presented to the Australian Society of Horticultural Science annual conference, Sydney, September 2002

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Other

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BL Interviewed for ABC radio science program "Nexus"

BL Interviewed for BBC World Service science program

ABC Landline item on Partial Rootzone Drying featured work at Waikerie with oranges

*In addition to the above, BL, PD, IG and RH gave over 70 presentations on irrigation management and plant response to environmental stress to visiting scientists and grower groups at their respective institutions during the 2000-2003 period***.**

Commercial potential

PRD is being increasingly adopted in the winegrape industry where growers see a number of advantages over conventional irrigation. For example, in areas where water supply is limited there is less risk of encountering crop-limiting water deficits associated with an irrigation scheme based on PRD than on conventional irrigation procedures because water should always be available to part of the root system. The method of delivery of irrigation water may not be critical, but there are advantages associated with sub-surface driplines buried one either side of the row. For example, evaporation of water from the soil surface is eliminated and weed growth in accordingly reduced. If necessary both lines can be turned on to provide some insurance on days of extreme evaporative demand.

Experience has shown that PRD works best in deeper soils with relatively high readily available water (RAW). Use of PRD in very shallow soils with low RAW may be less successful as the water in the relatively small wetted soil volume may be quickly depleted, exposing the plant to the risk of water stress. This can be overcome to some extent by shortening the PRD cycles.

Although PRD can be successfully applied using any conventional irrigation hardware for pressurised water or even by simply applying water to one side of a row in the case of flood irrigation, several manufacturers have produced dripline with two fused pipes. These can be fitted with in-line drippers or can be equipped with conventional drippers at intervals chosen for the particular application.

The development of these products arose from discussions with growers who had installed two conventional driplines but found that over time they moved relative to each other, thereby changing the desired alternating wetting pattern. The development of the fused dripline has also stimulated some new ideas about PRD application to crops growing in situations where the canopy is more or less continuous. In this situation it may be appropriate to consider the entire row as if it were one plant since the root mass associated with these plants will itself be more or less continuous. In this case the placement of the irrigation emitters, relative to the trunks, may not be critical as long as alternate wet and dry zones are created. These ideas are at this stage just that, and need to be substantiated by experiment.

As discussed above, the success of PRD in a range of crops may be related to the way that each deals with water stress. Our current understanding is that plants that rely on stomatal control to maintain their water status within tight limits may be best suited to

PRD or other irrigation strategies that deliberately expose them to water deficits. However, once again these ideas need to be investigated experimentally.

In summary, PRD is an irrigation strategy that offers a grower the opportunity to optimise crop response to challenging environmental conditions and improve the efficiency of water use. The use of such technologies may be indicated in situations where water availability becomes a limiting factor in crop production. However, it should be emphasised that for every crop there is a lower limit for water availability, below which productivity will suffer no matter how that water is applied.

Appendix 1. Tables and Figures referred to in the text.

Table 1. Fruit numbers from irrigation treatments and years. Navel orange, Yanco

Treatment	1997/98	1998/99	1999/00	2000/01	2001/02
Full flood	1344	464	-	-	-
Alt flood	1571	588	-	-	-
Full drip	1165	500	1255	636	1718
Alt drip	1026	443	1174	541	1574
P	>0.05	>0.05	>0.05	>0.05	>0.05

Figures are means from 15 (1997-1999) or 21 trees (2000 and 2001)

Table 2. Mean fruit weight (g) for irrigation treatments and years. Navel orange, Yanco

Treatment	1997/98	1998/99	1999/00	2000/01	2001/02
Full flood	60	79	-	-	-
Alt flood	58	76	-	-	-
Full drip	62	83	62	69	69
Alt drip	61	73	61	71	65
P	>0.05	>0.05	>0.05	>0.05	>0.05

Figures are means from 15 (1997-1999) or 21 trees (2000 and 2001)

Table 3. Rainfall, irrigation applied and ETo (mm). Navel orange, Yanco

Treatment	1997/98	1998/99	1999/00	2000/01	2001/02
Full flood	566	-	-	-	-
Alt flood	283	-	-	-	-
Full drip	433	467	396	548	446
Alt drip	232	273	249	304	323
Rainfall	225	209	255	249	160
ETo	1547	1439	1279	1592	1709

Table 4. Fruit quality characteristics 1998-99 harvest. Navel orange, Yanco

Treatment	% juice	^{o}Brix	% acid	Ratio
Full flood	43.9ab	13.6	1.49ab	9.13ab
Alt flood	42.1c	13.5	1.68c	8.03c
Full drip	44.9a	12.9	1.39a	9.34a
Alt drip	43.4bc	13.1	1.56bc	8.45bc
Significance	<0.05	ns	<0.05	<0.05

Figures followed by the same letter in a column are not significantly different

Table 5. Fruit quality characteristics 2001-2002 harvest. Navel orange, Yanco

Treatment	% juice	°Brix	% acid	Ratio
Full drip	47.7	13.5	1.42	9.55
Alt drip	46.5	13.9	1.59	8.75
Significance	<0.05	ns	<0.05	<0.05

Table 6. Irrigation performance, fruit yield and quality characteristics at harvest (31 Jan 02) and pruning weight (12 Sept 02) for pear under the control (1.0C), full (1.0PRD) and partial (0.5PRD) rootzone drying treatments during the 2001-02 irrigation season at Tatura.

Irrigated area	Irrigation (ML/ha)	WUE (t/ML)	Yield (t/ha)	TSS (°Brix)	Fruit size (g)	Flesh firmness (kg)	Pruning weight (kg/tree)	Dropped fruit (kg/ha)
1.0C	1.73	16.8 b	29 a	12.3 b	157 a	8.4 a	8.7 a	36 a
0.5PRD	0.87	28.2 a	24 a	14.3 a	129 b	8.1 a	5.1 b	50 a
1.0PRD	1.73	17.2 b	31 a	12.2 b	168 a	8.4 a	8.9 a	28 a
l.s.d.(*P*=0.05)	4.8	7	0.7	26	0.5	3.3	22	

Table 7. Leaf temperature as assessed by infrared thermometry in pear orchard at Tatura, 2002-03 season.

Treatment	31/10/02	05/11/02	19/12/02
Control	25.4	20.8	40.9
1.0 PRD	24.3	20.6	39.2
0.5 PRD	24.9	22.8	42.2
LSD (P<0.05)	1.0	1.9	1.7
Air temperature	22.6	19.8	35.5

Table 8. Stomatal conductance (mmol.m^2.s^{-1}) of Valencia orange trees at Waikerie 06/12/02. Figures are means of 40 measurements made between 9.00am and 11.00am Figures followed by a different letter are significantly different (P<0.001)

Control east	PRD east	Control west	PRD west
129a	94b	72c	78c

Table 9. Stomatal conductance (mmol.m^2.s^{-1}) of Valencia orange trees at Waikerie 03/01/03. Figures are means of 40 measurements made between 9.00am and 11.00am. Figures followed by a different letter are significantly different (P<0.001)

Control east	PRD east	Control west	PRD west
183a	102b	81c	65c

Table 10. Stomatal conductance (mmol.m^2.s^{-1}) of Valencia orange trees at Waikerie 16/01/03. Figures are means of 40 measurements made between 9.00am and 11.00am or between 2.00pm and 4.00pm. Figures followed by a different letter are significantly different (P<0.001)

Control east am	PRD east am	Control west pm	PRD west pm
136a	55bc	32c	34c

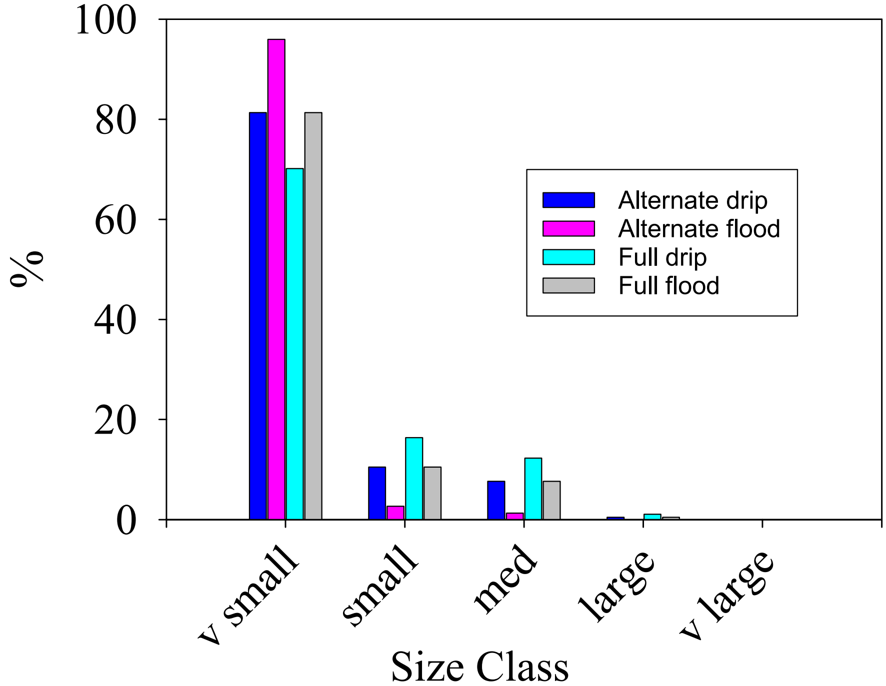
Table 11. Root dry weights (kg/m^3) in top 250mm of soil under Valencia orange trees in Waikerie. There were no significant differences between treatments. Trees were irrigated as per standard orchard practice (Manager) or as part of the PRD experiments for three seasons. Figures are means of 18 measurements.

Treatment	Manager east	Manager west	Experiment east	Experiment west
Mean	2.44	2.69	2.67	2.93
SEM	0.31	0.47	0.42	0.34

Table 12. Daily correlation coefficients between VPD (kPa) and sap flow (L/day) of pear trees before, during and after PRD irrigation. Figures followed by a different letter significantly different (P<0.05).

Irrigation	Coefficient
Both pots (day 1-18)	0.71a
One pot (day 18-31)	0.46b
Both pots (day 31-39)	0.59ab

1999 harvest fruit size distribution



2002 harvest fruit size distribution

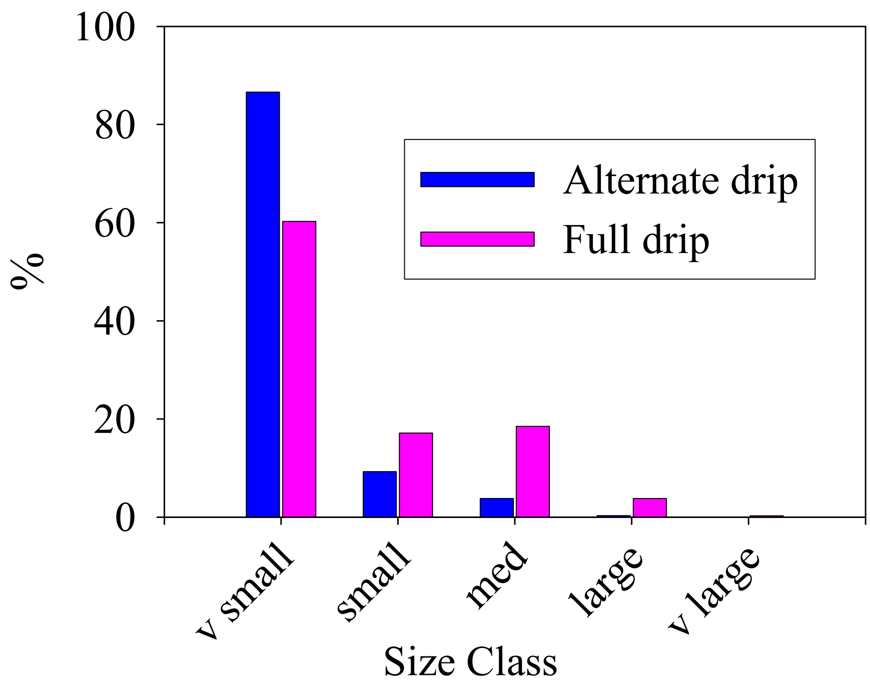


Figure 1. Size class distribution of Navel oranges from the 1999 and 2002 harvests at Yanco.

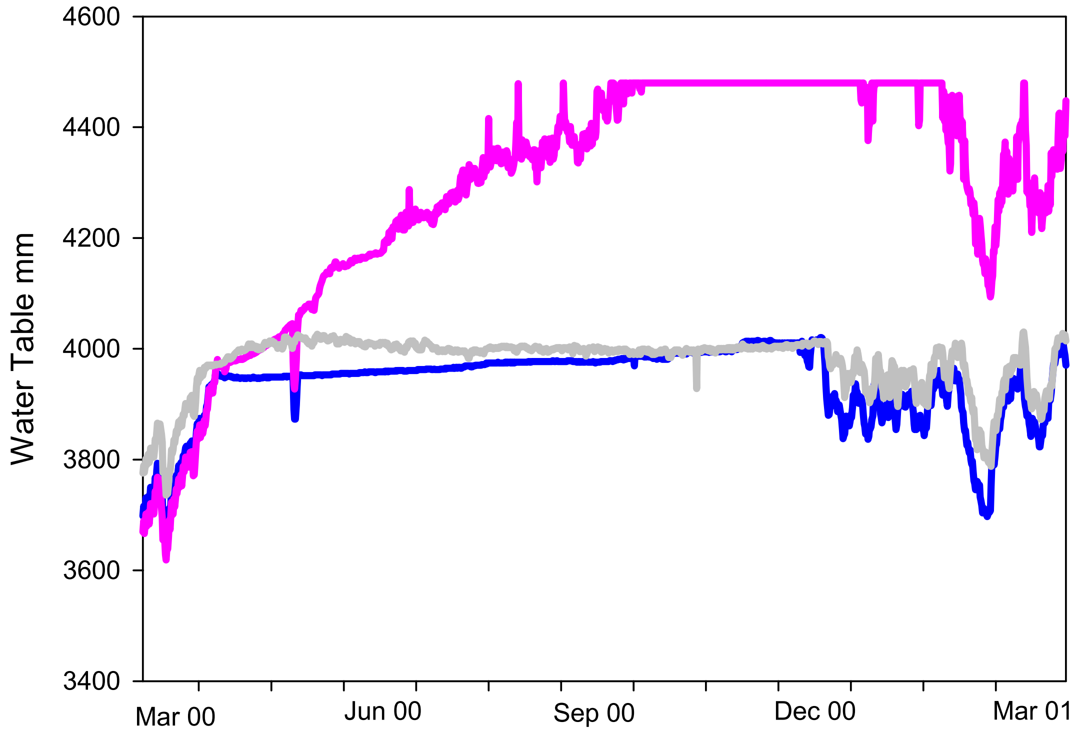


Figure 2. Water table depths at the Yanco site as assessed by piezometer tubes. From March 2000 to March 2001.

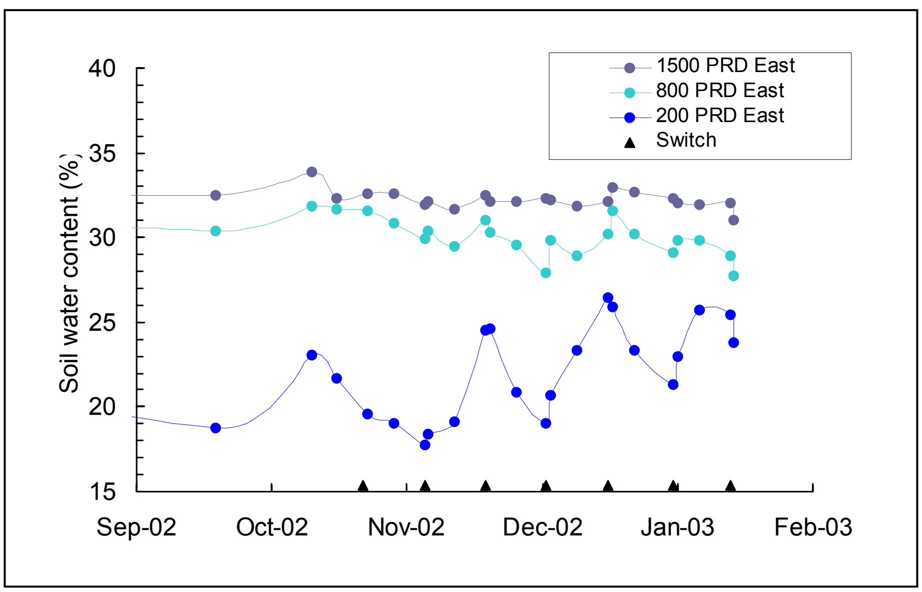


Figure 3 Soil water content at three depths in a pear PRD experiment at Tatura

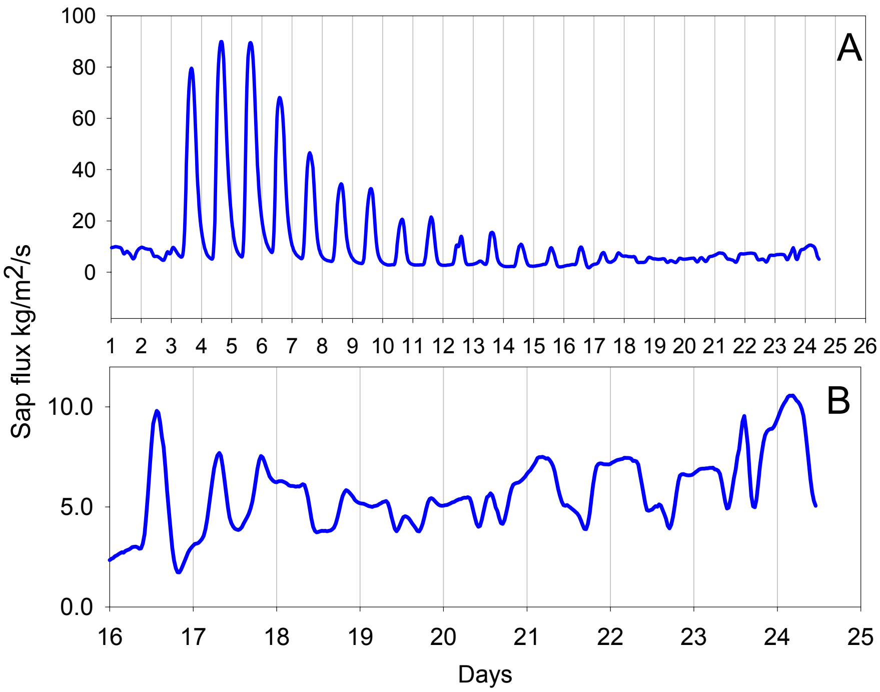


Figure 4 Sap flow in root of Valencia orange tree. Irrigation was applied to the side of the tree in which the sensors were inserted on day 3. Irrigation was then switched to the other side.

A. sap flow during 21 days of drying after one irrigation event.

B. Fine detail of sap flow during days 16 to 24

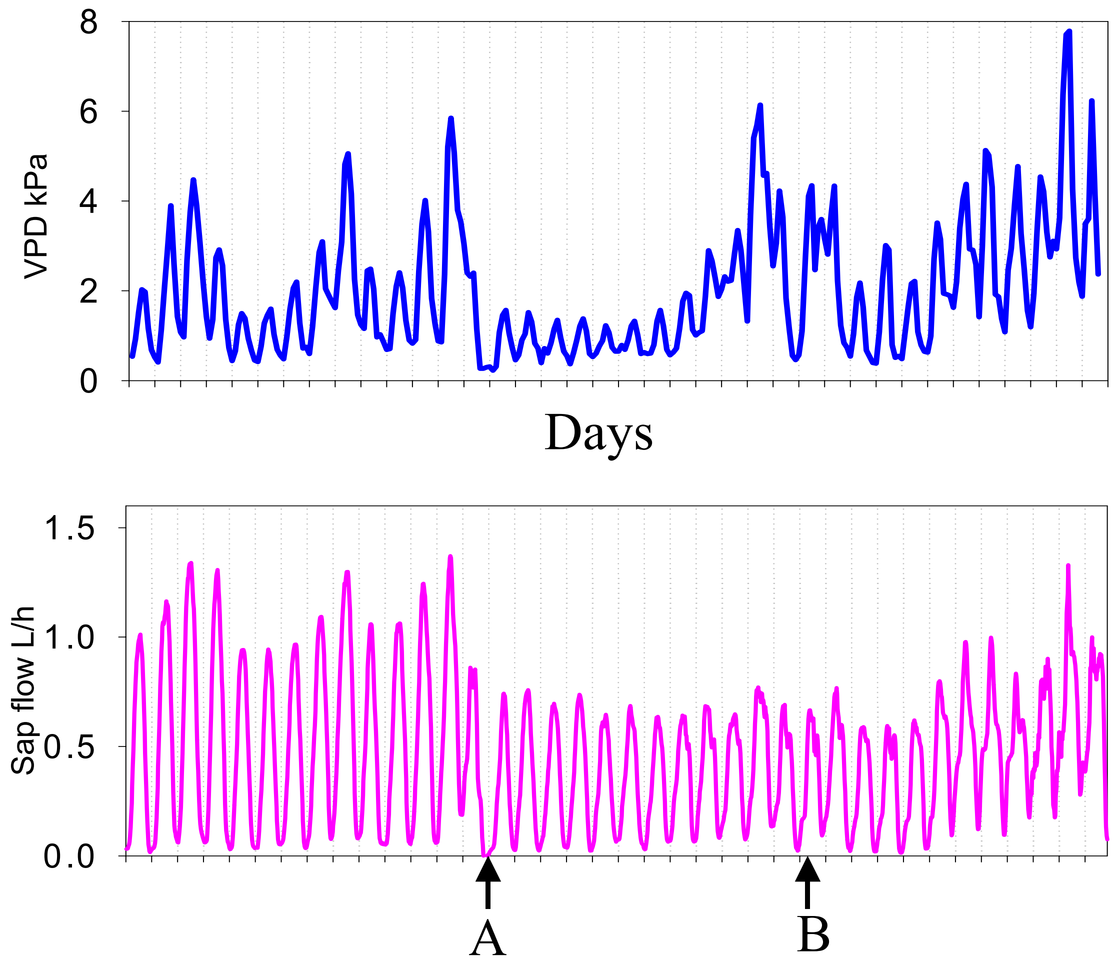


Figure 5 Sap flow and VPD during an experiment with pear trees. From the beginning of the experiment to Time A all of the roots were irrigated, from Time A to Time B half the roots were irrigated and from Time B to the end all roots were again irrigated.

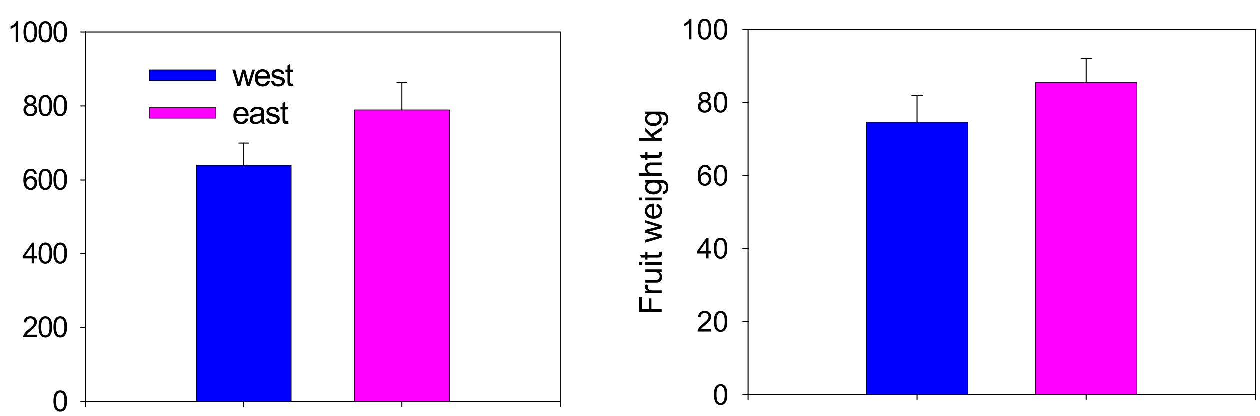


Figure 6. Effects of aspect on fruit numbers and fruit weight per tree of Navel orange. Aspect significantly affected fruit number (P=0.007) and fruit weight (P=0.07). n=12

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