STRATEGIC IRRIGATION MANAGEMENT IN AUSTRALIAN VINEYARDS

GESTION DES STRATÉGIES D'IRRIGATION DANS LES VIGNOBLES AUSTRALIENS

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P.R. DRY[1], B.R. LOVEYS[2], M.G. MCCARTHY[3] and M. STOLL[1, 4]

1 Department of Horticulture, Viticulture and Oenology, Adelaide University, Waite Campus, Glen Osmond SA 5064, Australia
2 Horticulture Research Unit, CSIRO Plant Industry, PO Box 350 Glen Osmond, SA 5064, Australia
3 South Australian Research and Development Institute, PO Box 245, Nuriootpa, SA 5355, Australia
1,4 School of Life Sciences, Division of Environmental and Applied Biology, University of Dundee, Dundee DD1 4HN, Scotland UK

Abstract: Regulated Deficit Irrigation (RDI) and Partial Rootzone Drying (PRD) are examples of strategic irrigation management. They have been successfully adopted for winegrape production in Australia with the aim of controlling vegetative growth to produce 'balanced' vines, and to improve both water-use efficiency (measured as tonnes of fruit per ML of irrigation water applied) and fruit quality for winemaking. This paper will outline some of the physiological principles that underpin these strategies and provide details of experimental and commercial experience in Australian vineyards.

Résumé : La RDI ('Regulated Deficit Iirrigation' ; Irrigation déficitaire contrôlée) et le PRD ('Partial Rootzone Drying' ; assèchement partiel des racines) sont des exemples de gestion des stratégies d'irrigation. Celles-ci ont été adoptées avec succès pour la production de raisins de cuve en Australie, dans le but de contrôler la croissance végétative pour produire des vignes'équilibrées' et d'améliorer l'efficacité de la gestion de l'eau (mesurée en tonnes de fruit par ML d'eau d'irrigation) ainsi que la qualité du fruit pour l'élaboration du vin. Cet article met en évidence certains des principes physiologiques sous-jacents à ces stratégies, et fournit des indications détaillées sur des études menées à titre expérimental et commercial dans des vignobles australiens.

Key words : grapevine, regulated deficit irrigation, RDI, partial rootzone drying, PRD, water-use efficiency, root signals

Mots clés : vigne, RDI, PRD, efficacité de la gestion de l'eau, signaux racinaires

INTRODUCTION

Australia is a dry continent: rainfall is distributed unevenly, both geographically and seasonally. The production of grapes in Australia is very dependent upon irrigation: in the majority of viticultural regions the climate is characterised by high potential evaporation and low rainfall during the growing season. Table 1 shows a comparison of rainfall, relative humidity (RH) and sunshine hours (SSH) of locations in Australia and France with similar growing season temperature conditions. The purpose of the comparisons is not to suggest that these locations are homoclimes. It is designed to demonstrate that Australian viticultural regions typically have much lower growing season rainfall, higher SSH and lower RH than their French counterparts. Comparable evaporation data are not available but it is likely that all Australian locations would have significantly higher potential evapotranspiration and thus a greater requirement for irrigation.

Of all water used in Australia, irrigation uses approximately 75 p. cent. With respect to irrigation, 73 p. cent is sourced from rivers, 18 p. cent from groundwater aquifers, and the remainder from harvested surface water (MEYER, 1999). The Murray Darling Basin (MDB) drains just one-seventh of continent but provides 75 p. cent of irrigation water; however, this resource is over-committed with irrigation and rural purposes utilising 95 p. cent of total flow. Importantly for the wine industry, the MDB is the only source of irrigation for almost two-thirds of Australian winegrape

Pour correspondance : peter.dry@adelaide.edu.au

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Table I - Comparison of rainfall, relative humidity and sunshine hours of locations in Australia and France with similar growing season temperature conditions (Source of data: Gladstones 1992)

Comparaison des précipitations, de l'humidité relative et des heures d'ensoleillement pour des lieux situés en Australie et en France, présentant des conditions de température comparables pendant la période de croissance (Source des données : Gladstones 1992)

Location	MJT[1] (°C)	Rainfall (mm) October–April (SH)[2] April-October (NH)	Rainfall (mm) May-September (SH) November-March (NH)	Relative humidity, average, 3 pm, % October–April (SH) April-October (NH)	Sunshine hours October-April (SH) April-October (NH)
Berri (Australia)	23.0	139	130	30	2002
Orange (France)	22.9	518	294	50	1869
Barossa Valley (Australia)	21.0	204	302	41	1802
Valence (France)	21.5	625	279	54	1648
Padthaway (Australie)	20.2	208	301	43	1720
Bordeaux (France)	20.5	427	406	59	1472

[1] Mean January temperature (SH), mean July temperature (NH) ; [2] SH Southern hemisphere, NH Northern hemisphere

production. However, a relatively small proportion of Australian irrigation water is actually used for winegrape production ; for example, the state of South Australia produces 50 p. cent of Australian winegrape tonnage, but only uses 5 p. cent of Australian irrigation water from all sources.

As in other developed countries, there is increasing diversion of water for urban and industrial purposes, leading to a decreasing proportion available for irrigation. This dependence on irrigation for viticultural production and the realisation that water resources can no longer sustain continued development requires that new vineyard development has become increasingly dependent on development of new resources, and to a greater extent, on improvements in the efficiency of water use. Both options are possible in viticultural regions.

Potential new resources include: a) groundwater aquifers - however local scarcity and high salinity will limit their use; b) « second-hand » or « grey » water - for vineyards close to urban areas this represents a significant resource; and c) diversion from one region to another at times of surplus – for example, MDB water will be available for irrigation at an economical price in the Barossa Valley from 2001. « Grey water » can be used successfully for irrigation so long as the irrigation system is well-designed and managed and salt balance monitored.

Increasing the efficiency of existing resources is possible in all regions. Conveyancing and application losses can be reduced by improving infrastructure – for example, replacement of open channels with pressurised pipelines. At the individual farm level, there can be a change from the relatively inefficient methods of irrigation such as flood and furrow to less wasteful micro-irrigation systems eg. trickle. Such changes have been occurring in many regions over the past 20 years: for example, more than 95 p. cent of the vineyard area in the Riverland region of South Australia is now irrigated by means other than furrow or flood (P. COLE, pers. comm.). To this can be added the increasing use of underground trickle systems to reduce evaporative losses, improved vineyard design where the irrigation system is matched with soil types, intensive soil water monitoring to enable better irrigation scheduling, and irrigation management strategies that can increase tonnes of fruit per ML of irrigation water, for example, « regulated deficit irrigation » (RDI) and « partial root-zone drying » (PRD). There is considerable potential for such improvement: a survey of 36 « well-managed » vineyards in the MDB showed that water-use efficiency ranged from 1 to 10 t/ml (SKEWES and MEISSNER, 1997). At the same time, there has been increasing recognition that fruit specification for a particular end-use may be manipulated by strategic irrigation management in the low summer rainfall regions of Australia. The data in table II indicate that, at least for some regions in Australia, eg Barossa Valley, Adelaide Hills, the amount of irrigation actually applied is less than the amount required for maximum yield due to either a lack of irrigation water or deliberate imposition of deficit irrigation.

The key to improving wine grape quality in irrigated vineyards is to achieve an appropriate balance between vegetative and reproductive development since an excess of shoot vigour may have undesirable consequences for fruit composition. It is well known that water stress has a major influence on shoot growth and that in general vegetative growth is more sensitive to

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Table II - Evaporation, rainfall and irrigation amounts for selected viticultural regions in Australia.
Mesures de l'évaporation, des précipitations et de l'irrigation pour les régions viticoles australiennes choisies.

Region	Annual Class A pan evaporation (mm)	Annual rainfall (mm)	Full irrign[1] (mL/ha)	Deficit irrign[2] (mL/ha)	Typical irrigation amount applied (mL/ha)
Barossa (Nuriootpa)	2008	515	4.6	2.2	0.5 to 1.5
Padthaway	1555	530	3.1	1.3	1.8
Riverland (Loxton)	2179	274	6.0	3.0	5.0 to 10.0
Adelaide Hills (Lenswood)	1774	1043	3.1	1.0	< 1.0

[1] Estimated irrigation amount required to maximise yield ; [2] Estimated irrigation amount required to maximise yield quality;
Assumption: 100 mm available soil water in all cases
Source of data: Primary Industries and Resources SA (2000)

water stress than berry (fruit) growth. For some winegrape varieties control of berry size is of importance and in many localities the key to achieving the correct balance is irrigation management. The consequences of supplying water, through irrigation or from rainfall, at a level which is less than optimal, will result in the activation of various water deficit response mechanisms in the crop. The plant function most likely to be influenced by water deficit is stomatal conductance and partial stomatal closure can lead to a decrease in transpiration and possibly an increase in transpiration efficiency, that is the dry matter produced per unit of water transpired (DAVIES *et al.*, 1978). The deliberate withholding of irrigation water may therefore be a legitimate management strategy to manipulate crop water use and this is embodied in the techniques known as RDI and PRD. RDI may also result in changes to specific characteristics such as the size of grape berries (McCARTHY, 1997). This is important because the flavour compounds which determine wine quality are located principally in the berry skin and an increase in skin to flesh ratio may improve fruit quality and value. We have investigated the possibility of stimulating some of these water deficit responses in a more controlled and sustained way with a view to improving water use efficiency. This has resulted in the development of an irrigation technique which we have called partial rootzone drying (PRD).

REGULATED DEFICIT IRRIGATION (RDI)

I - BACKGROUND

In recent years the concept of Regulated Deficit Irrigation (RDI) has been used to develop practical solutions to manipulate grapevine vegetative and reproductive growth (GOODWIN and MACRAE, 1990, MATTHEWS *et al.*, 1987; McCARTHY, 1997). This development has only been possible as a consequence of the widespread use of drip and other forms of microirrigation which enable the precise timing and quantity of water applied to each plant. In Australia RDI is now widely practised in red-winegrape vineyards to manipulate winegrape quality. This is most commonly achieved by applying a short duration of water stress immediately after berry set in order to control berry size and vegetative growth. In some instances a short period of water stress may be imposed after veraison in order to enhance anthocyanin accumulation. Although often referred to as RDI, the practice of simply irrigating at less than the full vineyard water requirement for the entire growing season is not considered to be RDI.

II - PRACTICAL APPLICATION

RDI uses water stress to achieve the desired result. It is therefore critical to have sufficient information about soil water availability to ensure excessive water stress is not inadvertently applied. Soil water monitoring is normally used to assist in the implementation of RDI in many Australian winegrape vineyards. A wide variety of instrumentation is available and, with experience, all have been used successfully. Where soil water content is measured, for example, with a neutron probe, the available rootzone soil water content is kept below the irrigation « refill » line during the period of water deficit. It is suggested that the total available water in the rootzone should not decline by an amount greater than the difference between the « full- and refill-line » (figure 1). In practice this may necessitate a light irrigation during the deficit period to avoid the development of an excessive water deficit. To control vegetative and reproductive growth it is recommended that water stress be limited to the period after fruit set in winegrape vineyards. This strategy is more applicable for red-wine varieties rather than white varieties for which control of berry size and canopy size is considered to be less important. Monitoring shoot extension (HARDIE and MARTIN, 2000) or comparing the rate of increase in berry weight with non-stressed vines has also been used to assess the effectiveness of the water deficit.

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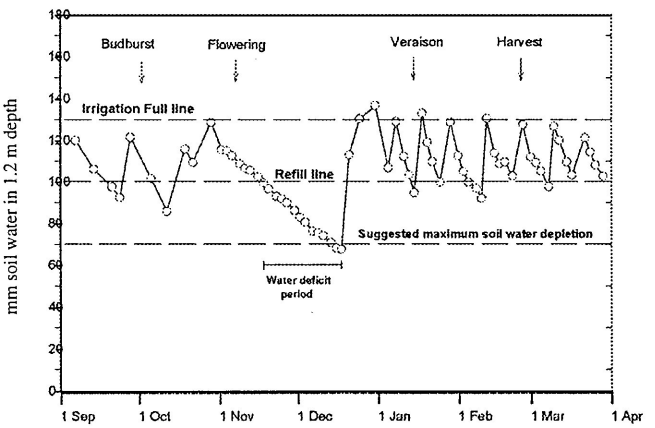


Figure 1 - An example of the use of a neutron probe to monitor change in soil water content between the irrigation full and refill lines between irrigations and decline in soil water content during application of post-flowering water deficit.

Un exemple de l'utilisation d'une sonde à neutrons pour suivre l'évolution de la teneur en eau du sol entre la CAPAC et le niveau d'assèchement justifiant une irrigation (refill line). Le schéma montre la baisse de la teneur en eau dans le sol, lors de l'arrêt de l'irrigation après la floraison.

RDI can result in a loss in yield through reduced berry size; however management practices which may compensate for the smaller berry size, for example lighter pruning, may minimise any potential yield loss. On the other hand, if the improvement in wine quality is significant (table III) grapegrowers are often compensated for crop loss with higher financial reward per tonne. Without this incentive, grapegrowers are unlikely to adopt irrigation practises that may result in yield reduction. RDI may result in an earlier harvest date (table IV), higher titratable acid and lower pH with little crop loss due to the avoidance of shrivel during the later stages of ripening.

II - IMPLEMENTATION DIFFICULTIES

In practice reduced irrigation application during the post crop–set period may not achieve the desired outcome due to the site being not responsive to irrigation due to:

- the presence of perched or regional water tables,
- deep soil with high water holding capacity and associated extensive root system,
- weather conditions such as rain and/or low temperatures resulting in low evaporative demand,
- inadequate knowledge of the changes in soil water content during periods of reduced irrigation due to lack of reliable soil water monitoring.

Sites with high water-holding capacity and winter rainfall can be made responsive to post–set deficit by a number of different approaches to vineyard management viz.:

- use of deep-rooted, spring-active cover crops to remove soil water,
- mounding soil along vine row to increase evaporation from soil surface,
- root pruning to reduce water uptake,
- high plant density,
- minimal pruning to increase crop water use early in the growing season as a result of earlier canopy development.

The use of irrigation water containing moderate to high levels of salt (sodium chloride) may necessitate monitoring soil salinity during periods of reduced irrigation application and potentially the application of a leaching irrigation at the end of the period of reduced application. Other factors that may limit the successful adoption of water deficit during the post crop set period are:

Table III - Post flowering water deficit effects on yield, maturity and wine spectral measures of Syrah, Riverland, South Australia.

Data sourced from a large-scale, non-replicated commercial trial.

Effets de l'arrêt de l'irrigation (après la floraison) sur le rendement, la maturité et les mesures spectrales du vin pour la Syrah, région du Riverland, Australie du Sud.

Données provenant d' une expérimentation commerciale sans répétitions, menée à grande échelle.

	Control	Post flowering deficit
T/ha	36.7	22.3
°Brix	23.6	26.4
OD_{280} (wine)	9.8	17.2
OD_{520} (wine)	1.9	4.6

Table IV - Effect of post-flowering water deficit on harvest date, yield and fruit composition of Cabernet Sauvignon, Riverland, South Australia.

Data sourced from a large-scale, non-replicated commercial trial.

Effets de l'arrêt de l'irrigation (après la floraison) sur le rendement, la maturité et les mesures spectrales du vin pour la Syrah, région du Riverland, Australie du Sud.

Données provenant d' une expérimentation commerciale sans répétitions, menée à grande échelle.

	Control	Post flowering deficit
Harvest date	1st April	18th March
T/ha	12.2	11.8
°Brix	13.3	13.7
Titratable acid (g/L)	5.4	6.6
pH (juice)	3.83	3.64

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- inability to re-schedule irrigation and application quantities when required,
- excessive variability in soil waterholding characteristics within each irrigation shift,
- poor distribution uniformity of the irrigation system,
- excessively high soil water availability from furrow and flood irrigation systems,
- general management skills.

Because RDI uses water stress to achieve the desired outcome, a more-than-basic understanding of vegetative and berry growth is required in relation to the effects of water abundance or deficit during each stage of vegetative and fruit growth. In some situations, either the duration of the water stress or the level of stress has been excessive, and this has resulted in excessive water stress leading to major crop reduction or even defoliation in extreme situations. In addition, the inappropriate use of water stress, for example during ripening in the belief that maturity will be enhanced, should be avoided.

PARTIAL ROOTZONE DRYING (PRD)

I - BACKGROUND

The background to the research on partial rootzone drying (PRD) has been described in DRY and LOVEYS (1998, 1999); DRY *et al.* (1996, 1999, 2000a, b, c); LOVEYS *et al.* (2000) and STOLL *et al.* (2000). Our early work showed that, if part of the grapevine root system was slowly dried and the remaining roots kept well watered, chemical signals produced in the drying roots reduced stomatal aperture. At the same time the fully hydrated roots maintained a favourable water status throughout the aerial parts of the plant. In other words, it was possible to separate the biochemical responses to water stress from the physical effects of reduced water availability. In addition to reduced stomatal conductance it was noted that shoot extension was also inhibited, and initially our experiments were aimed at producing a system for the control of canopy vigour. However, as work progressed it became apparent that the technique had the potential to influence not only growth but also water use efficiency and fruit quality. Most of our recent data have been obtained from field-grown vines at a number of experimental sites, for example, the Adelaide region, Barossa Valley, Padthaway and Riverland of South Australia. These have shown that it is possible to apply the technique to mature vines by simply modifying their irrigation management, ie. it is possible to achieve separate wet and dry zones by an appropriate combination of emitter spacing etc.

We learned from early experiments that by withholding water from half of the root system, stomatal conductance, photosynthesis and growth were reduced when compared with vines with all of their roots kept fully irrigated. A surprising finding was that the effect was transient, and despite the fact that part of the root system remained dry, conductance, photosynthesis and growth returned to pre-treatment levels within a few weeks. Evidence was accumulated that chemical signals such as abscisic acid (ABA), derived from the drying roots, were responsible for these responses. Armed with knowledge about the transient nature of the effect, it is possible to devise irrigation schedules which keep one part of the root system, or the other, always in a state of drying so as to maximise the production of ABA and hence its inhibitory effects on transpiration and growth. In practice this means applying water to one side of the vine for 10 to 15 days and then changing to the other side. During each irrigation cycle it is important that water is supplied with sufficient frequency to the « wet » side to prevent excessive soil drying and to meet the needs of the whole plant. If all of the vine's roots become dry, a water deficit will be induced and this may impact negatively on crop yield. Our experiments have also shown that the dry roots are maintained in a healthy condition by water supplied to them from the wet roots. If this water supply is inadequate, the water status of the whole plant will deteriorate.

We have now completed six years of field experiments where PRD has been applied to a range of varieties including Shiraz (syn. Syrah), Cabernet Sauvignon, Chardonnay and Riesling vines using a number of different irrigation methods. These have included standard drip emitters (2 or 4 L/hr), two per vine in the inter-vine space and placed about 450 mm from the vine trunk; sub-surface drip lines, one either side of the vine row at a depth of 200 to 250 mm and 350-400 mm from the centre of the row. We have also tried half-circle micro sprinklers throwing to either side of the row although these proved less satisfactory (however they are effective with tree crops). In all cases the intention was to create two wetted zones per vine which could be alternately irrigated on a cycle of approximately one to two weeks, ie. while one zone was wetted, the other zone would be dried. Soil moisture sensors were installed within each wetted zone to assess whether water applied to one side infiltrates to the other, supposedly dry, side. In all cases we found satisfactory separation of wet and dry zones in a range of soil types. There does not appear to be any varietal specificity in terms of the response to PRD although we are currently investigating the responsiveness of different rootstocks to PRD.

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II - HORMONAL CONTROL

Abscisic acid (ABA) is the plant hormone responsible for controlling plant transpiration through its effect on the aperture of the leaf stomata. When the entire root system experiences a water deficit, ABA synthesis is initiated in the drying roots and, as water leaf potential falls, in the leaves as well. The result is a very substantial increase in leaf ABA due to a combination of transport from the roots and in situ synthesis. However, when only part of the root system is exposed to a deficit, as in PRD, leaf ABA is only influenced by that amount which is transported from the roots. Leaf water potential is unaffected and thus the machinery for ABA synthesis in leaves is not activated.

The effects of PRD on stomatal conductance and on root ABA can be reproduced by applying synthetic ABA to one side of split-root vines. In an experiment with potted Cabernet Sauvignon vines 3 μM(±)ABA solution was applied to one side of the root system and water to the other side. The controls received water to both sides. Water was withheld from one side of the PRD vines. After 6 days stomatal conductance was significantly ($P<0.05$) reduced in both PRD and ABA-treated vines when compared with fully watered control vines. Analysis of ABA in the roots showed that the ABA treatment had raised the endogenous ABA content by almost exactly the same amount as the root drying treatment.

Exposure to water deficits has often been associated with an increase in the pH of xylem sap and so it was no surprise when it was noted that PRD induced an increase in xylem sap pH (figure 2). This observation may be important in gaining a complete picture of the consequences of PRD for leaf function. Abscisic acid is a weak acid and its degree of ionisation is controlled by the pH of the medium in which it is dissolved. As the pH increases, the proportion of the ionised form $[ABA]^-$ increases. This tends to decrease the removal of ABA into membrane-bound compartments and results in an increase in the ABA concentration in xylem sap and therefore the amount potentially in contact with the stomata. Both $[ABA]^-$ and ABAH are effective in inducing stomatal closure (HARTUNG, 1983). This effect of pH will be most marked at pH values close to the pKa of ABA (pH 4.8). For example, a change in xylem sap pH from 4.75 to 4.85 has an approximately ten-fold greater effect on the proportion of the ABA present as $[ABA]^-$ than a change of the same magnitude at pH 6.0. The pH of grapevine xylem sap expressed from canes or petioles is usually between 4.5 and 5.5 whereas that of most other crop plants is usually reported as being between pH5.5 and 6.5. This will tend to make grapevines particularly sensitive to small changes in xylem sap pH in terms of their response to ABA.

The effects of ABA on stomatal function are well documented and quite well understood, but another class of plant hormone, the cytokinins, is also known to influence stomatal function. The effect of cytokinins is opposite to that of ABA, causing stomatal opening. Cytokinins are also known to be involved in the stimulation of growth of lateral shoots and since lateral shoot growth suppression occurs in PRD vines we have measured the cytokinin concentration in shoot tips and lateral buds. PRD reduces the concentration of zeatin and zeatin riboside in all these tissues and also in roots (table V). Additional evidence for the involvement of cytokinins in the PRD response was obtained by spraying Chardonnay vines with benzyl adenine (BA), a synthetic cytokinin. PRD reduced stomatal conductance of these vines by 40 to 50 p. cent compared with normally irrigated control vines. By spraying the vines with BA (20 mg/L) stomatal conductance was returned to the same level as that of control vines. However, the effect declined over the following 5 to 6 days. This was probably due to metabolic degradation and dilution of the cytokinin in the target tissues. A second application of BA renewed the effect, however. As in previous experiments, the PRD treatment significantly ($P<0.05$) reduced lateral shoot growth and this effect was completely reversed by the BA treatment. It is clear that some of the observed responses to PRD, including partial stomatal closure and changes in the extent of lateral shoot development, can be reproduced by the application of synthetic plant hormones and this strongly suggests that their naturally-occurring analogues play a pivotal role in driving the PRD response. Considerable evidence suggests that ABA, derived in the drying roots, is responsible for changes in stomatal conductance and that the transport of this is facilitated by water which moves into these drying roots from more fully hydrated tissues. The changes in xylem sap pH, which accompany exposure of roots to water deficits and as a result of PRD, may augment the effectiveness of root-derived ABA by influencing the amount reaching the stomatal guard cells.

III - SHOOT GROWTH

In vines subject to PRD there is a consistent reduction in vegetative growth as measured by leaf area, pruning weight, shoot growth rate or other measures (table VI). In these experiments the control vines were normally irrigated and therefore received twice as much water as the PRD vines. Much of the reduction in canopy biomass is due to reduced leaf area associated with lateral shoots. Total leaf area of PRD vines

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is significantly less and this is due largely to a reduction in the area of leaves on lateral shoots.

IV - ROOT GROWTH

Shoots are not the only parts of the plant that may be affected by PRD. Roots, being the first part of the plant to be exposed to changes in soil moisture, may also be affected by long-term changes. One objective of our research was, therefore, to investigate the effect of PRD on root growth and root distribution. To determine the root distribution at different soil depths, roots of Riesling grafted on Ramsey rootstock were used. The vines were grown on levelled land in deep red sandy soil at Waikerie (Riverland, South Australia). The vineyard had a sprawl trellis system with minimal pruning (vine x row spacing: 1.3 m x 3.1 m). The vines were irrigated over 4 growing seasons using sub-surface drip lines. The drip lines for both treatments were buried at 0.2 m to 0.25 m depth and 0.5 m from the planting line on both sides. Two different irrigation treatments were used during the experiment. Water was either applied to both sides of the vines (control) or, in the other treatment, vines were irrigated using the PRD irrigation technique whereby one side was allowed to dry at a given time.

Six root samples of each irrigation treatment were taken at 2 different depths (0.1m to 0.4m and 0.4m to 0.7m) and according to the diameter of the roots they were sorted into 3 different classes: 1) < 1 mm; 2) 1 mm-3mm; 3) > 5mm. After drying the total weight of roots of each class was measured. We found that

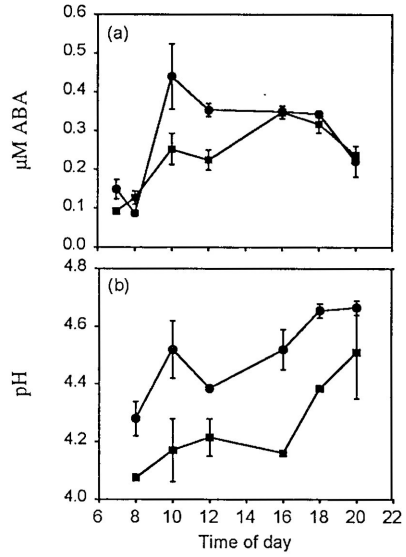


Figure 2

a) Changes in xylem sap ABA in control (watered both sides, ●) and PRD (watered one side only, ■) during one day in field-grown Cabernet Sauvignon vines. Data are means (n=4) with standard errors.

b) Changes in xylem sap pH in control (watered both sides, ●) and PRD (watered one side only, ■) during one day in field-grown Cabernet Sauvignon vines.

Values are mean (n=2) and bars are standard errors.
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a) Changement dans le ABA de la sève du xylème dans le témoin (arrosé des deux côtés, ●) et dans le PRD (arrosé d'un seul côté, ■) au cours d'une journée, pour des ceps de Cabernet Sauvignon ayant poussé en champ.

b) Changement dans le pH de la sève du xylème dans le témoin (arrosé des deux côtés, ●) et dans le PRD (arrosé d'un seul côté, ■) au cours d'une journée, pour des ceps de Cabernet Sauvignon ayant poussé en champ.

Table V - Zeatin and zeatin riboside concentrations (pmol/g fresh weight) in the shoot tips, axillary buds and roots of Cabernet Sauvignon field-grown grapevines.

Figures are mean values for 4 sampling times during one 10 day PRD cycle. There were 4 replicate samples at each sample time. For any tissue type a different letter within a column indicates a significant difference (P<0.05).
This table first appeared in Journal of Experimental Botany, 51, p1630 and is reproduced with permission.

Concentrations en zéatine et en zéatine riboside (pmol/g de poids frais) dans les apex, les bourgeons axilaires et les racines pour des ceps de Cabernet Sauvignon ayant poussé en champ.

		Zeatin	Zeatin Riboside
Shoot Tips	Control	21.3[a]	31.1[a]
	PRD	11.2[b]	15.6[b]
Buds	Control	10.9[a]	21.0[a]
	PRD	8.7[b]	14.3[b]
Roots	Control	8.1[a]	14.8[a]
	PRD wet	4.0[b]	7.1[b]
	PRD dry	2.9[b]	5.5[b]

Table VI - Effects of PRD on pruning weight. Cabernet Sauvignon and Shiraz vines were irrigated with above-ground drippers and the Riesling by sub-surface drip.

Effets du PRD sur le poids des bois de taille. Les ceps de Cabernet Sauvignon et de Syrah étaient irrigués par goutte-à-goutte de surface et le Riesling par goutte-à-goutte souterrain.

Description	PRD Pruning Weight (p. cent of control)
Cabernet Sauvignon mean of 4 seasons	77 *[a]
Shiraz - one season	84
Minimally pruned Riesling (total all size classes)	60 **
Canes > 500 mm	47 **
Canes 250-500 mm	82
Canes < 250 mm	103

*,** Significantly different to control (p<0.05, p<0.01) ; all other means not significantly different from control
a : Significantly different in 3 out of 4 seasons

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withholding water from one side of the root-system changed the distribution of roots and that PRD caused roots to grow to deeper soil layers (figure 3). At depths of 0.4m to 0.7m, the roots of the 1mm to 3mm diameter class had a significantly higher abundance for PRD vines compared to those which received water on both sides. Also, vines watered on both sides had a higher proportion of roots in soil layers closer to the surface compared to PRD vines. Here, dry weight of roots in the diameter classes smaller than 1 mm and 1 mm-3 mm was significantly increased. However, when the total masses of roots from both soil layers were combined, the total dry weight for the control and the PRD vines did not differ.

The greater abundance of roots in deeper soil layers in PRD-treated vines may contribute to the water stress tolerance of these vines. The same effect on root distribution was also observed in pot experiments, where soil drying forced root development to greater depths without changing the total amount of roots per pot (DRY *et al.*, 2000b). Furthermore, forcing roots to deeper soil layers may better prepare vines to withstand water deficit, because soil drying occurs slowly from the surface. A further implication of this result is that a redistribution of water from the roots on the wet side may be occurring. It is also possible that extraction of water from deep soil layers in response to PRD may improve aeration of the subsoil thereby creating a better environment for root growth.

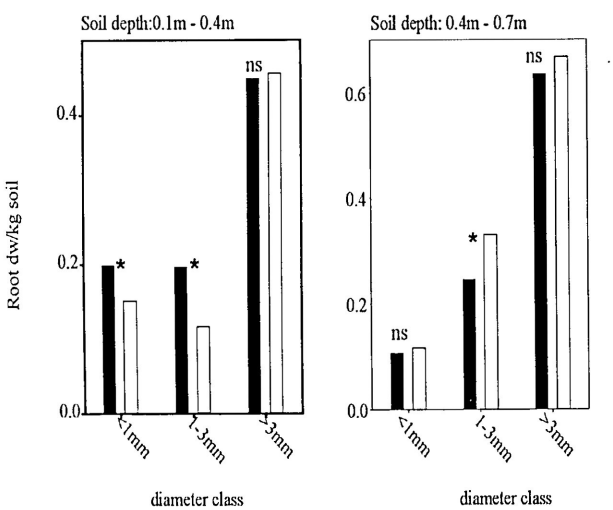


Fig. 3 - Effect of different irrigation treatments on root distribution of various diameter classes at two depths.
(■ control: both sides of the vine irrigated; ❑ PRD: partial root-zone drying; *P<0.05; ns P>0.05; *Vitis vinifera* cv. Riesling grafted on Ramsey rootstock)

Effets des différentes méthodes d'irrigation sur la distribution des racines pour plusieurs classes de diamètres à deux profondeurs.
(■ témoin : vigne irriguée des deux côtés ; ❑ PRD ; *P<0.05 ; ns P>0.05 ; *Vitis vinifera* cv Riesling greffé sur porte-greffe Ramsey)

V - SAP FLOW AND WATER REDISTRIBUTION

In many of our experiments with potted vines we have noticed that, even if water is withheld from one pot for extended periods of up to 12 weeks, there are still healthy, white roots present in the dry soil. We wondered if water was being redistributed within the plants to maintain these roots in this apparently healthy condition. The movement of water within plants in response to water potential gradients has been described previously and is variously known as « hydraulic redistribution » (BURGESS *et al.*, 1998), « hydraulic lift » (DAWSON, 1993) or « inverse hydraulic lift » (SCHULZE *et al.*, 1998). In relation to the application of PRD this phenomenon may be important for a number of reasons. Firstly, it would allow roots in dry soil to be maintained in a viable condition for extended periods. Secondly, the water moved into these roots under the influence of water potential gradients during the night may then contribute to transpirational water flow the following day, carrying with it any root-derived chemical signals such as ABA. Using sap flow sensors installed in the roots of both grapevines and citrus trees we have shown that such water movement does occur under the influence of the water potential gradients generated as a result of PRD irrigation (LOVEYS and STOLL unpublished data).

VI - THE IMPORTANCE OF ALTERNATION OF IRRIGATION WITH PRD

Under drying soil conditions chemical signals and plant hormones play an important role in the communication from roots to shoots. Maintaining a high relative water content in roots on the « dry » side of PRD-treated plants may be important for the export of such chemical signals from this part of the root system. However, evidently the grapevine root system is not able to maintain the effect for an extended period, as we have shown that after 2 to 3 weeks the reduction in stomatal aperture recovered, if « wet » and « dry » sides have not been alternated (DRY *et al.*, 1996). We propose that a continuous signal or a certain concentration of plant hormones is necessary to maintain a reduction in stomatal aperture or a reduction in growth and, for that reason, alternating « wet » and « dry » zones of the root system is essential. The frequency of the switch is determined according to soil type and other influences such as rainfall and temperature. In most of our experiments we have changed irrigation sides every 10 to 15 days. Due to our observations that roots of PRD-treated plants occur at greater depth, it is advisable to monitor the soil water content of deeper soil layers carefully when the switch from « dry » to « wet » side occurs so that deeper soil layers become refilled with water. In some instances, where soil drying is very rapid

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on the dry side, it may be necessary to switch more frequently than 10 days.

VII - YIELD AND WATER-USE EFFICIENCY

It has been a consistent feature of all experiments that there was no significant reduction in yield due to PRD treatment even though irrigation amount was halved. As a result, water use efficiency (WUE, the amount of crop produced per unit of water applied [t/ML]) was doubled in response to PRD (table VII). Also, there was no effect on berry size in response to a halving of irrigation amount: this is a very different result to most irrigation experiments where there is usually a significant decrease in berry size in response to a substantial reduction in the amount of irrigation applied, particularly where a deficit has been imposed between flowering and veraison, because this is the period when berry size is most sensitive to stress. Frequently, the decreased yield measured in deficit irrigation experiments can be largely attributed to an effect on berry weight.

In the majority of our experiments, the PRD treatment has received 50 p. cent of the irrigation water of the control. However, in some experiments, we have applied the same amount of water to PRD and control treatments. For example, on Shiraz at the Waite Campus: both treatments were pruned to same nodes/vine in season 1 with 20 p. cent more nodes retained on PRD in season 2. In both seasons, control and PRD were irrigated with 0.5 mL/ha (for previous 3 seasons, PRD vines had received half irrigation of control where control = 1.0 mL/ha; PRD = 0.5 mL/ha). PRD had higher yield in both seasons: in season 1, this was mainly due to increased berry weight; in season 2, this was mainly due to increased bunch number. PRD had a higher pruning weight in both seasons but there was no effect on fruit composition in either season. Control vines experienced hydraulic water stress for part of season at this low level of irrigation as evidenced by measurements of leaf water potential.

Table VII - Yield and water-use efficiency of control and PRD vines from experiments at several locations. Shiraz and Cabernet Sauvignon were irrigated with above-ground drippers and the Riesling by sub-surface drip.

Rendement et efficacité de la gestion de l'eau pour les ceps de vignes témoins et ceux ayant subi le PRD lors d'expérimentations menées en différents lieux. Syrah et Cabernet Sauvignon étaient irrigués par goutte-à-goutte de surface et le Riesling par goutte-à-goutte souterrain.

Variety/Location/ Season	Variable	Control	PRD
Shiraz, Adelaide, 1997/98	Yield (t/ha)	22.6	21.5
	Water applied (mL/ha)	1.4	0.7
	WUE (t/mL)	16.1	30.7
Cabernet Sauvignon, Adelaide, 1997/98	Yield (t/ha)	15.2	15.4
	Water applied (mL/ha)	1.4	0.7
	WUE (t/mL)	10.9	22.0
Riesling, Waikerie, 1996/97	Yield (t/ha)	29.1	28.9
	Water applied (mL/ha)	4.5	2.4
	WUE (t/mL)	6.4	11.9
Riesling, Waikerie, 1997/98	Yield (t/ha)	30.6	28.7
	Water applied (mL/ha)	5.2	2.6
	WUE (t/mL)	5.9	10.9

Data have been collected from several commercial vineyards where PRD has been evaluated (table VIII). In all cases, the water use efficiency (t/mL) was considerably improved. Furthermore the amount of water applied was reduced by almost 50 p. cent compared to standard regional irrigation practice. The effects on yield were minor, except in one case (Padthaway Shiraz).

The experience from the commercial trials (table VIII) shows that if PRD is properly applied, there should be no significant yield reduction, even though irrigation amount may be halved. For the Padthaway Shiraz, uncontrolled water stress may have occurred during the period from set to veraison which significantly reduced berry size. This stress may have been the result of a lack of adequate refilling of deep soil layers after switching the irrigation sides. This result draws attention to the need to carefully monitor soil moisture, particularly after switching from « dry » to « wet » sides and during the early part of the berry development. Provided the hydration status of vines is maintained with PRD, berry size and thus yield should be maintained, despite reductions in water of up to 50 p. cent of conventional irrigation. If berry size is significantly reduced with PRD, then this may be an indication that the soil moisture status of the « wet » side was not adequately maintained.

Even if irrigation water accounts for only a small amount of total production costs, it is becoming an increasingly valuable resource and with environmental pressures, such as water salinity increase, and increasing planted areas, changes in Australian water policies have already been prompted. A restriction in water availability in future will require improved irrigation practices and a higher water use efficiency for horticultural crops. In that regard, PRD holds much promise.

VIII - FRUIT COMPOSITION AND WINE QUALITY

In many of our experiments and in the commercial evaluation of PRD there has been a positive effect of

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PRD on fruit and wine quality. The reduction in canopy density that results from PRD appears to be a possible cause of changes in fruit quality components. The influence of the canopy microclimate on fruit composition has been well documented. Cabernet Sauvignon berries from PRD-treated vines had significantly lower juice pH and higher berry anthocyanins and phenolics than controls when the bunches on PRD vines were much better exposed than those on controls, for example, as in the 1994/95 season. The increase in secondary metabolite concentration per g berry weight in response to PRD in 1994/95 was almost entirely due to an increase in amount per berry. This distinction is important because it indicates a direct effect of PRD treatment on secondary metabolite accumulation and/or synthesis in the berry. When bunch exposure of the controls was increased by a combination of basal leaf removal and training system (the vines of both treatments were converted to the Smart Dyson trellis in 1995), there were no significant differences in fruit composition parameters in the 1996/97 season (table IX). However, wine made from PRD fruit in the 1996/97 season was rated more highly for aroma characteristics than wine from control fruit. In some of our most recent experiments, there has been no apparent effect on fruit quality as indicated by concentration of anthocyanins and phenolics in fruit. In these cases, the control vines were well-balanced with relatively open canopies: PRD did not substantially alter the canopy microclimate. In other words, we are confident that the fruit specification of Shiraz and Cabernet Sauvignon in these experiments was at least maintained even though irrigation amount was halved.

Table VIII - Commercial experience with PRD in different regions in Australia.

PRD is compared to conventional irrigation practice (control): differences are expressed as p. cent of control.

Expérimentation commerciale avec PRD menée dans différentes régions d'Australie.

Le PRD est comparé aux modes d'irrigation conventionnels (témoin) : les différences sont exprimées en pourcentage du témoin.

Region/variety	Treatment	Yield (t/ha)	Irrigation amount (mL/ha)	WUE (t/mL)
McLaren Vale/Shiraz	control	20.3	1.53	13.3
	PRD	19.0	0.77	24.7
	% difference	-6	-50	+86
Sunraysia/Shiraz	control	29.0	7.42	3.9
	PRD	26.9	4.45	6.1
	% difference	-7	-40	+55
Padthaway/Shiraz	control	13.3	3.9	3.4
	PRD	9.6	2.2	4.4
	% difference	-28	-44	+29
Langhorne Creek/Shiraz	control	12.3	3.2	3.8
	PRD	13.3	2.0	6.7
	% difference	+8	-37	+76
Riverland/Riesling	control	37.7	5.5	6.9
	PRD	37.0	2.8	13.1
	% difference	-2	-49	+90

Table IX - Composition of Cabernet Sauvignon berries - response to PRD. Fruit were picked at the same maturity (22.4 to 22.8 Brix).

Composition des baies de Cabernet Sauvignon – réponses au PRD. Fruits cueillis au même degré de maturité (de 22,4 à 22,8 Brix)

Variable	1994/1995		1996/1997	
	Control	PRD	Control	PRD
PAR at bunch zone (µmol/m²/s)	119	318 *	285	396 *
Berry weight (g)	0.76	0.74	0.96	0.91
Total soluble solids (°Brix) [a]	22.8	22.9	22.2	22.1
Titratable acidity (g/L) [a]	5.8	8.4 **	5.8	5.8
pH [a]	3.44	3.25 **	3.62	3.58
Total anthocyanins (mg/berry) [b]	0.89	1.28 **	0.97	0.96
Total anthocyanins (mg/g berry weight) [b]	1.19	1.72 *	1.01	1.06

* Significantly different from control ($p<0.05$); ** ($p<0.01$); all other comparisons are not significantly different

a, b Measured in berry juice and homogenate respectively

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CONCLUSIONS

Both RDI and PRD are examples of strategic irrigation management. In Australia the concept of applying water stress immediately after fruit set to control vegetative growth, and, in particular for the variety Syrah to control berry size, has been widely adopted. In many instances this practice has resulted in a significant improvement in red-wine quality, albeit sometimes at the expense of high yield. In addition, controlled irrigation is recommended to avoid water stress during the fruit ripening period (post veraison). This is particularly the case in drip irrigated vineyards where, as a result of drying of deeper soil layers and a reduced wetted soil volume compared with furrow irrigation, drought stress can rapidly develop during periods of high evaporative demand. The evaluation of PRD in vineyards has now progressed well beyond the experimental stage. Considering that the first results of our work on PRD were only published in 1996, there has been a very rapid rate of adoption. We are now aware of substantial areas of vineyards either currently using or intending to use PRD in Australia, California (USA), Spain, Israel, Argentina, New Zealand and South Africa. PRD with furrow/flood irrigation has been successful in experiments with pears and citrus and in commercial vineyards in the NSW Riverina (Australia).

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