IMPROVING THE WATER USE EFFICIENCY OF HORTICULTURAL CROPS

Final Report

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NPIRD project CDH1

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ABSTRACT

The results of this project show that there is considerable scope for improving the water use efficiency of fruit production in Australia. The two year project has sought to test the partial rootzone drying (PRD) irrigation method, originally developed for grapevines, in a range of woody perennial horticultural crops. The technique requires that both wet and dry rootzones are simultaneously created. Results with grapes, citrus and pears have given exciting results.

Fruit trees with their roots divided between two large containers responded within a few days when water was withheld from one half of the roots. Stomatal conductance was reduced by between 30 and 50% compared with a fully irrigated controls for as long as one root system remained dry. Conductance recovered once the trees were returned to full irrigation. Changes in root abscisic acid were consistent with these responses.

PRD irrigation was applied to citrus and pear orchard trees. Navel orange trees in the MIA were converted from flood to drip irrigation and PRD treatments applied by both flood and drip. In the PRD flood treatment water input was reduced by 40% but the trees experienced a degree of water stress, attributed to poor water infiltration into the soil. Drip irrigated trees, on the other hand, showed no water stress symptoms, in trees irrigated on both sides or on one side only (PRD), even when water input was reduced by up to 80% compared with the fully irrigated flood treatment. Fruit quality and yield remained acceptable. Substantial improvements in water use efficiency were also obtained with Valencia oranges with PRD irrigation and significant changes in root abscisic acid were detected. There was substantial night-time movement of water within citrus trees in response to the creation of both wet and dry roots and some of the effects of PRD could be attributed to this. The addition of PRD appears to add another dimension to the water management of citrus trees, although the mechanisms by which this is achieved are not fully understood.

PRD was applied to flood irrigated pears in the Goulburn valley by watering only one side of the row. Water input was thus halved. Tree performance in terms of crop yield and quality was unchanged, as were measures of tree physiology such as stomatal conductance and shoot water potential. Measurement of soil water provided no evidence that the trees were accessing stored soil water.

INTRODUCTION

This project was initiated as a result of a research project, principally funded by the Grape and Wine Research and Development Corporation, which demonstrated that by maintaining wet and dry areas in the grapevine rootzone it was possible to achieve considerable savings in irrigation input with no penalty in terms of crop yield or quality. We have called the irrigation technique partial rootzone drying (PRD) The PRD technique, as it applies to grapevine, is now in the adoption phase, with significant commercial plantings in Australia and overseas. The success of the technique depends on the production of stress-related chemicals in the drying roots and the transport of these to the leaves where they bring about physiological changes which result in increased water use efficiency.

We believe that crops other than grapevine should also behave in this way and may therefore benefit from PRD. This would result in improved irrigation efficiency, less accession to water tables and other benefits which may accrue from a reduction in irrigation input. A project based on these arguments has been funded by LWRRDC through the NPIRD initiative.

The two year project may be summarised under the following main objectives:

1. establish a range of fruit trees with their roots divided between two large (75L) containers for assessment of physiological responses to partial root drying
2. on a grower property in South Australia Riverland, modify the irrigation of Valencia orange trees from total cover under tree sprinklers to allow PRD and assess water use and tree performance
3. on the NSW Agriculture research station at Yanco, change the irrigation of navel orange trees from flood to drip and impose PRD treatments on both flood and drip irrigated trees. Assess tree performance and irrigation input under these treatments
4. on a grower property in the Goulburn valley, apply PRD to flood irrigated Packham pears and assess tree performance
5. install sap flow sensors in the roots of Valencia orange trees to assess the importance of bidirectional sap flow in maintaining the PRD effect and the viability of roots in drying soil

1. Summary and conclusions

Objective 1: *establish a range of fruit trees with their roots divided between two large containers for assessment of physiological responses to partial root drying*

Results and conclusions

Cherry, apple, pear and apricot trees were established with their roots divided equally between two containers. The trees were irrigated automatically as required to maintain the medium at close to field capacity. During 10 and 7 week periods in years one and two respectively water was withheld from one container. Control trees received water to both sides. Stomatal conductance was measured twice weekly for the duration of the experiment. In year two abscisic acid (ABA) was measured in the roots of the trees as an indicator of PRD response. Abscisic acid is a plant hormone to which many of the PRD responses of grapevine have been attributed.

A range of woody perennial fruit trees were assessed for their response to partial drying of the root system. Stomatal conductance was reduced by between 30 and 40% for as long as one root system remained unirrigated. The concentration of abscisic acid, which is considered to be an indicator of stress response, was significantly elevated by the treatment in the drying roots. Reversing the irrigation side caused a period of intensified inhibition and this was associated with elevated ABA levels in both wet and dry roots. The conductance of the leaves slowly recovered to control values after the trees were fully watered. The effect of the treatment on trunk growth was small (<10%), and significant only in the case of the cherrys. It is concluded that allowing part of the root system to dry causes physiological changes in the trees which result in a reduction in stomatal conductance, and therefore transpiration. The effects on growth were relatively minor.

Objective 2: *on a grower property in South Australia Riverland, modify the irrigation of Valencia orange trees from total cover under tree sprinklers to allow PRD and assess water use and tree performance*

Results and conclusions

Irrigation to a commercial block of mature Valencia orange trees which had previously been irrigated with full coverage under canopy sprinklers has been modified to supply water selectively to either both sides of the trees (control) or to one side or the other (PRD treated). Irrigation input to the control trees has been approximately 70% of the average for that fruit block (11ML/ha/y) since it was estimated that the new under-tree sprinklers left approximately 30% of the traffic lane between the tree unirrigated.. Water application rates are monitored with meters in each irrigation line. Tree performance indicators such as fruit growth, fruit number, stomatal conductance were monitored. Physiological indicators of PRD effects were also measured, namely root and leaf ABA concentrations.

The PRD treatment reduced water application rates by between 42 and 50% compared with normal grower practice for the property and by between 32 and 43% compared with the district average. There was no significant effect on fruit size at harvest in 1998, although samples from the PRD trees taken approximately 4 months prior to the 1999 harvest were 5% smaller in diameter than fruit in the rest of block, but not significantly smaller than the fully irrigated experimental control. Factors other than irrigation cannot be ruled out as the cause of this size difference. In 1998 the PRD fruit had a lower sugar to acid ratio than controls. Fruit quality parameters of the 1999 crop will be assessed in November. There were no significant effects of the treatment on leaf stomatal conductance or shoot water potential. The treatment significantly increased root, but not leaf, abscisic acid, suggesting that the physiology of the trees had been altered by the treatment. The results show that large water savings are possible, but there may be minor changes in fruit quality. The design of the experiment did not allow us to attribute these changes to water management alone.

Objective 3: *on the NSW Agriculture research station at Yanco, change the irrigation of navel orange trees from flood to drip and impose PRD treatments on both flood and drip irrigated trees. Assess tree performance and irrigation input under these treatments*

Results and conclusions

Four irrigation strategies were evaluated from 1997 to 1999. Some of the experimental trees (mature navel orange trees) were converted from permanent furrow flood to drip irrigation. Control flood irrigated trees (watered both sides) received 13.5ML/ha/y in the 1998/99 irrigation season. This was slightly more than the district average. During the same season, drip irrigated trees received only 4.8ML/ha/y. Flood and drip irrigated trees subjected to partial rootzone drying (PRD) treatments, where only one side of the trees was watered for periods of 4 weeks before switching to the alternate side, received even less water (Table 1). PRD trees received approximately half the respective amounts applied in both flood and drip treatments. We have not been able to detect any consistent, statistically significant, difference between full drip and PRD drip irrigated trees in terms of water potential or stomatal conductance, although fruit on the PRD trees tended to be slightly smaller. PRD flood irrigated trees showed some signs of water stress, probably resulting from poor water infiltration.

There was no yield penalty following conversion to drip irrigation when completed before the start of the irrigation season and where drip lines were placed 15-20cm inside the outer canopy line on both sides of the tree.

Table 1. Water applied for 98-99 season

Irrigation method	Water applied ML/ha/ye	Water applied % of full flood
Full flood	13.5	100
PRD flood	8.0	59
Drip	4.8	35
PRD drip	2.8	21

It is clear that highly significant increases in water use efficiency have been achieved. What is not so clear is the mechanism whereby this has been achieved. In citrus, we have been unable to demonstrate significant physiological responses typical of plants experiencing PRD. However, huge water savings appear possible. Reduced water application is partly due to the more efficient water delivery of drip compared with flood, but the addition of PRD appears to add another dimension to the water management of citrus trees.

Continuing physiological studies are providing some clues as to the mechanisms operating when trees are subject to the PRD treatment and this knowledge will be invaluable in making modification to our irrigation strategies in citrus in the future, but it is clear we do not yet have all the answers.

Objective 4: *on a grower property in the Goulburn valley, apply PRD to flood irrigated Packham pears and assess tree performance*

Results and conclusions

The objective was to trial Partial Rootzone Drying (PRD) in an established pear orchard under typical flood irrigation conditions in the Goulburn Valley. In this situation water use efficiency is traditionally low and very difficult to improve above a basic level. The trial would also establish whether the physiological responses to PRD in pears were similar to those reported in wine grapes. The outcomes expected were a practical answer on the feasibility of improving water use efficiency in flood irrigated orchards, to determine at which stages of fruit growth PRD could be safely applied and to provide a basis for extending PRD to tree line irrigation systems such as microjet.

The PRD treatments were applied in two ways: by watering only one side of the row at each irrigation and switching the wetted side at each irrigation (Flip-Flop treatment) or by applying the irrigation water to one side of the rows and retaining the other side as permanently dry (Permanent treatment). The control was normally irrigated, that is it received water to both sides at every irrigation. PRD treatments did not affect yield or fruit size in either year and were continued throughout the irrigation seasons. In year 2 the yield over the experimental orchard was 82 tonnes per hectare, an unusual high yield particularly given the large fruit size. This high yield indicates that tree performance was severely tested and close to optimum by commercial standards. Details are shown in Table 2. In another experiment (data not shown), in a block of WBC pears, one side of one row was allowed to remain unirrigated for the whole season and, similarly to the Packham results, fruit growth was not affected.

Table 2. Packham pear yield data from year 2. The differences between means were not significant (P>0.05)

Treatment	Yield (kg/tree)	Average fruit weight (g)	Fruit number per tree	Yield efficiency (kg/cm^2 Butt Area
Control	244	200	1232	0.36
Flip/Flop PRD	237	184	1321	0.38
Permanent PRD	256	191	1343	0.35

The results clearly show that applying half the irrigation water, either as an alternating or a permanent PRD treatment, did not affect fruit growth and had only minor effects on tree water status. When compared to Regulated Deficit Irrigation (RDI) treatments, PRD would be expected to give similar results during the period of slow fruit growth in November and early December (though in the last two years PRD was not effective during that time because of rain). Earlier results have shown that when RDI is continued past December, fruit size is reduced and sugar content is increased. In contrast, PRD treatments maintained fruit growth and sugar content was not affected. The physiological response of pear to PRD is apparently quite different to the response of wine grapes. In grapes, PRD causes ABA levels to increase while conductance was reduced and water potential was maintained. No consistent effect on the level of ABA or conductance was detected in pear.

After two years of field trials it is not possible to reconcile the results from measurements of soil moisture and tree water status with documented irrigation applications. It is not clear how the trees, in both PRD treatments, obtained the water supply required to maintain the observed leaf water status. There is no doubt that irrigation input was reduced by about 50% and this had the visible result that the grass in the dry row of the Permanent treatment dried off.

Several different mechanisms could have contributed a small component, that in itself is difficult to detect, towards maintaining the water balance in PRD rows. It is very unlikely that water moved into the root zone from below at a high enough rate to compensate for the reduced irrigation input, but some contribution could be expected and would be very difficult to measure. The orchard floor component of water use may be larger than expected and therefore the true crop factor of the pear trees would have to be correspondingly smaller. Therefore, tree water status may have been maintained while using less water than is presently accepted. A reduction of 0.9 mm per day in water use by the Permanent PRD is likely to be largely due to reduced water loss from the row with dry grass. It is also possible, but considered highly unlikely, that the root system of pear trees is far more extensive that expected and the trees negate treatment effects by drawing water across several rows.

The results indicate the need for a basic re-evaluation of the water relations of pear orchards. Whether, in the end, the mechanisms governing water use will include the hormonal and physiological changes identified in the PRD response of wine grapes, remains to be seen. At least under Goulburn Valley conditions, the results of the present trials justify the careful extension of “Pear PRD” to commercial orchards, provided that fruit development is monitored and benchmarked against expected growth rates. The grower could revert to normal irrigation if fruit growth was reduced. This would lead to a potential water saving of 30-40%. Results detailed in the next section suggest that root health will not be affected by the PRD treatment.

Objective 5: *install sap flow sensors in the roots of Valencia orange trees to assess the importance of bidirectional sap flow in maintaining the PRD effect and the viability of roots in drying soil*

Results and conclusions

One of the concerns with irrigation treatments such as PRD which seek to manipulate the tree by withholding water for significant periods of time is that roots in the dry soil may die or lose function so that when water is finally restored to those roots they may be less effective, thus predisposing the tree to water stress. Measurements of shoot water potential have suggested that this is not the case and we have made the assumption that roots in drying soil may have the capacity to draw water from the more hydrated soil on the other side of the tree, thus maintaining their viability. To test this assumption we have installed sap flow sensors in the roots of Valencia orange trees in such a way that they are able to measure sap flowing from the soil to the tree and also flow from the tree towards the drying soil. We believe that information about water movement within trees is important to our understanding of the PRD principle and will be necessary in formulating recommendations.

Sap flow sensors installed in the roots of Valencia orange trees provided information about the movement of water throughout the tree during several irrigation cycles. Water moved within the tree, from the soil to the tree and from the tree to the soil according to the water potential gradients established by irrigation and transpiration. There was substantial sap flow at night from irrigated soil to the tree. This water could have been used to rehydrate the aerial parts of the tree but a proportion also moves along roots which are in dry soil in the direction away from the tree. On some days the magnitude of the tree-to-soil sap flow during the night was as great as the soil-to-tree flow during the day, suggesting a relatively small proportion of the water transpired through the roots on the dry side of the tree actually came from the soil. The redistribution of water may serve to transport chemical signals, such as plant hormones, out of roots in dry soil. It will also serve to maintain the roots in drying soil in a viable condition. This may be one of the major differences between PRD and other irrigation strategies such as RDI which may expose the whole root system to simultaneous drying.

2. Detailed results against objectives

2.1 Objective: *establish a range of fruit trees with their roots divided between two large (75L) containers for assessment of physiological responses to partial root drying*

2.1.1 Introduction and procedures

Cherry (var. Sunburst/Mazzard F12-1), Apple (var. Gala/Northern Spy), pear (WBC/Callereyana D6) and apricot (var. Moor Park/Myrobalan H29) trees were established with their roots divided equally between two 40L containers. After two years growth the containers were increased to 75L capacity. The trees were irrigated automatically as required to maintain the medium at close to field capacity. Soil moisture sensors (Theta probes, Delta T Devices) were installed to monitor soil water content. During 10 and 7 week periods in years one and two respectively water was withheld from one container. Control trees received water to both sides. Stomatal conductance was measured twice weekly for the duration of the experiment. In year two abscisic acid (ABA) was measured in the roots of the trees as an indicator of PRD response. Abscisic acid is a plant hormone to which many of the PRD responses of grapevine have been attributed (Loveys et al. 1999).

2.1.2 Results and discussion

In 1997/98 and 1998/99 seasons cherry and apple trees responded quickly to partial drying of the root system. Stomatal conductance fell rapidly over the first few days of treatment and then showed recovery up to 10 days after the start of the experiment, which was similar to the situation in grapevine. However, recovery was incomplete and over the following 3 weeks conductance remained inhibited by about 40% compared with a fully irrigated control (Appendix 1, Figure 1). At the end of the experiment dry sides of the treated trees were rewatered and there followed a period of recovery during which conductance of the treated plants attained that of the controls. In the first year of the experiment the apricot was less responsive than the apples and cherry. The pears were characterised by high values of stomatal conductance when compared with the other crops and a relatively smaller reduction of stomatal conductance (average of 30% inhibition over a 40 day period).

Abscisic acid in the roots of the trees was measured at strategic times during the experiment. It was not possible to take a large number of samples due to the risk of causing excessive damage to root systems which may have influenced tree response to the irrigation treatments. ABA had increased significantly in the drying roots of the treated trees (Appendix 1, Table 1) 7 days after water was withheld. 56 days after the start of the experiment irrigation to the wet and dry sides were reversed. A period of intensified inhibition of conductance followed for about a week. During this time another ABA sample was taken. There was an increase in ABA on the new dry side but the ABA on the previously dry side also remained high. This may explain the intensified inhibition of stomatal opening during this period as the total amount of ABA in the system was greater than before the watering sides were swapped. Furthermore, the potential for exporting ABA from the previously dry side would have been enhanced due to the availability of water for transpiration from that side. Root ABA in apples and cherries showed recovery towards levels in irrigated roots within 2 days of fully rewatering the trees.

Growth, as measured by butt circumference was reduced significantly (P=.02) by the treatment in the cherry trees, but not so for the apples and apricots. The magnitude of the reduction (<10%) was relatively small, however.

2.1.3 Conclusions:

A range of woody perennial fruit trees were assessed for their response to partial drying of the root system. Stomatal conductance was reduced by between 30 and 40% for as long as one root system remained unirrigated. Abscisic acid levels in the drying roots was significantly elevated by the treatment. Reversing the irrigation side caused a period of intensified inhibition and this was associated with elevated ABA levels in both wet and dry roots. The conductance of the leaves slowly recovered to control values after the trees were fully watered. The effect of the treatment on trunk growth was small (<10%), and significant only in the case of the cherrys.

2.2 Objective: *on a grower property in South Australia Riverland, modify the irrigation of Valencia orange trees from total cover under tree sprinklers to allow PRD and assess water use and tree performance*

2.2.1 Introduction and procedures

Irrigation to a commercial block of mature Valencia orange trees on Rough Lemon rootstock which had previously been irrigated with full coverage under canopy sprinklers has been modified to supply water selectively to either both sides of the trees (control) or to one side or the other (PRD treated). Irrigation input to the control trees has been approximately 70% of the average for that fruit block (11ML/ha/y) since it was estimated that the under-tree sprinklers left approximately 30% of the traffic lane between the tree unirrigated.. Water application rates are monitored with meters in each irrigation line. Soil moisture is continuously logged with 8 TDR probes (Campbell Scientific). The data from these soil probes and the pressure in each irrigation line can be remotely accessed from Adelaide. This provides confirmation that irrigation events have occurred. A remotely accessed automatic weather station is also located at the site.

Tree performance indicators such as fruit growth, fruit number, stomatal conductance were monitored. Physiological indicators of PRD effects were also measured, namely root and leaf ABA concentrations.

2.2.2 Results and discussion

Water application rates were modified according to season, with the highest rates being applied between October and March. Irrigation was applied every 4^{th} or 6^{th} day, depending on season. Irrigation side of the treated trees was switched after 3 or 4 cycles. Total water application to the control and treated trees was 7.5 to 8.2 and 5.4 to 6.4ML/ha/year respectively. The treated trees thus received water at a rate between 49% and 58% of the rest of the block, which was irrigated by the owner. The average for the Riverland/Sunraysia district is 9.4ML/ha (Skewes and Meissner (1997).

Shoot water potential was measured on a number of occasions and there was never a significant difference between control and PRD trees and the midday values of water potential of between –1.1MPa and -1.9MPa suggested that the trees were adequately watered. Stomatal conductance values showed large leaf to leaf variation and generally low values. However, although there was a tendency for the PRD trees to have lower conductance, the differences between treated and control trees were never statistically significant.

Fruit sizes were not affected by the PRD treatment when compared with the fully irrigated control in either year of the study, although there was a slight reduction in mean fruit diameter when the PRD treatments were compared with some adjacent trees which had been irrigated according to the grower's schedule. However, it is possible that this slight reduction may be attributable to a number of other causes such as nutrition, soil type etc. At the time of measurement the fruit had not attained their maximum size. A more detailed assessment of this effect on fruit size will be made before the fruit are harvested in November 1999. There was no significant difference in fruit numbers per tree, either between the two irrigation treatments or the grower-irrigated trees (P=0.21). In the 1998 harvest there was no difference in size classes when PRD fruit were compared with control (Appendix 1, Figure 2). We did not make a comparison with fruit in the remainder of the block at this harvest. Fruit from the PRD treatment had significantly lower total soluble solids at harvest compared with the fully irrigated controls (9.1 compared to 10.1 ^{o}Brix) but no difference in titratable acididty. We will repeat these test for the 1999 harvest in November.

Abscisic acid was measured in the surface feeder roots at a number of times during 1999. Mean concentration of ABA in these roots was double that in equivalent roots of control trees (Appendix 1, Table 2). ABA levels fell in the 3 to 4 days following an irrigation event but then rose again before the next irrigation. Levels in all trees fell following 7.4mm rain in February. We could not detect any difference in leaf ABA between treatments (P=0.65).

2.2.3 Conclusions

The PRD treatment reduced water application rates by between 42 and 50% compared with normal grower practice for the property and by between 32 and 43% compared with the district average. There was no significant effect on fruit size at harvest in 1998, although samples from the PRD trees taken approximately 4 months prior to the 1999 harvest were 5% smaller in diameter than fruit in the rest of block. In 1998 the PRD fruit had a lower sugar to acid ratio than controls. There were no significant effects of the treatment on leaf stomatal conductance or shoot water potential. The treatment significantly increased root, but not leaf, abscisic acid, suggesting that the physiology of the trees had been altered by the treatment. The results show that large water savings are possible, but there may be minor changes in fruit quality parameters. The design of the experiment did not allow us to attribute these changes to water management alone.

2.3 Objective: *on the NSW Agriculture research station at Yanco, change the irrigation of navel orange trees from flood to drip and impose PRD treatments on both flood and drip irrigated trees. Assess tree performance and irrigation input under these treatments*

2.3.1 Introduction, procedures, results and discussion

Four irrigation strategies were evaluated from 1997 to 1999. Some of the experimental trees (mature navel orange trees) were converted from permanent furrow flood to drip irrigation. Control flood irrigated trees (watered both sides) received 13.5ML/ha/y in the 1998/99 irrigation season. This was slightly more than the district average. During the same season, drip irrigated trees received only 4.8ML/ha/y. Flood and drip irrigated trees subjected to partial rootzone drying (PRD) treatments, where only one side of the trees were watered for periods of 4 weeks before switching to the alternate side, received even less water (Table 3). PRD trees received approximately half the respective amounts applied in both flood and drip treatments. We have not been able to detect any consistent, statistically significant, difference between drip and PRD drip irrigated trees in terms of water potential (Appendix 1, Figure 4) or stomatal conductance (Appendix 1, Figure 5), although fruit on the PRD trees tended to be slightly smaller (Appendix 1, Figures 6 Aand B).

There was no yield penalty following conversion to drip irrigation when completed before the start of the irrigation season and where drip lines were placed 15-20cm inside the outer canopy line on both sides of the tree.

Table 3. Water applied for 98-99 season

Irrigation method	Water applied ML/ha/year	%
Full flood	13.5	100
Drip	4.8	35
PRD flood	8.0	59
PRD drip	2.8	21

Maximum fruit growth rate and size was recorded in drip irrigated trees. Under conditions of extreme evaporative demand during the mid-summer period, drip trees were slightly less stressed than those in other treatments. Plant response in PRD Drip (65% water saving relative to industry standard) was similar to flood irrigated trees. Smaller fruit size resulted from PRD flood irrigation, suggesting that these trees were water stressed. Water potential and stomatal conductance measurements confirmed this.

Fruit size was increased by 5% in drip irrigated trees, compared to flood irrigation. Where fruit size was reduced (PRD Flood irrigation and standard flood irrigation) relative to the drip irrigation treatments, both Brix and %acid of juice increased, but Brix/acid ratio decreased. Highest Brix/acid ratio and %juice was recorded for drip irrigated trees. (Appendix 1, Table 3).

With the exception of PRD flood irrigation which induced more intense flowering and heavier fruit set classically seen in water stressed trees, irrigation treatments had no significant effect on yield in either the first or subsequent years of the trial (excluding the effect of alternate cropping cycle) (Appendix 1, Figure 7).

At this trial site, the majority of the rootzone was limited to the top 30cm of the soil profile due to structural changes at the B horizon forming a physical barrier to root penetration.

Maximum water extraction was observed to occur in the top 20cm. In this situation, plant available water was limited to <5% (between 30-35%VWC in the 0-20cm layer).
This indicated a need for frequent low volume applications of irrigation water to maintain optimum soil moisture conditions for maximum plant growth using drip irrigation.

Extremely low infiltration capacity was recorded in permanent furrows (4mm/hr), due to repeated compaction occurring over many years. Ponding in furrows remained for up to 2 days, resulting in temporary waterlogging. Water stress (leaf curling) was evident 7-10 days after watering using flood irrigation. These two factors contributed to the slower fruit growth recorded in flood irrigated trees.

High infiltration rates were recorded under tree canopies (12-14mm/hr). Use of 2L/hr drippers at 0.5m spacing and run for 5-6 hours wet to the bottom of the rootzone (30-40cm) and lateral spread was limited to 20cm each side of the drip line. This strategy optimised soil moisture availability whilst achieving significant savings in water.

Drip irrigated trees performed better than trees watered by the other irrigation treatments. Water savings of up to 80% relative to conventional flood irrigation were achieved in drip irrigated trees where PRD was implemented. Measures of plant water status, fruit growth rate and fruit size at harvest were only slightly less when irrigating by this method relative to full drip irrigation. The physiological basis of this responses remains to be determined. Sap flow measurements in roots confirmed that upward movement of water through the roots subsides as the soil dries out with increasing PRD interval. However, water status measurements in leaves did not reflect this. Evidence was found for rehydration or redistribution of water within trees by reverse flow to the roots at night. This needs further investigation to better understand how PRD works.

2.3.2 Conclusions

It is clear that highly significant increases in water use efficiency have been achieved. What is not so clear is the mechanism whereby this has been achieved. In citrus, we have been unable to demonstrate significant physiological responses typical of plants experiencing PRD. However, huge water savings appear possible. Reduced water application is partly due to the more efficient water delivery of drip compared with flood, but the addition of PRD appears to add another dimension to the water management of citrus trees.

Continuing physiological studies are providing some clues as to the mechanisms operating when trees are subject to the PRD treatment and this knowledge will be invaluable in making modification to our irrigation strategies in citrus in the future, but it is clear we do not yet have all the answers.

2.4 Objective: *on a grower property in the Goulburn valley, apply PRD to flood irrigated Packham pears and assess tree performance*

2.4.1 Introduction and procedures

The objective was to trial Partial Rootzone Drying (PRD) in an established pear orchard under typical flood irrigation conditions in the Goulburn Valley. In this situation water use efficiency is traditionally low and very difficult to improve above a basic level. The trial would also establish whether the physiological responses to PRD in pears were similar to those reported in wine grapes. The outcomes expected were a practical answer on the feasibility of improving water use efficiency in flood irrigated orchards, to determine at which stages of fruit growth PRD could be safely applied and to provide a basis for extending PRD to tree line irrigation systems such as microjet.

The trial site was a typical Goulburn Valley Packham pear orchard with large, old trees planted at 5.5x5.5m. The tree lines were hilled up to form a check bank about 1.5m wide. This bank normally contains a high root density and is wetted by capillary infiltration during irrigation. Irrigation water floods across the approximately 4m wide traffic lane. In most seasons such an orchard would be irrigated 7-8 times. In the trial orchard water supply was pumped and piped with an outlet in each row.

In year 1, the experiment was set out on the first 10 trees of 18 rows of the orchard by connecting a 50m long bypass hose to the irrigation outlet whenever the row was required to be dry. This enabled the treatments to be easily implemented without exposing more than the minimum number of trees to PRD. In year 2, the orchardist agreed to PRD being applied over the whole orchard. The treatments in both years were control, PRD flip/flop (dry and irrigated sides of the trees changed over with each PRD irrigation) and PRD permanent (the dry and wet sides were maintained for all PRD irrigations). Flood irrigation experiments require a large area of orchard for replication and as there was some uncertainty about the effects of the treatments on productivity, only two replicates with two measured trees in each were used to initially show the feasibility and safe operation of PRD. In year 2 four trees were measured in each row.

Gypsum blocks in year 1 and Gopher tubes in year 2 were installed in spring to measure soil moisture across the tree line in five positions between the centres of adjacent rows. Soil moisture was measured two times per week. Fruit growth was measured weekly and stomatal aperture (Delta T AP4 Porometer) and leaf water potential (Scholander Bomb) on three and nine occasions during the irrigation period in the two years. At harvest total yield and fruit number per tree, average fruit size, sugar content, seed count and firmness were measured. In both years seasonal conditions were quite wet in spring so that the first irrigation was not required until 28 November and 9 December, reducing the total number of irrigations to seven and four respectively. The strategy was to continue using PRD unless fruit growth indicated a loss of size. If that occurred, then PRD treatments would be changed to control irrigation until harvest. The critical time for fruit size to be affected by water stress was late December when Packham fruit goes into rapid growth. The main vegetative growth period is in November and therefore occurred under non PRD conditions in both years due to rainfall. Since we did not detect any effect of PRD on fruit size the irrigation treatments continued throughout both seasons.

2.4.2 Results and discussion

The results were similar in both years. More detailed measurements were taken in year 2 and these are presented below, though the discussion applies to data from both years. PRD treatments are referred to as Flip/Flop or Permanent. All measurements were taken on each side of the tree to identify any effect of dry and wet sides due to PRD treatments. No consistent or significant differences were found between wet and dry sides of the tree. The data are combined for the whole tree in the results given below.

Yield, fruit size and fruit quality

PRD treatments did not affect yield or fruit size in either year and were continued throughout the irrigation seasons. In year 2 the yield over the experimental orchard was 82 tonnes per hectare, an unusual high yield particularly given the large fruit size. This result indicates that tree performance was severely tested and close to optimum by commercial standards. Details are shown in Table 4. The yield per tree was essentially identical in all treatments but fruit number was about 10% higher with PRD. The average fruit size in PRD treatments appears slightly lower compared to the control but, when these figures are corrected for the greater fruit number per tree, fruit weight in the Flip/Flop and Permanent treatments are estimated at 192 and 201 g/fruit respectively. Weekly fruit growth measurements had shown the lower growth rate for PRD fruit (data not shown) but the difference was not considered big enough to justify ending PRD treatments. Yield efficiency, or yield per unit size of tree, (calculated as production based on the cross sectional area of the trunk) was also nearly identical for all treatments. At this time it is not possible to determine if the higher fruit number on PRD trees is an effect of the treatments applied in the first year. At harvest, fruit firmness, sugar content and number of seed per fruit were not significantly affected by PRD (data not shown). In another experiment, in a block of WBC pears, one side of one row was allowed to remain unirrigated for the whole season and, similarly to the Packham results, fruit growth was not affected.

Table 4. Packham pear yield data from year 2. The differences between means were not significant (P>0.05)

Treatment	Yield (kg/tree)	Average fruit weight (g)	Fruit number per tree	Yield efficiency (kg/cm^2 Butt Area
Control	244	200	1232	0.36
Flip/Flop	237	184	1321	0.38
Permanent	256	191	1343	0.35

Soil moisture

Only four irrigations were applied in the 1998/99 season, partly because a late November rain replaced one irrigation and the grower wanted to save water in a year of low water allocation. He had also become aware of the potential moisture reserve in his orchard as a result of the year 1 data. It was not possible to measure infiltration of irrigation in the different treatments, partly because of the orchard layout below the PRD experiment. However, outlet flow was similar in all rows and the irrigator reported that the water reached the far end of each row at similar times. This indicated that infiltration in the Flip/Flop row and in the irrigated row of the permanent treatment was not sufficiently higher to noticeably delay the progress of the irrigation front.

Soil moisture was measured each week at 10 cm intervals to 110 cm. For all Gopher access points the data were integrated into the total moisture content in the root zone, 0-60 cm, and below the root zone, 60-110 cm. The results (Appendix 1, Figures 8-10, Control, Flip/Flop, and Permanent) showed the expected difference between irrigated and dry rows. For clarity of presentation the measurements from the centre of the traffic row are not shown but they closely followed values for the Offset Centre position on the edge of the tree line bank. Absolute calibration of Gopher data was difficult but the relative readings over the moisture range from Field Capacity to severe water stress were considered to be accurate. The difference in water content of the 60 cm root zone between the end of free drainage about 3 days after irrigation and the dry rows in the Permanent PRD was about 65-70 mm. Heavy rain over several days about the 11th of November wetted the profile and tree line more completely than subsequent irrigations. Tree water use dried out the tree line to a greater extent than at the edge of the bank or in the traffic row. In the Permanent dry row the grass sod gradually dried off, indicating permanent wilting point in the surface soil.

Root distribution and soil moisture data strongly suggest that the trees could not have accessed water from below the 60 cm layer in large enough quantity to contribute significantly to day-time water use. A test well to 140 cm showed that there was no high water table under the experiment. Root distribution as seen in two soil pits at the site, and many others in the same soil type, shows that few roots exist below 60 cm. This was also supported by the low level of water extraction at 70 cm and below, even though the soil moisture content was estimated to be higher than field capacity but not saturated. Also, soil moisture tension measured in year 1 with gypsum blocks, showed that the 60 cm layer became drier than field capacity for most of the season. The moisture reserve below 70 cm is large but, given that the soil is not saturated, the rate of movement to an active root surface would be slow and does not have the potential to maintain high transpiration rate during the day. Night-time water use occurs at a much lower rate and essentially acts to rehydrate the tree and maintain fruit growth. However, as all treatments had access to readily available water in some part of their upper root zone, it seems doubtful that water from below 60 cm contributed to the demand for night-time fruit growth.. One other possibility is that the lateral extension of the roots is far greater than expected and that trees integrate soil conditions over several rows. This seems highly unlikely.

Tree water use

Mid day leaf conductance and leaf water potential were measured on 9 occasions (Appendix 1, Figures 11, 12) over the fruit growing period. On all dates leaf conductance was high and particularly during the period of very rapid fruit growth in January and February, conductance further increased to 800 mmol/m2/sec (Appendix 1, Figure 12). There were no significant differences between treatments but the Permanent PRD treatment tended to higher values on two of five dates during rapid fruit growth in the 5 weeks before harvest . Mid-day leaf water potentials were in the range of -2.0 to

-2.4 MPa, which in pear indicates a moderate stress level that is not unexpected during rapid fruit growth when the trees are carrying a heavy crop (Appendix 1, Figure 5). Leaf water potentials generally indicated higher stress when conductance was also at its highest, in January and February. During that time, the PRD treatments on average showed significantly greater stress (0.2 to 0.3 Mpa) than the control. Though significant, the treatment difference was small. In comparison, under Regulated Deficit Irrigation (RDI) on similar trees, water potential differences of up to 1 Mpa were observed with maxima of -3 MPa. In the present experiment, water potential and conductance results were more typical of well irrigated rather than water stressed trees. The high rate of fruit growth in all treatments also supports this interpretation. Shoot growth was also similar on all treatments but, as it largely occurred during the rain-fed period in spring and early summer, the results can not be related to PRD treatments.

Total orchard water use was also estimated from soil moisture measurements over 8 periods during which there was no rain and no irrigation was applied. Gopher data for the 0-60 cm zone was used to estimate relative water consumption between treatments. Relative to the control, water use in Flip/Flop was reduced by 0.33 mm/day and in Permanent by 0.9 mm/day. Over the 120 day irrigation season, water consumption was reduced by 40 mm and 96 mm respectively. From the present experiment it is not possible to tell whether the difference was the result of tree water consumption or the effect of PRD on the water loss from the grass sward in the traffic rows.

2.4.3 Conclusions

The results clearly show that applying half the irrigation water, either as an alternating or a permanent PRD treatment, did not affect fruit growth and had only minor effects on tree water status. When compared to RDI treatments, PRD would be expected to give similar results during the period of slow fruit growth in November and early December (though in the last two years PRD was not effective during that time because of rain). Earlier results have shown that when RDI is continued past December, fruit size is reduced and sugar content is increased. In contrast, PRD treatments maintained fruit growth and sugar content was not affected. The physiological response of pear to PRD is apparently quite different to the response of wine grapes. In the latter, PRD causes ABA levels to increase while conductance was reduced and water potential was maintained. No effect on the level of ABA was detected in pear.

After two years of field trials it is not possible to reconcile the results from measurements of soil moisture and tree water status with documented irrigation applications. It is not clear how the trees, in both PRD treatments, obtained the water supply required to maintain the observed leaf water status. There is no doubt that irrigation input was reduced by about 50% and this had the visible result that the grass in the dry row of the Permanent treatment dried off.

Several different mechanisms could have contributed a small component, that in itself is difficult to detect, towards maintaining the water balance in PRD rows. As discussed above it is very unlikely that water moved into the root zone from below at a high enough rate to compensate for the reduced irrigation input, but some contribution could be expected and would be very difficult to measure. The orchard floor component of water use may be larger than expected and therefore the true crop factor of the pear trees would have to be correspondingly smaller. Therefore, tree water status may have been maintained while using less water than is presently accepted. The reduction of 0.9 mm per day in water use by the Permanent PRD is likely to be largely due to reduced water loss from the row with dry grass. It is also possible, but considered highly unlikely, that the root system of pear trees is far more extensive that expected and the trees negate treatment effects by drawing water across several rows.

It appears that the results indicate the need for a basic re-evaluation of the water relations of pear orchards. Whether, in the end, the mechanisms governing water use will include the hormonal and physiological changes identified in the PRD response of wine grapes, remains to be seen. At least under Goulburn Valley conditions, the results of the present trials justify the careful extension of "Pear PRD" to commercial orchards, provided that fruit development is monitored and benchmarked against expected growth rates. The grower would revert to normal irrigation if fruit growth was reduced. This would lead to a potential water saving of 30-40%.

2.5 Objective: *install sap flow sensors in the roots of Valencia orange trees to assess the importance of bidirectional sap flow in maintaining the PRD effect and the viability of roots in drying soil*

2.5.1 Introduction and procedures

One of the concerns with irrigation treatments such as PRD which seek to manipulate the tree by withholding water for significant periods of time is that roots in the dry soil may die or loose function so that when water is finally restored to those roots they may be less effective, thus predisposing the tree to water stress. Measurements of shoot water potential have never suggested that this may be the case and we have made the assumption that roots in drying soil may have the capacity to draw water from the more hydrated soil on the other side of the tree, thus maintaining their viability. To test this assumption we have installed sap flow sensors (Greenspan, Warwick, Queensland) in the roots of Valencia orange trees in such a way that they are able to measure sap flowing from the soil to the tree and also flow from the tree towards the drying soil. Roots of two trees which were receiving PRD irrigation were excavated and roots 20 to 30mm in diameter were chosen for implantation. Eight sensors were installed, four measuring flow from soil to tree and four from tree to soil. The results shown are mean values for pairs of sensors. Similar data resulted from all sensors. The sensors were wrapped in insulation and in plastic sheeting before being buried. Data were logged at 60 minute intervals over several irrigation cycles.

We believe that information about water movement within trees is important to our understanding of the PRD principle and will be necessary in formulating recommendations.

2.5.2 Results and discussion

Sensors measuring sap flow from soil to tree detected large variations in flow which were dependent on the progression of the irrigation cycle (Appendix 1, Figure 13A). Maximum sap flow occurred at about 14.00 h each day and the magnitude of this maximum declined towards the end of the cycle. There was a peak of sap flow during the irrigation event which occurred between 19.00h and midnight, followed by a large peak the following day. Sap flow during the night did not return to zero during the days immediately following an irrigation. For three days after an irrigation no sap flow could be detected in roots on the irrigated side of the tree in the tree to soil direction. However, for the last three or four days before the next irrigation some flow could be detected. The pattern on the dry side of the tree was quite different. Sensors measuring soil to tree flow detected a normal diurnal flow, with a maximum at about 14.00h and zero flow at night. The magnitude of this flow did not vary greatly as the irrigation cycle progressed. A distinctive feature of flow on this side of the tree was a consistent flow during the night in the tree to soil direction (Appendix 1, Figure 13B). Soil moisture was also being monitored for these trees. There was a general trend for soil moisture on the unirrigated side of the tree to fall (Appendix 1, Figure 14), but superimposed on this trend there was a rise in soil moisture between about 22.00h and 04.00h which coincided with the apparent export of water from the roots.

There are a number of implications from these data. There was considerable sap flow, even at the end of an irrigation cycle, in the conventional soil to tree direction, suggesting that soil water reserves had not been depleted. This was confirmed by the relatively high water potentials noted for these trees. However, the high nocturnal sap flow in the days immediately following an irrigation suggests that some recharge of the aerial parts of the tree were occurring. There was no corresponding increase in tree to soil flow on the dry side of the tree during this post-irrigation phase, suggesting that part of the nocturnal flow out of the soil on the wet side was going to above-ground structures and part to the roots on the dry side. The magnitude of the tree to soil flow on the dry side was between about 30% and 100% of the soil to tree flow, suggesting that a high proportion of the sap which was being transpired through these roots had its origin in water supplied to the other side of the tree. This has important implications for the survival of roots in dry soil and for the redistribution of chemical signals such as abscisic acid from the dry roots into the rest of the tree. It might also explain how it is that pear trees which did not receive water to one side for the whole season ("permanent" treatment, section 2.4.2) behaved in much the same way as those which had their wetted side switched at each irrigation ("flip-flop" treatment).

2.5.3 Conclusions

Sap flow sensors installed in the roots of Valencia orange trees provided information about the movement of water throughout the tree during several irrigation cycles. Water moved within the tree, from the soil to the tree and from the tree to the soil according to the water potential gradients established by irrigation and transpiration. There was substantial sap flow at night from irrigated soil to the tree. This water could have been used to rehydrate the aerial parts of the tree but a proportion also moves along roots which are in dry soil in the direction away from the tree. On some days the magnitude of the tree to soil sap flow during the night was as great as the soil to tree flow during the day, suggesting a relatively small proportion of the water transpired through the roots on the dry side of the tree actually came from the soil. The redistribution of water may serve to transport chemical signals, such as plant hormones, out of roots in dry soil. It will also serve to maintain the roots in drying soil in a viable condition. This may be one of the major differences between PRD and other irrigation strategies such as RDI which may expose the whole root system to simultaneous drying.

3. References

Dry P, Loveys BR, Botting D and During H, 1996. Effects of partial root-zone drying on grapevine vigour, yield, composition of fruit and use of water. Proceedings of the 9th Australian Wine Industry Technical Conference pp. 126-31

Loveys, B., Stoll, M, Dry, P. and McCarthy, M. 1998. Partial rootzone drying stimulates stress responses in grapevine to improve water use efficiency while maintaining crop yield and quality. Australian Grapegrower and Winemaker, Technical issue. 414, 108-114

Loveys, B.R., Dry, P.R., Stoll. M. and McCarthy, M.G. 1999. Using plant physiology to improve the water use efficiency of horticultural crops.
Acta Horticulrturae, In Press

Skewes, M. and Meissner, A. 1997. Irrigation benchmarks and best management practices for citrus. Primary Industries and Resources SA, Technical Report No. 258

4. Acknowledgments

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

Table 1. Abscisic acid levels in roots of fruit trees. Figures are mean of 3 replicates. Technical problems prevented analysis of apricot root samples. * significantly different from the wet/wet control

Treatment	Abscisic acid % of wet/wet			
	Before treatment	+ 7 days	+ 42 days	+ 59 days
Cherry				
wet of we/dry	71	124	633	239
dry of wet/dry	95	349*	178	156
Significance	ns	P=0.009	ns	ns
Apple				
wet of wet/dry	112	115	463*	89
dry of wet/dry	101	326*	131	125
Significance	ns	P<0.001	P=0.007	ns

Table 2. Abscisic acid in the roots of Valencia orange trees

	Abscisic acid ng/g fresh weight		
	Control	East side of tree	West side of tree
Mean	26.2	52.3	55.8
SEM (n=4)	2.6	8.2	7.0
Significance (same letter = ns) P=0.006	a	b	b

Table 3. Fruit quality parameters, navel oranges Yanco 1999 harvest.

	Sugars (oBrix)	Citric acid %	Ratio sugar/acid	% juice
PRD drip	13.27	1.49	8.98	44.60
Control drip	13.06	1.43	9.17	44.98
Control flood	13.38	1.49	9.02	44.15
PRD flood	13.54	1.58	8.59	43.58

Figure 1. Stomatal conductance of split-root cherry, apple and apricot trees subject to PRD as a percentage of well watered contols. Each line is the mean of three replicates. Water initially withheld on day 1, swap sides on day 38, rewater on day 56

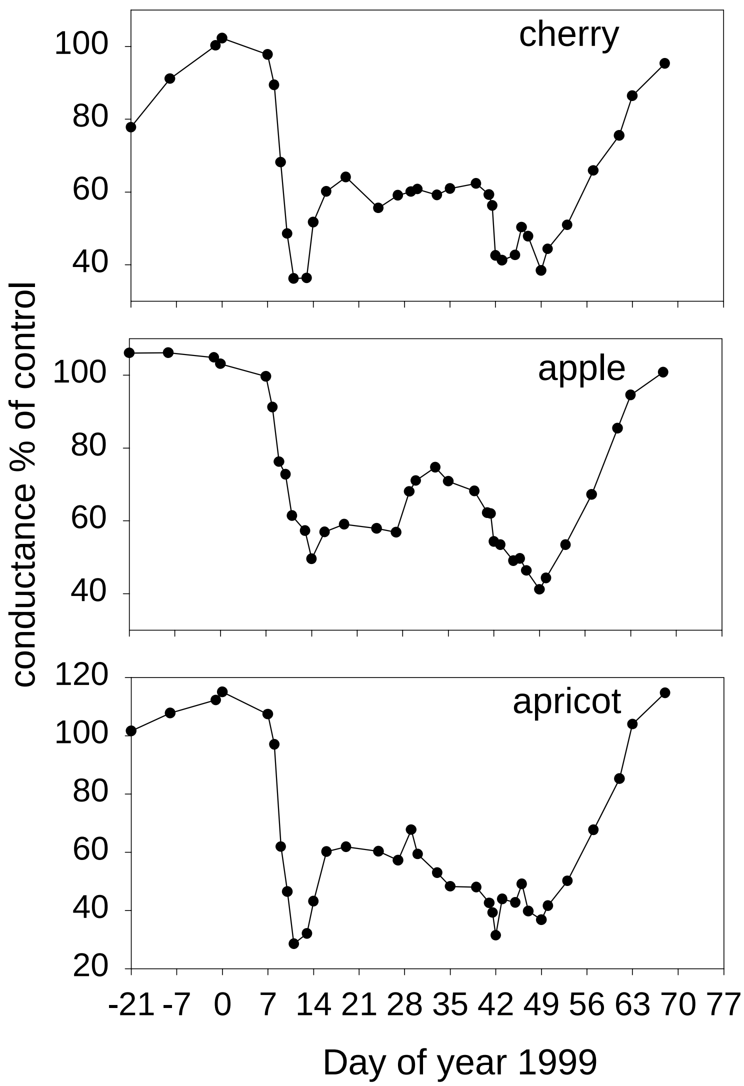


Figure 2. Size class distribution of Valencia fruit. 1998 harvest.

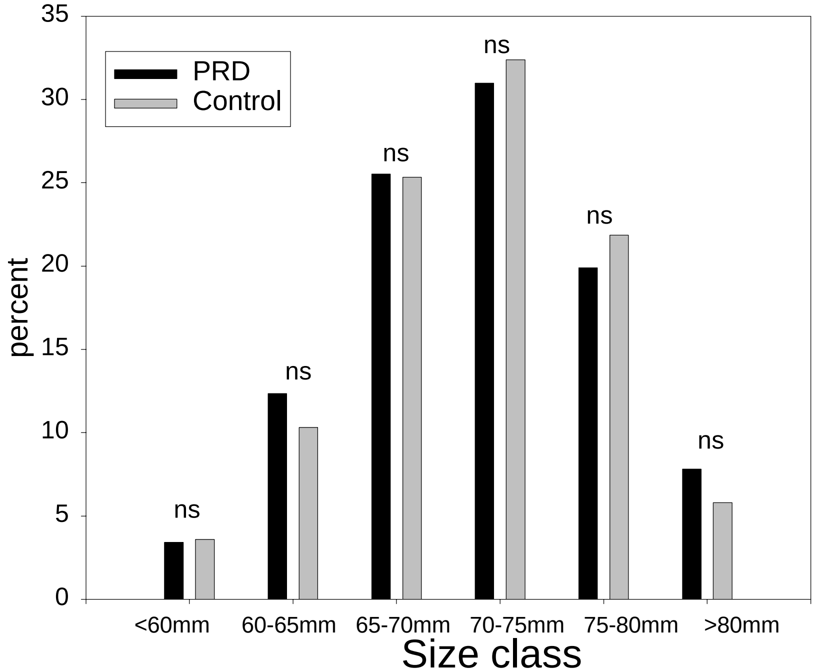


Figure 3. Irrigation events, rain and abscisic acid levels in the roots of Valencia orange trees.

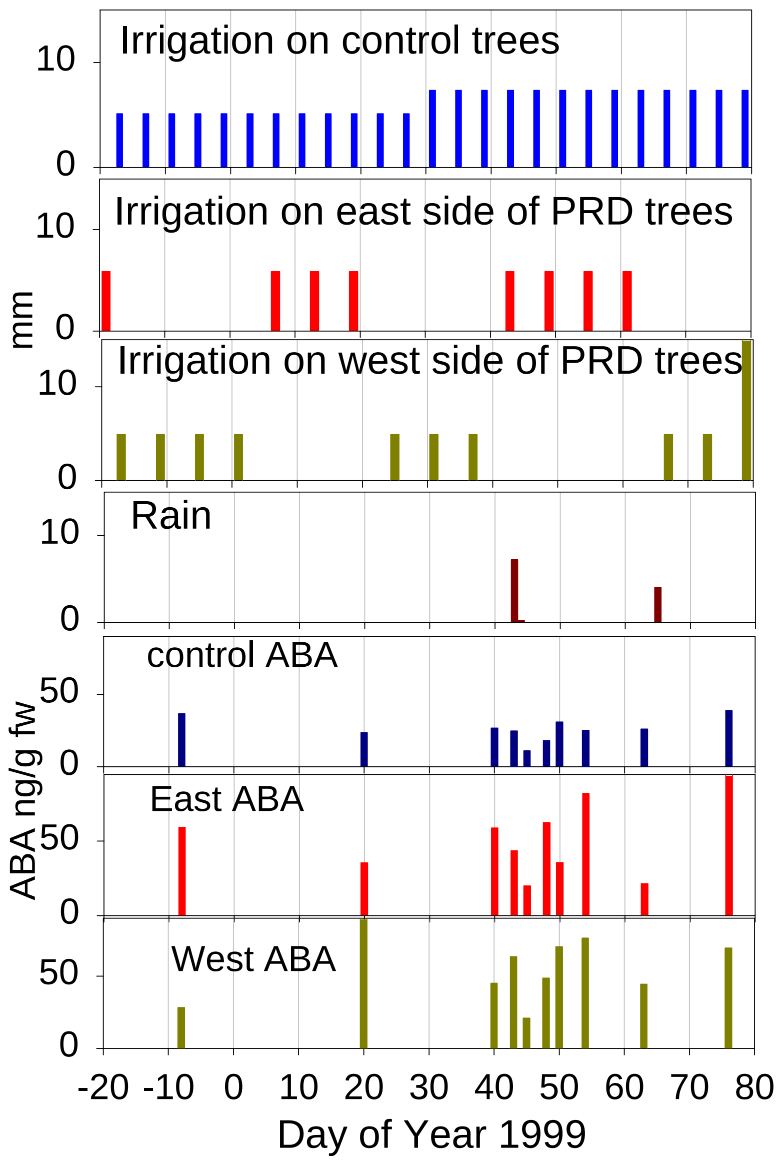
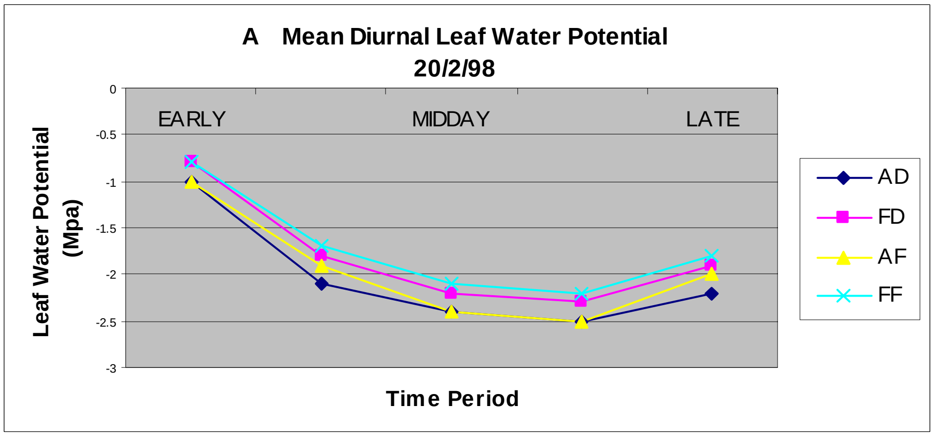


Figure 4. Diurnal changes in leaf water potential, Navel oranges at Yanco. AD, alternate drip; FD, full drip; AF, alternate flood; FF, full flood. A sampled 20/2/98, B sampled 7/12/98.



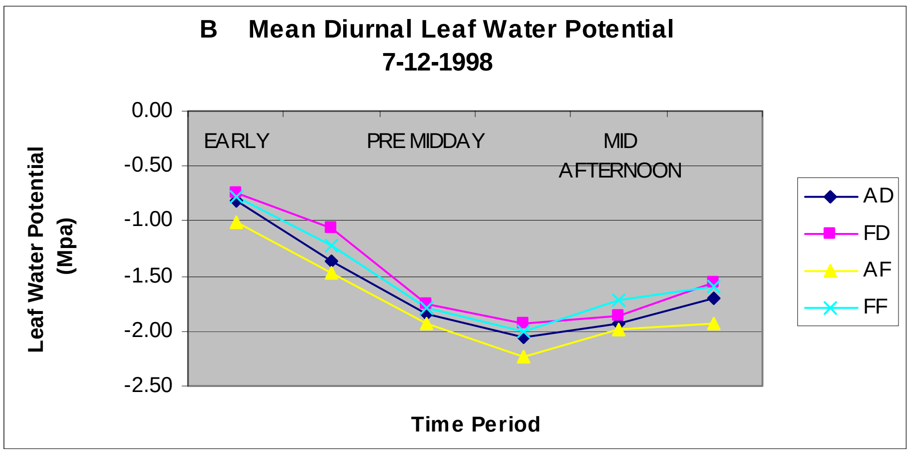
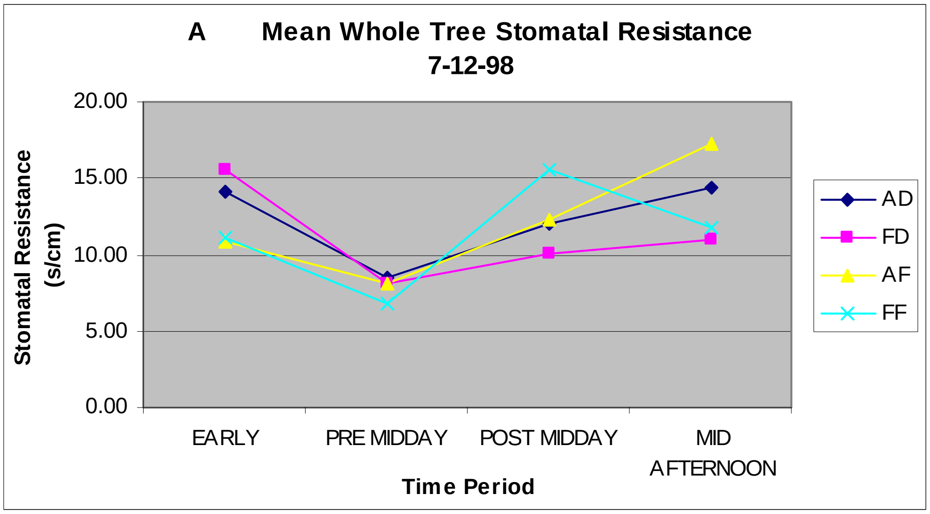


Figure 5. Diurnal changes in leaf stomatal resistance, navel oranges, Yanco. AD, alternate drip; FD, full drip; AF, alternate flood; FF, full flood. A sampled 7/12/98, B sampled 20/2/99.



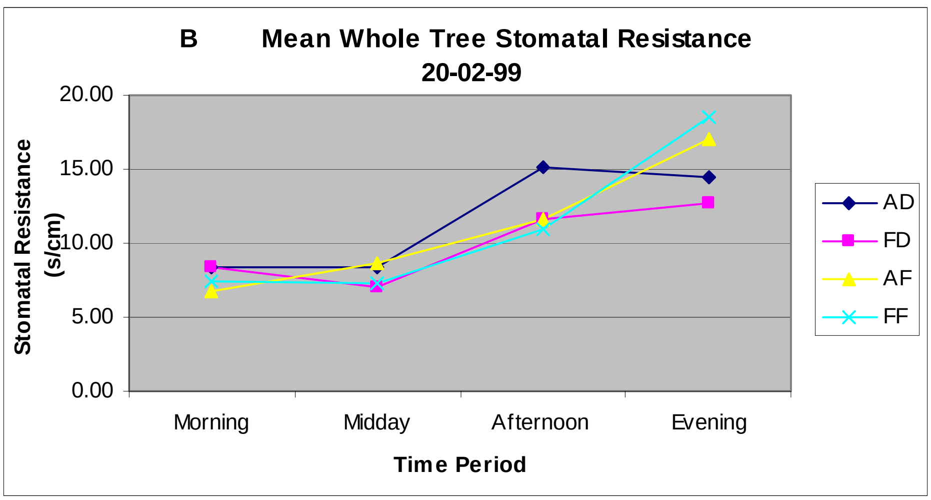
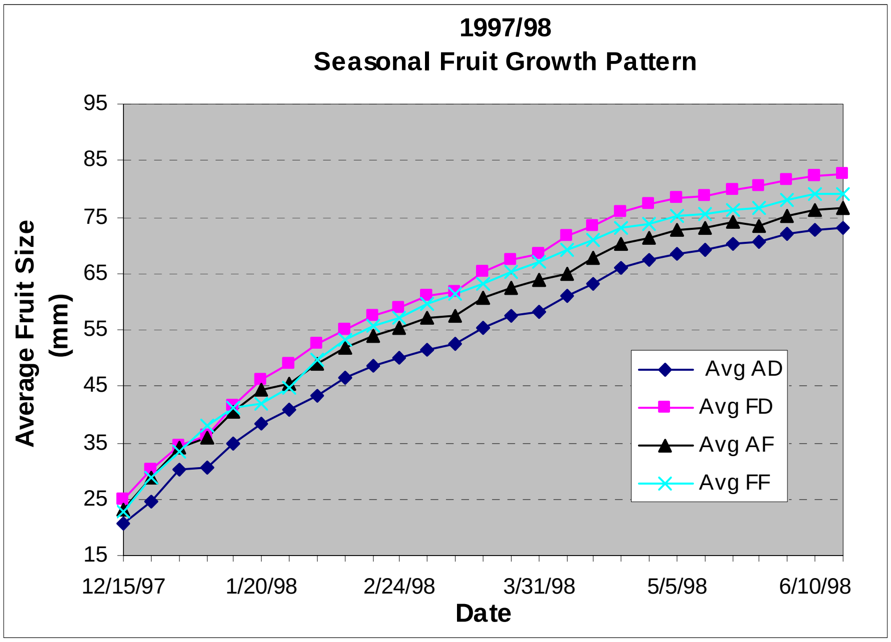


Figure 6. Fruit growth of navel oranges, Yanco. AD, alternate drip; FD, full drip; AF, alternate flood; FF, full flood



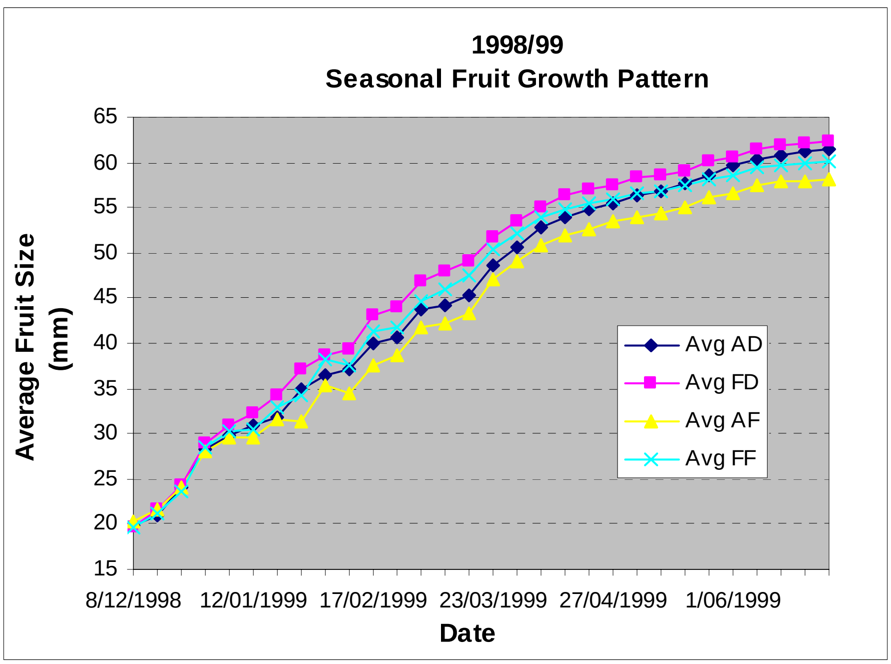


Figure 7. Fruit yield of navel oranges, Yanco. AFROW, alternate flood; FFROW, full flood, FDROW, full drip; ADROW, alternate drip

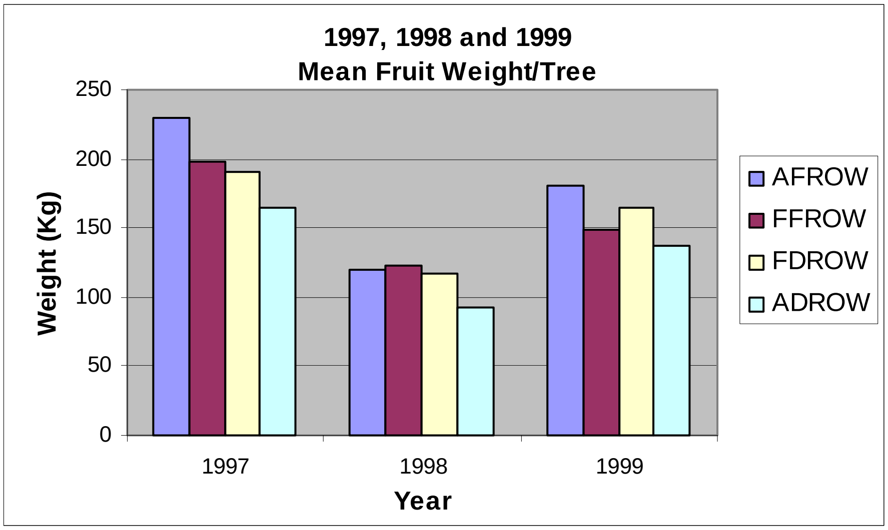


Figure 8. PRD pear trial 1998/99. Total soil water 0 to 60cm depth. Permanent dry treatment

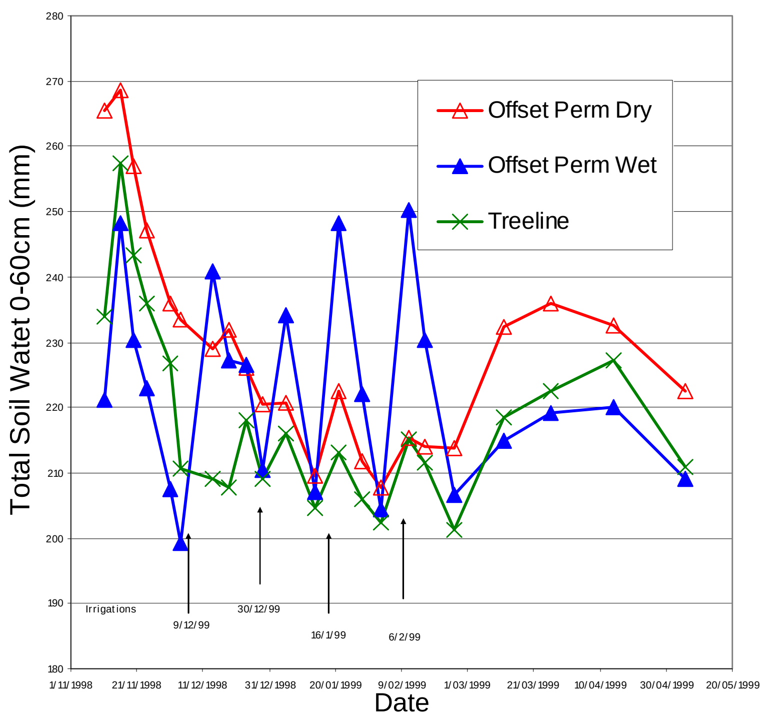


Figure 9. PRD Pear experiment 1998/99. Total soil water 0 to 60cm depth. Flip-Flop treatment.

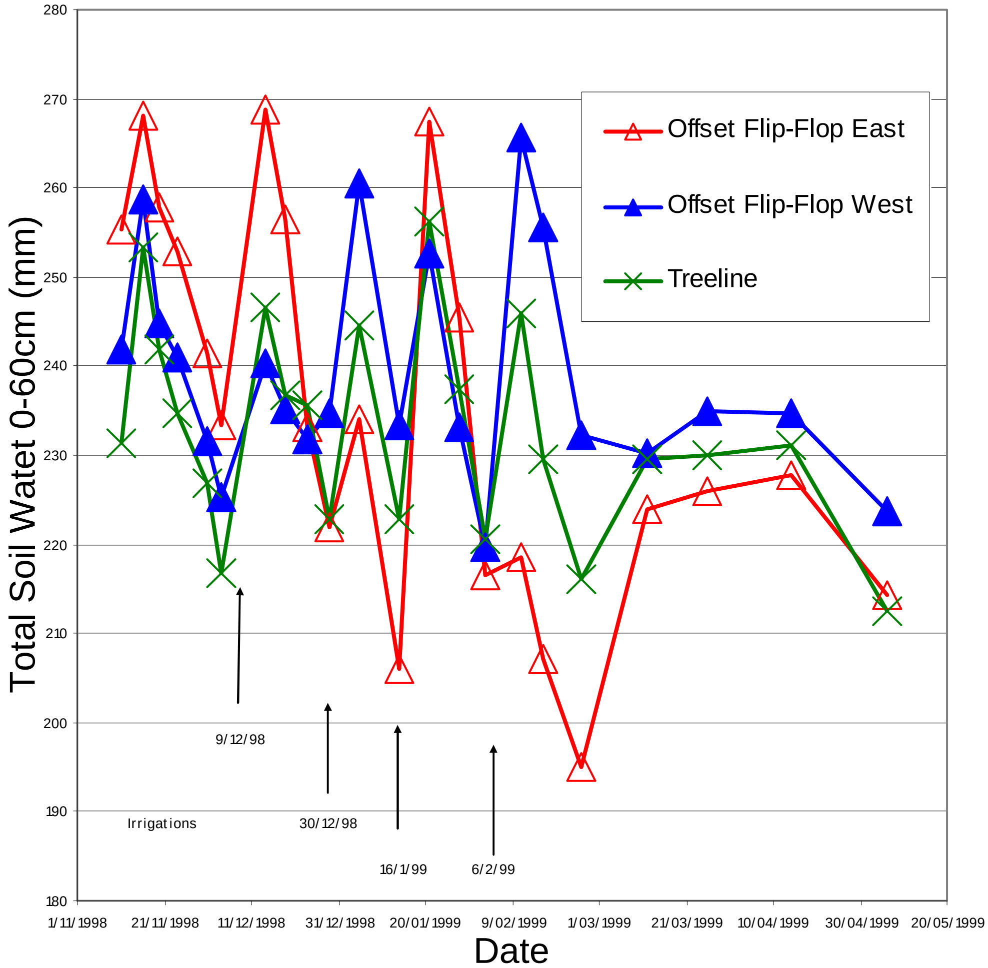


Figure 10. Pear PRD experiment 1998/99. Total soil water 0 to 60cm. Control

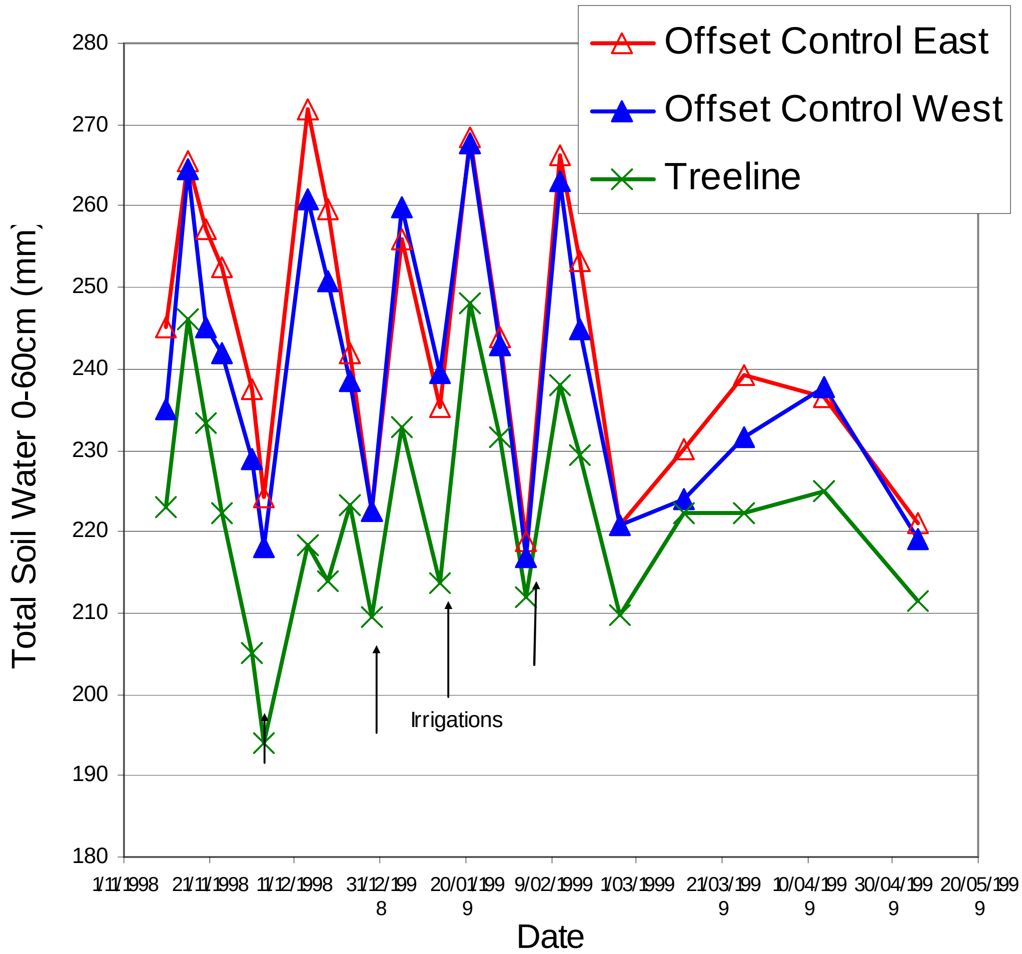


Figure 11. Pear PRD experiment 1998/99 leaf water potentials

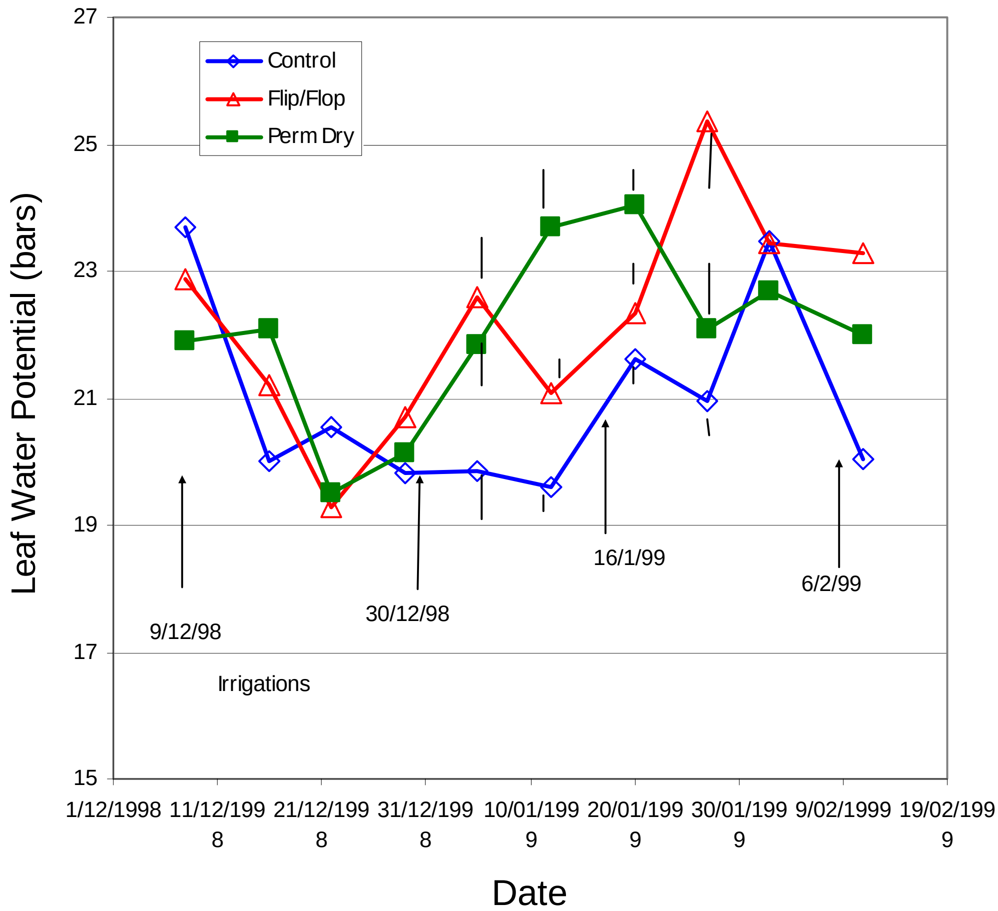


Figure 12. Pear PRD experiment 1998/99. Stomatal conductance

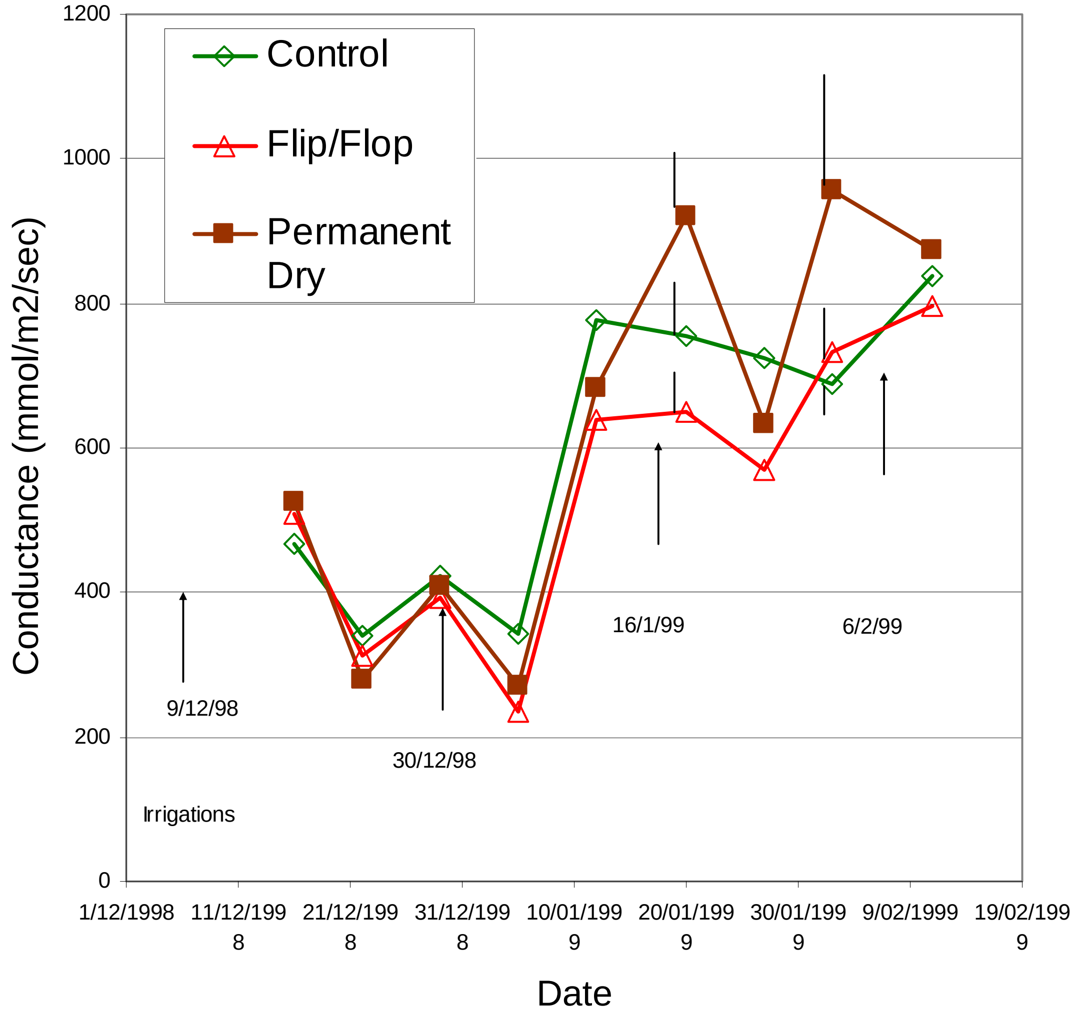


Figure 13. A, sap velocity on irrigated side of Valencia orange tree. B, sap velocity on dry side of Valencia orange tree

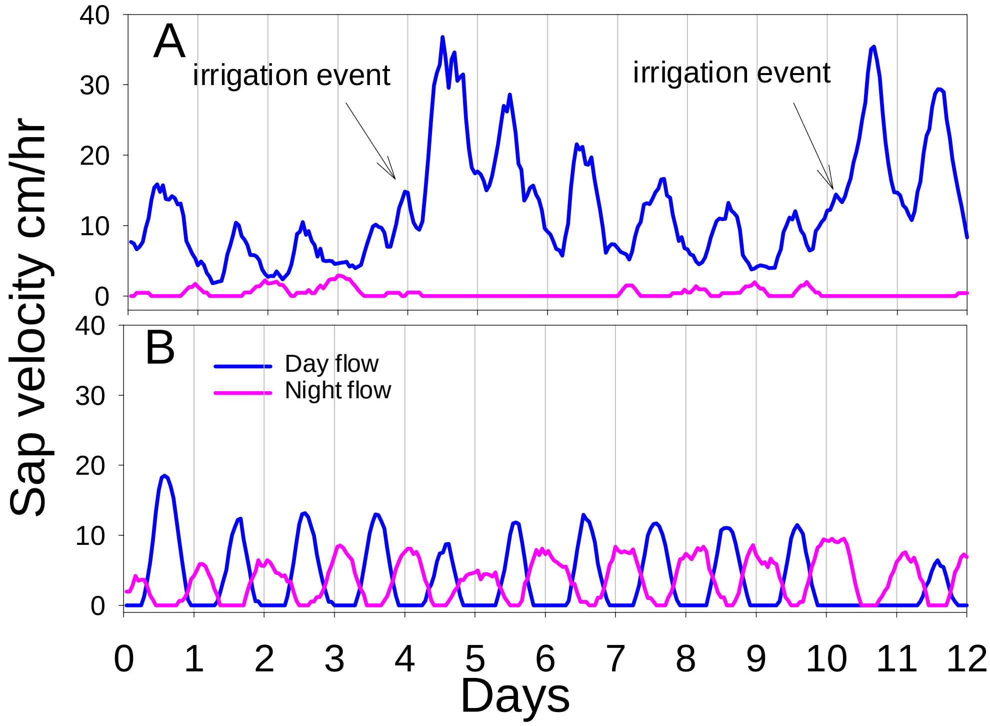


Figure 14. Sap flow and soil water on the dry side of a PRD-irrigated Valencia orange tree during three days