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Grape and Wine Research and Development Corporation

Development of methods for the control of vine vigour and water use optimisation based on the concept of Partial Rootzone Drying



GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

FINAL REPORT

Project Numbers: **CSH 92-2 and CSH 95-3**

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Research Organisation: **CSIRO Plant Industry**

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Index

Non-technical summary 4

Introduction and Background 6

Objectives of the research project 9

Introductory technical information concerning the problem or research need 10

Research methodology - including a description and justification of the methodology
A)Plant Material 12

a)Glasshouse trials with potted vines
b) Field vines in pots.
c) Field vines with split roots
d) Commercial and experimental field vines

B) Methods.....14

Detailed results

Response of grapevines to partial drying of the root system 16

Effects of partial rootzone drying on grapevine physiology and fruit quality 20

Published papers arising from the projects.

Refereed publications 24

Non-refereed publications 28

Conference Presentations and Posters.....29

Awards.....30

Discussion of results including an analysis of research outcomes compared with the objectives

The background to the study 31

Development of the PRD strategy 32

Leaf water potential 33

Symptoms of water stress 33

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The evidence for ABA as the signal which mediates the response of shoot growth to PRD....34

Recovery of shoot function 35

Response to partial drying 36

Shoot growth and stomatal function recover before the plant-available soil water on the 'dry' side of the vine is completely depleted 39

Reduction in the amount of irrigation with PRD 41

The Role of Cytokinins 42

Possibilities for future research 44

Implications and recommendations 45

Intellectual property arising from the research 46

Technical summary 46

References 47

Appendix 1
Response of grapevines to partial drying of the root system

Appendix 2
Effects of partial rootzone drying on grapevine physiology and fruit quality

Appendix 3
Published papers arising from the project

Appendix 4
Media articles arising from the project

Non-technical summary

GWRDC projects CSH92-2 and CSH95-3 have involved researchers from the CSIRO, University of Adelaide and the South Australia Research and Development Institute. The research has resulted in the development of a new strategic irrigation management technique called partial rootzone drying (PRD).

In broad terms, the aims of these projects were to:

- Develop management practices for the control of vine vigour based on observations which showed that if only part of the rootzone was irrigated, the drying roots in the remainder of the soil exerted an inhibitory influence on shoot growth
- Investigate the effects of these novel irrigation management practices on vine water use efficiency and winegrape quality
- Describe the physiological changes which occur in vines subject to these irrigation regimes
- Make recommendations for the implementation of the irrigation systems developed in these projects

The objectives of the project have been met and partial rootzone drying (PRD) is now well recognised by the winegrape industry, which has established a number of independent trials or has implemented PRD on quite a large scale. In addition, PRD trials and significant implementation has occurred overseas, principally in California. However, the projects show that there are continuing opportunities to capture benefits from this science and its applications.

The major findings from the research projects may be summarised as follows:

1) Pot trials
   - Shoot growth and transpiration were significantly reduced when half of the root system was exposed to drying soil
   - These effects were transient, the vines recovering after 2 or 3 weeks, even if the soil around half of the roots remained dry.
   - By alternating the dried and wetted side of the root system on a 12 to 14 day cycle it was possible to sustain the inhibition of growth and transpiration. This was the basis of the PRD irrigation technique
   - The abscisic acid (ABA) production in the drying roots followed the same time course as the effects on growth and transpiration. ABA is known to be responsible for transpiration control in many other plants. This strongly suggests that ABA production in the drying roots is what is driving the effects of PRD on transpiration.
   - Roots exposed to dry soil remain healthy provided some of the roots on the same plant have access to water, suggesting that water moves from the wet to the dry roots. This was confirmed by showing that isotopically-labeled water moves from roots in the wet zone into roots surrounded by dry soil.
   - Shoot tips and buds and the drying roots of vines under PRD irrigation have reduced cytokinin levels (cytokinins are endogenous plant hormones responsible for stimulating bud growth and transpiration). By spraying vines with a synthetic cytokinin (benzyl adenine) it was possible to reverse the effects of PRD on growth and transpiration, suggesting that cytokinins, as well as ABA are involved in vine response to PRD.

2) Trials with split-root vines in the field
   - Application of PRD to Cabernet Sauvignon/Ramsey vines for seven consecutive seasons has had no detrimental effect on the vines in terms of trunk growth, bud fruitfulness or fruit set

- Yield components such as bunch number, berry size, berries per bunch were not affected nor was TSS accumulation
- Total leaf area was reduced by the PRD treatment and this reduction was mostly due to a reduction in leaves associated with lateral shoots. Consequently, the light penetration into the canopy was significantly increased.
- Total anthocyanin and phenolic concentrations in the fruit increased under PRD irrigation and this is most likely due to the increase in light penetration to the bunch zone since the differences between PRD and control fruit were reduced when selective leaf removal equalised the bunch light environment. Nevertheless, some quantitative and qualitative differences in anthocyanin species may be due to the PRD treatment.

3) Trials with mature commercial vines
   - PRD irrigation was applied to established vines in a number of ways: by applying water to either side of the vines through sub-surface drip lines, by adding additional surface drippers to allow the creation of two wetted zones per vine, by converting vines from overhead sprinklers to under-vine half circle micro-jets. We are also aware of some growers who have used alternate row flood irrigation to good effect. Of the pressurised water systems the sub-surface and drip were successful in achieving PRD effects. The conversion from overhead sprinklers was less successful because the large reduction in soil wetted volume resulted in vines of very low vigour. Project time constraints did not permit longer-term evaluation.
   - PRD significantly increased the water use efficiency of the vines and had no detrimental effect on yield
   - At water application rates which are close to the district average for vines, PRD caused a reduction in vigour as judged by pruning weights.
   - In experiments where both control and PRD vines received the same amount of water many differences between the vines could be demonstrated. Under conditions where water supply was adequate for both treatments, the stomatal conductance and growth of the PRD vines was restricted as had been observed in many previous experiments. However, as total water input was reduced, the stomatal conductance of PRD vines became greater than controls, suggesting that the latter were experiencing a degree of water stress, whereas the PRD vines were not. This may have been due to the greater depth of water penetration in the case of the PRD vines, where water was applied to a smaller surface area. This distinction between PRD and control vines, at very low water application rates, was also reflected in pruning weights, which were actually greater in PRD vines, as was crop yield. It was concluded that at low water application rates, the PRD vines were more resistant to water stress and made more efficient use of available water.

Introduction and Background

In 1992 a proposal was submitted to the Grape and Wine Research and Development Corporation (GWRDC) which outlined a project, the aims of which were: *"to determine the importance of interactions between root distribution, root hydration and irrigation practice in the control of vigour in both own-rooted and grafted vines and to develop management practices to control vine vigour based on the findings"*. The proposal recognised that grapevines grown in cool climates frequently suffer from excess vigour, which results in problems with disease, bunch shading and a reduction in grape quality. This project aimed to provide a physiological explanation for these problems and to suggest changes in management practice to improve the situation. This three year project (CSH92-2) provided information, from a number of sites, on the responses of grapevine to partial wetting of the rootzone, or as it was rather clumsily called then, *heterogeneous rootzone hydration.* Systems were developed for the production of experimental potted plants with two root systems which could be independently irrigated, and field vines with two root systems which again could be independently irrigated without concerns about water movement from one rootzone to the other. The broad conclusions from this project were that by withholding water from part of the root system there were significant reductions in canopy vigour without significant loss in crop yield or quality. The treatment did not have any effect on plant water relations as measured by leaf water potential. Throughout these experiments physiolgical explanations were sought for the observed phenomena as it was argued that if the underlying mechanisms were understood then it would be easier to optimise the irrigation treatments by monitoring some measurable biochemical change. It was shown that changes in the plant hormone abscisic acid (ABA) were responsible for many of the responses observed to accompany the treatments.

Although the primary focus of CSH92-2 was to produce an irrigation treatment for controlling vine vigour, it was soon realised that because the treatment involved irrigating only half of the rootzone at any one time, and the size of the crop was not significantly affected, the water use efficiency of the vines had been greatly improved. The focus of the project therefore changed to concentrate on issues associated with crop water use, rather than canopy vigour control. To some extent this was driven by a growing awareness of water conservation issues and the realisation that the massive expansion in the Australian winegrape industry which was underway in the 1990's would have to be accompanied by improvements in the efficiency of irrigation water use.

This was stated clearly by Scales (1995) in his report on the winegrape and wine industry in Australia "*.....future development is contingent upon the availability of water for irrigation"* and *"It appears that the scope for simply increasing water allocation from current supplies is, in some irrigation areas, not feasible"*. Furthermore, in the Australian wine industry's **Strategy 2025** document it was stated that *"Vineyard expansion will create an additional demand for water estimated at 68,000ML by 2025. Processing expansion will generate demand for an additional 2000ML. This water will come from efficiency gains in vineyards and wineries (40,000ML), crop diversions (20,000ML) and new sources (10,000ML)."* It was also stated in this document that *"There is unlikely to be an increase in water provisions in existing dryland viticultural areas and increases will come from greater water use efficiency"*.

The focus of a new project application to GWRDC therefore shifted towards optimising the new irrigation method to improving water use efficiency, rather than controlling canopy vigour. The new project (CSH95-3) was titled *"Development of methods for the control of vine vigour and water use optimisation based on the concept of heterogeneous rootzone hydration"*. This project concentrated on developing irrigation systems for the commercial application of the technique, but retained a theme of improving our knowledge of the underlying physiological processes which drive the plant responses. This aspect was given additional resources thorough the provision of a third GWRDC project "*Partial Rootzone Drying: a new irrigation technique which improves production efficiency by reducing water requirement and improving grape quality"* which ran partly in parallel with CSH95-3 and was given the same project number. This latter project was principally to support the operating costs of a PhD studentship. The major theme of work undertaken by this student was to further study the physiological mechanisms which change in response to the irrigation treatment, with particular emphasis on factors which influence winegrape quality. The title of this project introduces for the first time the name by which the irrigation technique has come to be known: Partial Rootzone Drying (PRD).

This report therefore covers two GWRDC-funded projects, CSH92-2 and CSH95-3. The bulk of the experimental results from these projects are encapsulated in two PhD theses submitted to the University of Adelaide, one written by Dr Peter Dry and the second by Mr Manfred Stoll. These are attached to this report as Appenix 1 and Appendix 2 respectively. Additional experimental results are shown in a number of published papers in both refereed and non refereed journals, and these are attached as Appendix 3. Media interest in PRD has been substantial and this is summarised in Appendix 4. In addition to this documented material there have been many TV

and radio interviews. Perhaps most notable were stories in the ABC's Landline and Channel 7's Countrywide programmes.

The authors of this report: Dr Brian Loveys, Dr Peter Dry, Dr Michael McCarthy and Mr Manfred Stoll, wish to thank all of the wine companies who have provided material assistance in the form of irrigation supplies, grafted and ungrafted plants and access to their properties. These include Southcorp Wines, Wingara Wine Group, Yalumba, Orlando Wyndham. We also wish to thank Ms Sue Maffei, Mr David Botting, Mr Jim Grant, Mr Jared Lawrence, Ms Vicki Barrett, Ms Georgia Pfennig for their assistance.

Objectives of the Research Project

In broad terms, these projects aimed to develop novel irrigation methods, which would stimulate the endogenous stress response mechanisms of grapevine so that vigour was reduced and the efficiency of water use was enhanced. This was to be achieved by testing the hypothesis that the manipulation of the hydration status of parts of a grapevine's roots could be used to control vegetative vigour without detrimental effects on canopy water relations. The proposed work also examined the hypothesis that chemical signals, passing from the drying portions of the root system to the shoots, were responsible for the control of cane growth and canopy water use. Preliminary work with potted vines had shown that partial drying of one half of the roots of plants grown with two root systems was rapidly translated into a reduction in transpiration and assimilation of all the leaves.

In addition to these broad objectives the projects were designed to answer a number of questions relating to the practical application and longer-term consequences of the proposed irrigation methods. These included:

- What are the impacts on crop yield and grape quality?
- How can the proposed irrigation changes be cheaply and effectively implemented?
- Are there any long-term consequences in terms of bud fruitfulness, fruit set, carbohydrate partitioning, nutrition?
- Does the treatment affect root development?
- Does the treatment become less effective over time due to acclimation?

Although the main objective of the projects was the development of cheap and practical methods for vigour control and the improvement of water use efficiency, we have also attempted to gain a sound appreciation of the underlying physiological changes which accompany the manipulation of root hydration status. We reasoned that the success of the irrigation techniques may be measured in terms of changes in hormonal status that can be measured, thus providing a means of assessing the effectiveness of a treatment without waiting for the long term expression of growth responses. We knew from previous work that many of the PRD responses were explainable in terms of increased ABA production in the drying roots, but the roots are also the source of other hormones which control important aspects of canopy development such as lateral shoot development. We therefore needed to know the involvement of other hormonal substances, particularly cytokinins. The following objectives covered these aspects of the projects:

- develop an effective assay for the most important cytokinins in grapevine tissues.
- provide a detailed description of the hormonal changes which occur when grapevines experience cyclical wetting and drying of the rootzone.

Introductory technical information concerning the problem or research need

Grapevines grown in cool climates frequently suffer from excess shoot vigour, which results in problems with disease, bunch shading and a reduction in wine quality. The projects aimed to provide a physiological explanation for this problem and to suggest changes in management practice to improve the situation.

Excessive vegetative vigour has many consequences for the long term management of grapevines. There is a reduction in floral differentiation, non-uniformity of bud break, increased disease of fruit and leaves due to the development of unfavourable microclimates in the dense canopy and difficulties with achieving adequate spray penetration and decrease in grape quality. Measures taken to achieve a more satisfactory balance between vegetative and floral development have included chemical treatments (Lavee, 1987, mechanical trimming and the selective use of rootstocks (Pouget, 1987). In Australia chemical means of vigour control have not been widely adopted and environmental and cost considerations will probably preclude developments in this direction in the future. In Europe limited use is made of rootstocks for vigour control but in Australia rootstock selection has been primarily for Phylloxera and nematode resistance. Mechanical trimming therefore remains the predominant means of vigour control in Australia.

In the long term rootstocks which impart the desired mix of vigour control and disease resistance may be increasingly adopted but in the meantime methods of vigour control based on irrigation management and an understanding of appropriate areas of vine physiology may prove to be cost-effective.

As emphasis swings increasingly towards overseas markets for Australian wine it will be important to maintain and improve grape quality. The proposal aimed to provide the basis for improvements to management practice, which are not dependent on chemical usage and would not require high labour inputs.

Research carried out by the principal investigator and other CSIRO colleagues provided a detailed picture of the involvement of the plant hormone abscisic acid (ABA) in the control of

photosynthesis and water consumption of grapevines (Loveys 1984a; Loveys 1984b; Downton *et al.* 1987). Related research in Australia and overseas (Zhang and Davies, 1990; Gowing *et al.* 1990) showed that a chemical signal is produced in drying roots which is transported to the shoot where it can cause inhibition of shoot development. This can occur even when only part of the root system is stressed, sufficient water being supplied by the irrigated part of the root to maintain the water status of the canopy. The aerial parts of the plant can thus appear green and healthy but their growth and development is restricted. Preliminary experiments with split-rooted grapevines carried out in Adelaide (Loveys and Düring, unpublished) showed that photosynthesis, shoot and leaf development are responsive to partial root drying. There is considerable evidence that a root-derived factor, abscisic acid (ABA), is responsible for the inhibition of photosynthesis and canopy growth. It was proposed that this detailed background information could be exploited to develop an irrigation system, which stimulated partial root drying.

The practical implications for this research are considerable. Any situation which results in the uneven distribution of water through the soil profile and the consequent differential drying of roots will influence the growth potential of the canopy. The application of water to a small area under a vine from a dripper or micro jet will satisfy the water requirements of the canopy and can be thought of as analogous to the well watered part of the root system of the split root experiments described above. The remainder of the root system, which may have developed in response to earlier irrigation practice or to water available throughout the soil profile after winter rains, will not receive water and may be analogous to the dry roots of the split root experiment which are able to exert significant inhibitory effects on the canopy. Conversely, irrigation of the majority of the root system, with few "dry spots" may result in excess vigour. This situation may develop as a result of type of irrigation, soil type or prevailing climatic conditions.
The possibility therefore exists to exert control over vine vigour through the reasoned manipulation of irrigation and other management techniques.

Any treatment which seeks to impose changes in vine development through manipulation of irrigation has the potential to impact of water use efficiency (the amount of carbon gained for a given loss of water). This is possible because the primary effect of the treatment is on the production of hormonal substances in roots, which affect stomatal conductance. Stomata are the leaf pores through which virtually all of the water transpired by the vine passes. A reduction in stomatal conductance therefore directly reduces vine water use. Unfortunately, carbon dioxide for photosynthesis must also pass into the leaf through the stomata and so a reduction in stomatal

conductance will reduce carbon intake as well as reducing water loss. However, the relationship between water loss and carbon uptake is not linear, and for a given reduction in transpiration there will be a less than proportional reduction in photosynthesis, resulting in an increase in water use efficiency. This is especially true at high values of transpiration, which the PRD technique seeks to reduce. The improvement in water use efficiency, which can be gained from strategic irrigation management therefore becomes a primary focus of these projects since the winegrape industry has clearly recognised the need for efficiency improvements to sustain its vineyard expansion program.

Research methodology - including a description and justification of the methodology

A) Plant Material

The experimental work for these projects was carried out primarily on field-grown vines of commercially important varieties. Some trials were also carried out on potted vines in both glasshouse or in the field. Own-rooted and grafted vines were used. Details of these classes of experimental plants are as follows:

a) Glasshouse trials with potted vines

Experimental plants were grown with divided root systems in large (20 L) plastic containers. These were housed in air-conditioned glasshouses with supplementary light. Own-rooted *Vitis vinifera* cvs. Chardonnay, Pinot Noir, Cabernet, Shiraz and Sultana vines were used. In addition, *Vitis champini* (cv. Ramsey) was also used. The twin rooted plants were grown to allow independent irrigation of each root system. Grafted (Cabernet on Ramsey) twin-rooted plants were also used in some glasshouse trails. Approach-grafted vines were also used. For these trials Shiraz and Ramsey vines were grafted to allow the development of shoots from nodes both above and below the graft union. This effectively allowed both own-rooted (below graft union) and grafted (above graft union) responses to be monitored in the one experimental unit.

b) Field vines in pots.

The same range of vines as above were utilised. Care was taken to ensure that water deficits did not develop under desiccating conditions by providing adequate soil volume in the pots (up to 75L per pot) and providing frequent irrigation (up to 3 times per day).

c) Field vines with split roots

As an intermediate stage between potted vines and mature commercial field vines we have utilised vines grown in the field, but with their roots divided equally on either side of a plastic membrane buried to a depth of 1.5m in the soil. For this purpose Cabernet Sauvignon vines grafted to Ramsey rootstock were used as it was felt that the high vigour characteristics of Ramsey would provide good material for experiments, the aim of which, was to reduce vigour. Another similar experiment was set up on the same site with own-rooted Cabernet Sauvignon vines. In this experiment the native soil was removed and replaced with a uniform soil mix with no stones to facilitate root sampling. The irrigation was such that both control and PRD vines received the same amount of water. Soil moisture was measured with capacitance probes inserted to a depth of 1.5m on either side of the plastic membrane. It was felt that the plastic membrane would ensure a clear differentiation between wet and dry zones, which could be used as a benchmark for future experiments, which did not employ such a membrane. It was never intended that the inclusion of a membrane would be part of any commercial system.

d) Commercial and experimental field vines

It has been an aim of the project to define irrigation systems, which can be applied to mature commercial vines or to young vines during their establishment. Consequently, much of the experimental work was carried out on grower's properties or on experimental vines grown under commercial conditions on the Waite campus. These included:

- Riesling grafted to Ramsey rootstock at Waikerie. These vines were irrigated with sub-surface drip lines, one on either side of the vine row. Irrigation frequency was determined by the vineyard manager. Treated (PRD) vines received water to one side only at any one time and control to both sides. The PRD vines therefore received half the water of control vines. Water application rates were measured by water meters.
- Own-rooted Shiraz at Waikerie. These vines had been previously irrigated with overhead sprinklers and were converted to irrigation with full circle (control) or half circle (PRD) micro-jets. Water application rates were measured with meters and were such that vines received water at the same rate as the rest of the block (full control), half that amount but uniformly applied (half control), half that amount but applied as a PRD treatment (half PRD) or the full amount but applied as a PRD treatment (full PRD).
- Own-rooted Shiraz at the Waite campus. These vines were irrigated with drippers such that both controls and PRD vines received the same amount of water.

- Own-rooted Cabernet Sauvignon at the Waite campus. These vines were irrigated with drippers such that the controls received twice the water application rate as the PRD treated vines. Water application rates were measured with water meters.

In all these experiments the control vines received water at a rate within a range, which was commercially acceptable for the region.

B) Methods

The parameters, which were used to assess treatment effects varied from experiment to experiment and are detailed in the individual relevant reports detailed in Appendices 1,2 and 3. However, since one of the primary effects of exposing root tissues to drying soil is the production of ABA and the effect of this appears to be the stimulation of partial stomatal closure, a recurring measurement throughout this work has been stomatal conductance. This was measured with a diffusion porometer (Delta-T AP4). This instrument determines the time taken to raise the relative humidity in a chamber adpressed to the lower leaf surface by a preset amount and is an indirect measure of stomatal aperture and hence stomatal conductance. Another recurring measure was that of ABA, either in root tissues, leaf tissues or xylem sap. The reasoning behind the need to measure ABA is shown above. For all our measurements of ABA we have employed a stable isotope dilution analysis. This involves the addition of deuterium-labeled ABA (D-ABA) to the tissue at an early stage of extraction. The ratio between endogenous (native) ABA and the added internal standard is established at that point and is assumed to be reflect the *in vivo* ABA content, since losses up to that point would have been minimal. The extract was purified according to a protocol determined by the particular tissue, but usually involved solvent partitioning, HPLC purification and methylation. The ratio of ABA to D-ABA does not change throughout purification, since they are chemically identical. This ratio is finally determined by gas chromatography/mass spectrometry selected ion monitoring. The mass of ABA present in the original tissue per unit mass of tissue could then be determined by reference to a calibration curve which related ABA to D-ABA, and correction for mass of tissue extracted and mass of internal standard. This method was chosen in preference to any other because of its sensitivity and the fact that the ABA is unequivocally identified. A similar technique was developed for the analysis of cytokinins in grape tissues.

Another important variable, common to all experiments, was soil moisture. A variety of techniques were employed for the measurement of soil moisture. In pot experiments time domain

reflectometry (TDR) was employed using point measurements taken with a Trase Instruments (Santa Barbara, Ca) TDR meter. In some experiments the same instrument was used to log volumetric soil water content at 30min intervals. This instrument was also used for some field measurements using 600mm waveguides, although most field measurements were obtained using capacitance sensors (Sentek, Environmental Solutions, Adelaide) at depths of 100, 200, 300, 400, 500, 600, 700, 1000mm, logged at 30min intervals. Soil moisture was also determined in some experiments using a range of other loggable TDR-type sensors (Delta-T Theta probes, Campbell CS125). In all cases an attempt was made to relate volumetric soil water to soil suction for the particular soil type in question.

Fruit quality characteristics and yield components were measured according to Iland *et al.* (1996).

Detailed Results

Detailed results generated by these projects are presented in appendices 1, 2 and 3. These constitute the PhD thesis written by Peter Dry, the PhD thesis written by Manfred Stoll and published papers resulting from the projects respectively. The titles of the two theses are given below, followed by a summary or brief description of each.

RESPONSE OF GRAPEVINES TO PARTIAL DRYING OF THE ROOT SYSTEM

Summary

An excess of vegetative growth ('excess vigour') is detrimental in most vineyards. For grapevines in general, excess vigour has negative implications for fruit yield, disease control, costs of production and efficient water-use. For winegrapes in particular, the association between vigour and wine quality is important: excessively-vigorous vines tend to have dense, shaded canopies and grapes from shaded canopies tend to produce wines of lower quality. Therefore, control of excess vigour should result in a more open canopy with a concomitant improvement in the quality of fruit for winemaking. Withholding irrigation can form the basis of a useful management tool for improving water use efficiency and reducing vine vigour. However, difficulties may be experienced in obtaining the required degree of water stress, and yield may suffer in comparison with fully irrigated vines. The general hypothesis tested in this study was that: '*partial drying of the root system of grapevines will result in reduced vegetative growth with beneficial effects for fruit yield, fruit composition and water-use efficiency.*' The ideas which allowed the formulation of this hypothesis came from the previously published work of Loveys and Düring (1984), Loveys, 1992 and Gowing et al. (1990) which suggested that partial drying of the root system may give rise to non-hydraulic root-derived signals capable of changing leaf development and transpiration.

Experiments were initially conducted with container-grown grapevines (*Vitis vinifera* cultivars Chardonnay, Shiraz; *Vitis champini* cv. Ramsey; *Vitis berlandieri* x *Vitis riparia* cv. Kober 5BB; *Vitis berlandieri* x *Vitis rupestris* cv. Richter 110) with the root system divided between two containers (= 'split-root plants'). When half of the root system was slowly dried while the remaining half was kept well-watered (='half-drying'), both shoot growth rate (SGR), stomatal conductance (g_S) and photosynthetic rate (Pn) were significantly reduced relative to control plants

with both halves of the root system maintained in a well-watered state. The initial decrease in both SGR and gas exchange in response to half-drying coincided with the decrease in soil water content of the dried half of the root system. For half-dried plants, there was a relative increase in root development in moist soil layers, both in the 'wet' container as a whole or in the lower part of the 'dry' container. All species of grapevine appear to respond to half-drying of the root system, but genotype may affect the degree of response. The effect of half-drying was transient and both gas exchange and SGR returned to pre-treatment levels within one or two weeks, despite the fact that one half of the root system remained dry. Shoot function of half-dried, non-fruiting vines in the field also recovered in the absence of rewatering of the dried half of the root system, and as with pot experiments, recovery coincided with a slowing in the rate of soil drying on the non-irrigated side. This appears to be the first report of this phenomenon for any species.

During the course of this study, it became apparent that the benefits of a single brief period of shoot growth depression during the season were likely to be marginal for field vines: significant and long-term reduction in shoot growth would only be possible if the recovery of shoot growth was minimised. Therefore, the strategy of alternating the drying from one half of the root system to the other was tested on both non-fruiting potted vines and fruiting field vines with split-root systems. The aim was to minimise or prevent recovery of shoot function by timing the switch so that it occurred at, or just before, the start of recovery. This strategy was successful in both situations: for container-grown vines, alternation of drying of half of the root system every 11 days on average maintained shoot growth at a substantially lower rate than the well-watered controls and reduced components of shoot growth by up to 40% while average g_s was reduced by ca. 30% over a period of 66 days. There was no significant effect on total root weight per plant in response to treatment but the ratio of shoot weight to root weight was increased.

Field experiments were conducted with *Vitis vinifera* cv. Cabernet Sauvignon grafted to Ramsey at two sites near Adelaide, South Australia. One-year old rootlings with split-root systems were planted with each half of the root system on either side of a plastic membrane, buried to a depth of about 1.6m, which separated the root systems. Drip irrigation to each side of the plastic membrane was controlled independently. The 'treated' vines were maintained with one half of their root system, or the other, without irrigation at any one time: in practice this meant that one side was watered for 1-2 weeks while the other side was dried. The situation was then reversed so that the previously dried part of the root system was irrigated and the previously wetted part was dried. By comparison, both sides of the control vines were well-watered at all times. Soil

water content, measured with capacitance probes, was used to determine both the timing of irrigation events and the alternation of the irrigation on 'treated' vines. The irrigation strategy, termed 'partial root-zone drying' (PRD), was evaluated for three seasons at one site (University of Adelaide, Waite campus) and for one season at the other (Blewitt Springs, South Australia) on fruiting vines, commencing in their third growing season. For the last season at the Waite site, PRD was applied over the whole of the irrigation period; in all other cases, it was applied from fruit set to harvest. The timing of the alternation was successful in limiting the recovery of shoot growth: most indices of vegetative growth were reduced by up to 30 to 35% relative to the control. Lateral shoot growth was particularly responsive to PRD treatment: total lateral shoot length per main shoot was reduced by 50 to 66% relative to the control in the Waite experiment, due to a combination of fewer and shorter lateral shoots. Average stomatal conductance over the whole experimental period was reduced by 12 to 30%. There was a substantial reduction (up to 50%) in the amount of irrigation applied to PRD vines at both sites, without any detrimental effect on fruit yield. The reduction in vegetative growth in response to PRD significantly reduced canopy density and increased bunch exposure. Fruit quality was often significantly improved by PRD, with concentration of secondary metabolites (anthocyanins and phenolics) increased relative to the control: this was not associated with any significant change in berry weight, or any other yield component.

As for container-grown vines, both shoot growth and stomatal conductance were reduced in response to PRD without any significant effect on shoot water status (as indicated by leaf water potential Ψ_L), suggesting that a non-hydraulic signal is produced by roots in drying soil which affects shoot function. There was a positive linear relationship between stomatal conductance and shoot growth rate: this suggests that either the two physiological processes are influenced by the same non-hydraulic signal, or that SGR is influenced by a change in g_s, which is affected directly by the signal. The substantial reduction in vegetative growth in response to PRD was not associated with many of the characteristic symptoms of grapevine water stress. For example, shoot diameter, berry size and internode elongation were not greatly affected, nor was there any significant effect on Ψ_L. On the other hand, some of the responses to PRD were characteristic of water-stressed vines; however, the magnitude of the response and/or degree of expression of the symptoms were relatively less than with moderate to severe water stress. Furthermore, the reduction in SGR in response to partial drying was mainly due to a termination of node initiation rather than a reduction in the rate of internode elongation, whereas the latter component of SGR is more typically affected in response to water stress.

The amount of irrigation water applied to PRD-treated vines was substantially reduced relative to the control vines in all field experiments. For example, during the 1995/96 season in the Waite experiment, the control vines received 1.34 ML/ha while the PRD-treated vines received 0.7 ML/ha, ie. the amount of irrigation was effectively halved. The actual amount of irrigation water applied in all seasons to control vines in the Waite experiment was less than that applied to commercial vineyards in a nearby region with similar growing season rainfall and comparable yield per hectare. This study was commenced with the main aim of achieving vine balance through control of shoot vigour. However, the water conservation potential of the partial root-zone drying technique has proven to be more important from an environmental perspective.

The results from these experiments suggested the possibility of a non-hydraulic signal produced by roots in drying soil. For example, shoot function of half-dried plants recovered at the time when there were no more roots dried in the 'dry' container. Recovery may be best explained in terms of a positive signal, ie. when there is no further decline in water content and/or matric potential of the soil around the drying roots, there is a decrease in flux of the signal from roots to shoots and thus shoot function rapidly recovers. Also, both shoot growth and gas exchange were affected without any associated effect on shoot water status. Consequently, the role of ABA as a putative signal mediating this response was investigated. Stomatal conductance of partially-dried grapevines was negatively correlated with concentration of ABA in xylem sap ([X-ABA]). For grapevines grown in the field, g_s decreased coincidentally with the reduction in soil water content of the dried part of the root system and the increase in [X-ABA]; recovery of g_s coincided with no further soil drying and a decrease in [X-ABA]. Changes in [X-ABA] were not associated with any significant effect of partial drying on shoot water status as indicated by Ψ_L.

The results of this study allowed the original hypothesis to be accepted. The major findings were that:

a. The effect of half-drying was transient and both gas exchange and SGR returned to pre-treatment levels within one or two weeks, despite the fact that one half of the root system remained dry;
b. Prolonged inhibition of shoot growth was achieved by alternation of root-zone drying from one half of the root system to the other;

Vegetative growth and water-use of the grapevine were substantially reduced by partial root-zone drying without any detrimental effect on yield; at the same time, fruit quality was significantly improved.

EFFECTS OF PARTIAL ROOTZONE DRYING ON GRAPEVINE PHYSIOLOGY AND FRUIT QUALITY

Summary

The general hypothesis tested during this study was that *"partial drying of the root system gives rise to a change in the supply of root-derived chemical signals which determines changes in grapevine physiology and thereby affects fruit quality"*.

Experiments were conducted on either split root vines (*Vitis vinifera* cvs. Cabernet Sauvignon and Chardonnay) grown in pots of different sizes, on field grown vines which had either their root system divided by a plastic membrane (*Vitis vinifera* cv. Cabernet Sauvignon on own roots or grafted on Ramsey rootstocks) or conventional vines (*Vitis vinifera* cv. Cabernet Sauvignon, Shiraz and Riesling) with a commercial PRD irrigation design. The treatments were vines receiving water on both sides (control) and PRD treated vines, which only received water on one side at any time. The frequency of alternation of 'wet' and dry' sides was determined according to soil moisture and other influences such as rainfall and temperature. In most of the experiments the irrigation was alternated from one side to the other every 10 to 15 days. In some experiments the control vines received twice as much water as the PRD vines and in others both control and PRD vines received the same amount of water.

Studies on chemical signals have concentrated on ABA and cytokinins (CK). An improved stable isotope dilution protocol, which enables analysis of ABA and CK from the same tissue sample, was developed. Analysis of cytokinins was focused on zeatin (Z), zeatin riboside (ZR), zeatin glucoside (ZG) and iso pentenyl adenine (iP).

Roots are relatively inaccessible, particularly in field situations. To enable easier access to roots of field grown vines, split-root vines were planted in a trench which was filled with a sandy soil, thus creating a homogenous soil substrate and not restricting root growth but still allowing access to roots under field conditions. Analyses of root samples of field grown vines have shown that cytokinins and ABA may originate in roots and their concentrations can be substantially altered

during an irrigation cycle. Alternating soil water conditions showed that [ABA] in roots on the 'dry side' was significantly higher compared with the 'wet side'. Due to a reduction in CK on the 'dry side' of PRD-treated vines, the ratio between ABA and CK was substantially changed during an irrigation cycle.

The ABA levels in root tissue and in petiole xylem sap were negatively related to stomatal conductance. This provides further evidence that [ABA], mostly synthesized on the 'dry side' of the roots system, is responsible for the decline in stomatal conductance. Furthermore, a higher pH of petiole xylem sap was observed in PRD-treated vines which may also contribute to the regulation of stomatal conductance. Studies on stomatal patchiness showed that non-uniform stomatal aperture occurred in field grown vines under natural environmental conditions and was more abundant under PRD conditions. The proportion of patches with open stomata, determined by using a water infiltration technique, correlated positively with stomatal conductance.

Exogenous application of a synthetic cytokinin (benzyl adenine) can override the ABA-mediated stomatal closure resulting from PRD treatment, providing further evidence for the *in vivo* role of growth regulators in the control of stomatal conductance. The effect of benzyl adenine was transient, however, requiring repeated applications to sustain the reversal. Furthermore, CK may also be important in influencing grapevine growth. Following several weeks of repeated spray applications with benzyl adenine it was found that the development of lateral shoots in PRD-treated vines was enhanced compared to PRD-treated vines sprayed only with water. This supports the idea that the reduction in lateral shoot development seen in PRD vines is due to a reduced production of CKs (Dry *et al.*, 2000). By measuring shoot growth rate it was found that one common feature of PRD-treated vines, which were not sprayed with CK, was a reduction of lateral shoot growth. It can therefore be speculated that the reduction in lateral growth is related to a reduced delivery of cytokinins from roots. Zeatin and zeatin riboside concentration in shoot tips and subtending buds were reduced by the PRD treatment providing further evidence in support of this hypothesis.

Using stable isotopes of water and heat-pulse sap flow sensors water movement was traced from wet to dry roots in response to PRD. The redistribution of water from roots grown in a soil of high water potential to roots growing in a soil of low water potential may be of significance with regard to the movement of chemical signals and the control of water balance of roots. Measurement of the relative water content (RWC) of vine roots showed a slower decline of RWC

in the non-irrigated roots in response to PRD when compared with roots of vines which received no water, despite similar soil water content. The redistribution of water may help to sustain the response to PRD for longer periods and to support the activity of fine roots in drying soil Field vines, irrigated with PRD over several growing seasons, altered their root distribution relative to control. PRD caused a greater concentration of fine roots to grow in deeper soil layers and this may contribute to a better water stress avoidance. The effect on root growth may be augmented by the water movement and by the large effects of PRD on ABA and cytokinins, both of which are known to alter root growth.

The initial aim of the research which led to the development of PRD was to achieve better control of undesirable, excessive shoot and foliage growth which, from a viticultural point of view, has many disadvantages. Grapevine shoot growth rate responds very sensitively to drying soil conditions. The irrigation strategy used in the PRD experiments maintained a reduction of both main shoot and lateral shoot growth. In response to PRD a decrease in shoot growth rate and leaf area was observed. Much of the reduction in canopy biomass was due to a reduced leaf area associated with lateral shoots, thus influencing the canopy structure. This was one major factor improving the light penetration inside the canopy.

Control of vegetative vigour results in a better exposure of the bunch zone to light and, as a consequence, in improved grape quality. It is likely that changes in canopy density, as a result of PRD, is causing changes in fruit quality components. Anthocyanin pigments such as derivatives of delphinidin, cyanidin, petunidin and peonidin were more abundant in berries from PRD vines; by comparison the concentration of the major anthocyanin, malvidin, was reduced. When leaves were deliberately removed from more vigorous control vines, which improved bunch exposure, the differences in fruit composition were much reduced. This further supports the idea PRD improves fruit quality by affecting the canopy structure. Fruit quality consequently determines the quality, style and value of the finished wine. Wines have been produced from experimental vines under control and PRD irrigation and data on wine quality from commercial wineries are also available. Sensory evaluations have demonstrated that high wine quality from PRD-treated vineyards can be achieved without any yield-depressing effects.

In experiments where both control and PRD vines received the same amount of water many differences between the vines could be demonstrated. Under conditions where water supply was adequate for both treatments, the stomatal conductance and growth of the PRD vines was

restricted as had been observed in many previous experiments. However, as total water input was reduced, the stomatal conductance of PRD vines became greater than controls, suggesting that the latter were experiencing a degree of water stress, whereas the PRD vines were not. This may have been due to the greater depth of water penetration in the case of the PRD vines, where water was applied to a smaller surface area. This distinction between PRD and control vines, at very low water application rates, was also reflected in pruning weights, which were actually greater in PRD vines, as was crop yield. It was concluded that at low water application rates, the PRD vines were more resistant to water stress and made more efficient use of available water.

This study has provided evidence to support the original hypothesis. The major findings were:

a) Chemical signals, altered under PRD and mostly originating from roots, play an important role in the root to shoot communication in grapevines.

b) The movement of water from 'wet' to 'dry soil zones may help to sustain chemical signals as a response of grapevines to PRD and to support the activity of fine roots in drying soil.

c) A reduction in vegetative growth, in particular of lateral shoots, was sustained using PRD and this affected the canopy structure which, in turn due to a better light penetration into the canopy, improved the fruit quality.

d) The reduction in irrigation water applied did not have a detrimental effect on grape yield and thus the efficiency of water use was improved.

Published papers arising from the projects.

Refereed publications

During, H., Loveys, B. and Dry, P. 1996. Root signals affect water use efficiency and shoot growth. Proceedings of Workshop: Strategies to Optimise wine grape quality. Acta Hort. 427, 1-13.

Abstract

Under conditions of soil water deficiency plant water relations and chemical signals affect stomatal conductance of grapevine leaves. The abscisic acid (ABA) concentration is shown to increase in stressed roots and ABA is transported in xylem to the leaves where it reduces photosynthesis slightly, whereas transpiration is reduced more severely. In experiments with glasshouse-grown and outdoor-grown twin root vines this lead to an increase in water use efficiency. Root signals appear to inhibit vegetative growth as well: at a high leaf water status shoot growth, leaf number and leaf area are significantly reduced, increasing the fruit-to-pruning weight ratio. A model integrating hydraulic and chemical signaling in water stressed plants (Tardieu and Davies, Plant, Cell and Environment, 16, 341-349, 1993) is presented to interpret the results obtained with grapevines. It is concluded that chemical root-to-shoot communication is an integral part of adaptation processes leading to a reduction in water loss *before* the water status of grapevine declines.

Dry, P.R. and Loveys, B.R. 1998. Factors influencing grapevine vigour and the potential for control with partial rootzone. Australian Journal of Grape and Wine Research. 4:3, 140-148

Abstract

Maintaining the most cost-effective balance between vegetative and reproductive growth is one of the most testing problems in modern viticulture. Grapevines which exhibit excessive vegetative vigour are likely to produce less fruit of reduced quality, and vines with inadequate vigour may be compromised in terms of their yield potential. The requirement for techniques to better manage excess vigour has become more acute in recent years with the increased use of irrigation, adoption of vigour-imparting rootstocks and the expansion of vineyards into cooler geographic regions. A number of strategies may be used to control vine vigour. Chemical growth regulators, although capable of reducing shoot vigour, have never received acceptance due to undesirable side effects and concerns over chemical residues. Devigorating rootstocks, likewise, may have the potential to control vigour but none are in wide commercial use. Restriction of the

effective root volume, achieved through manipulation of planting densities, competition by cover crops, regulation of the soil volume wetted by drip irrigation or regulation of water availability can all achieve a degree of devigoration but often at the expense of fruit yield. Manipulation of vines through pruning and trellis design are probably the most commonly used methods for the control of shoot vigour. A high number of nodes retained at pruning combined with trellises which allow open canopies have proved successful. Advances in the understanding of the physiological factors influencing shoot growth and transpiration have allowed the development of novel irrigation methods for the control of vine vigour. These techniques exploit the fact that chemical signals originating in the roots are primarily responsible for the control of shoot growth and transpiration. Stimulation of the production of these signals through partial drying of the root system results in a significant reduction in shoot growth and water-use while maintaining crop yield and improving fruit quality. These new techniques, in combination with appropriate pruning and trellising methods, are providing new viticultural tools for controlling vine vigour and water-use efficiency.

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Dry, P.R. and Loveys, B.R. 1999. Grapevine shoot growth and stomatal conductance are reduced when part of the root system is dried. Vitis 38, 151-156

Abstract

Half-drying of the root system significantly reduced shoot growth of grapevines growing under controlled conditions. Changes in both shoot growth and stomatal conductance in response to half-drying took place in the absence of any change in shoot water status suggesting the involvement of a non-hydraulic signal in mediating this response. Recovery of both shoot growth rate and stomatal conductance appeared to start before rewatering of the dried half of the root system and at the time when the minimum soil water content of the dried half was reached. Shoot growth and stomatal conductance appear to be influenced by the same non-hydraulic signal but shoot growth appears to be more sensitive; on the other hand, shoot growth may be responding to changes in assimilation rate. This appears to be first report of a significant decrease in shoot growth in response to partial drying of the root system of grapevines.

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)

Abstract

A study of water and hormone relations in a range of horticultural plants, conducted over a number of years, resulted in the development of a model which described the physiological mechanisms operating in these crops which control transpiration. The model relied heavily on information relating stomatal function to the ability of the roots to supply abscisic acid via the transpiration stream. Published work by other groups, which utilised split root experimental systems also lent support to this idea. Using this knowledge, we have been able to develop a commercially viable irrigation system for grapevines which has been designed to reduce vegetative vigour and improve water use efficiency. We have called the technique Partial Rootzone Drying (PRD) and it requires that the roots are simultaneously exposed to both wet and dry zones. This results in the stimulation of some of the responses normally associated with water stress such as reduced vigour and transpiration but does not result in changes in plant water status. Crop yield is relatively unaffected. Implementation of the PRD technique is simple, requiring only that irrigation systems are modified to allow alternate wetting and drying of part of the rootzone. Commercial-scale trials are currently being evaluated and further studies on the physiological mechanisms involved in modifying water use efficiency in a range of horticultural plants is continuing.

Dry, P.R., Loveys, B.R.and Düring, H. (2000a) Partial drying of the root-zone of grape. 1. Transient changes in shoot growth and gas exchange. Vitis 39(1): 3-8.

Abstract

Split-root plants, where the root system was divided between two containers, were used to study the effect of partial drying of the root system on shoot growth and gas exchange of Shiraz (syn. Syrah) [*Vitis vinifera*], Kober 5BB [*Vitis berlandieri* x *Vitis riparia*] and 110 Richter [*Vitis berlandieri* x *Vitis rupestris*]. The initial decrease in both shoot growth rate and gas exchange in response to half-drying coincided with the decrease in soil water content of the dried half of the root system. Recovery of shoot function of half-dried grapevines occurred without any change in soil water content of the dried half of the root system, and coincided with the point at which there was no further decrease in soil water content. There was no effect of half-drying on Ψ_L at the times of greatest inhibition of

SGR and g_s relative to control; this suggests the involvement of a non-hydraulic signal originating from the roots in drying soil. Changes in stomatal conductance in response to half-drying were strongly correlated with shoot growth rate.

Dry, P.R., Loveys, B.R.and Düring, H. (2000b) Partial drying of the root-zone of grape. 2. Changes in the pattern of root development. Vitis 39(1): 9-12.

Abstract:

Split-root plants, where the root system was divided between two containers, were used to study the effect of partial drying of the root system on gas exchange and root growth of 110 Richter [*Vitis berlandieri* x *Vitis rupestris*]. The initial decrease in gas exchange in response to half-drying coincided with the decrease in soil water content of the dried half of the root system. Recovery of gas exchange of half-dried grapevines occurred without any further change in soil water content of the dried half of the root system, and coincided with the point at which there was no further decrease in soil water content. For half-dried plants, there was a relative increase in root development in moist soil layers, both in the 'wet' container as a whole or in the lower part of the 'dry' container. Recovery of gas exchange of half-dried plants occurred at the time when there were no more roots dried in the 'dry' container. We propose that, for half-dried plants, the part of the root system in dry soil can survive because water moves from 'wet' roots to 'dry' roots.

Manfred Stoll, Brian Loveys and Peter Dry (2000). Hormonal changes induced by partial rootzone drying of irrigated grapevine. Journal of Experimental Botany (In Press)

Abstract

Partial rootzone drying (PRD) is a new irrigation technique which improves the water use efficiency (by up to 50%) of winegrape production without significant crop reduction. The technique was developed on the basis of knowledge of the mechanisms controlling transpiration and requires that approximately half of the root system is always maintained in a dry or drying state while the remainder of the root system is irrigated. The wetted and dried sides of the root system are alternated on a 10 to 14d cycle. Abscisic acid (ABA) concentration in the drying roots increases 10-fold (Loveys *et al.* 2000) but ABA concentration in leaves of grapevines under PRD only increased by 60% compared with a fully irrigated control. Stomatal conductance of vines under PRD irrigation was significantly reduced when compared with vines receiving water to the entire root system. Grapevines from which water was withheld from the entire root system, on the other hand, show a similar reduction in stomatal conductance but leaf ABA increased 5-fold compared with the fully irrigated control. PRD results in

increased xylem sap ABA concentration and increased xylem sap pH, both of which are likely to result in a reduction in stomatal conductance. In addition, there was a reduction in zeatin and zeatin-riboside concentrations in roots, shoot tips and buds of 60, 50 and 70% respectively, and this may contribute to reduction in shoot growth and intensified apical dominance of vines under PRD irrigation. There is a nocturnal net flux of water from wetter roots to the roots in dry soil and this may assist in the distribution of chemical signals necessary to sustain the PRD effect. It was concluded that a major effect of PRD is the production of chemical signals in drying roots which are transported to the leaves where they bring about a reduction in stomatal conductance.

Non-refereed publications

Loveys, B.R. and Dry, P. 1996. Improving grapevine water use efficiency. GWRDC Seminar series: Water for viticulture: optimising the resource.

Dry, P., Loveys, B.R., 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., Grant, J., Dry, P. and McCarthy, M., 1997. Progress in the development of partial rootzone drying. Australian Grapegrower and Winemaker, July 1997

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

Dry, P.R., Loveys, B.R., Iland, P.G., Botting, D.G., McCarthy, M.G. and Stoll, M. 1999. Vine manipulation to meet fruit specifications. 10th Australian Wine Industry Technical Conference. pp208-214

Stoll, M., Dry, P.R, Loveys, B.R, Stewart, D. and McCarthy, M.G. (2000)
Partial rootzone drying: effects on root distribution and commercial application of a new irrigation technique. Aust NZ Wine Industry J. 15(2): 74-77.

Dry, P.R., Loveys, B.R., Stoll, M., Stewart, D., and McCarthy, M.G. (2000) Partial rootzone drying - an update. Aust Grapegrower and Winemaker 438a: 35-39

Wiley, S. 1997. Trialling New Techniques to Grow Better Fruit. The Austyralian Grapegrower and Winemaker, May 1997 pp 24-29

Hayes, P. 1998. GWRDC projects are Relevant and Results-Oriented. Australian Viticulture, September/October 1998, pp 6-11

Conference Presentations and Posters

Dry, PR and Loveys, BR (1995) The use of partial root-zone drying to control grapevine vigour. Proceedings of Spring School in Grapes and Wine, Lincoln University, New Zealand, September, 1995: 38-40.

Using Plant Physiology to Improve the Water Use Efficiency of Horticultural Crops
Brian Loveys, Peter Dry, Michael McCarthy and Manfred Stoll
Third International Symposium on Irrigation of Horticultural Crops
Lisbon, June 28th to July 2nd 1999

Brian Loveys, Manfred Stoll, and Peter Dry
Improving the Water Use Efficiency of Irrigated Horticultural Plants
Invited pare at the: XVI International Botanical Congress, St Louis, 1999

Stoll, M., Dry P.R., Loveys, B.R.. Stewart D,. and McCarthy M.G. 2000. Partial Rootzone Drying: effects on root distribution and commercial application of a new irrigation technique. Proceedings of the 5th international Symposium on Cool Climate Viticulture & Oenology Melbourne

Manfred Stoll. Brian Loveys, Peter Dry and Michael McCarthy, 1999
Partial Rootzone Drying: A New Irrigation Technique for Grapevines
Poster: Tenth Australian Wine Industry Technical Conference
(best poster award)

Brian Loveys, Peter Dry and Manfred Stoll, 1999
Partial Rootzone Drying: Grape Quality and Water Use Efficiency Improvements
Workshop presentation: Tenth Australian Wine Industry Technical Conference

Brian Loveys, Peter Dry, Manfred Stoll and Michael McCarthy 1998
Plant Physiology and the Development of Partial Rootzone Drying, A New Irrigation Technique For Grapevines.

Dry, P.R., Loveys, B.R. and Stoll, M. 1998
Partial Rootzone Drying: Short and Long Term Physiological Responses to Soil Drying
ASPP Symposium: Commercial Outcomes of Plant Physiology Research

Dry, P.R., Loveys, B.R., Stoll, M. (1998) Partial rootzone drying: short- and long-term physiological responses to soil drying. Paper presented at Aust Society for Biochem. and Molecular Biology/Aust Society of Plant Physiologists Combined Conf., Adelaide, Sept. 1998.

Dry, P.R. (1999) Flavour manipulation in the vineyard. Annual Meeting, Virginia State Horticultural Society, 11-13 January, 1999, Roanoke VA

Brian Loveys. Water Efficiency in Grape and Citrus Production. Paper presented at a seminar "Water – The Ultimate Resource", The Earthwatch Institute, Cape Schanck, June 2000

M.G. McCarthy, B.R. Loveys, P.R. Dry, & M. Stoll. Partial Rootzone Drying, Applications for NZ Viticulture Proceedings 5th Annual Romeo Bragato Conference 26-29 August 1999 Auckland New Zealand.

M.G. McCarthy, B.R. Loveys, P.R. Dry, , & M. Stoll. Partial Rootzone Drying. Workshop presentation. Irrigation Association of Australia 2000 National Conference and Exhibition 23-25 May 2000 Melbourne

M.G. McCarthy, B.R. Loveys, P.R. Dry, & M. Stoll. Partial Rootzone Drying. Netafim USA Workshop presentations Paso Robles & Lodi, California USA December 4-5 1999

M.G. McCarthy. The improvement of the quality of wines due to irrigation :Australian Experiences. VII Latin-American Congress of Viticulture & Oenology, Mendoza, Argentina November 30 1999.

Awards

Inaugural Wine Industry Innovation and Achievement Award 1997
Brian Loveys
SA Wine and Brandy Corporation and Malaysia Airlines

Wine Industry Innovation and Achievement Award 1998
Peter Dry
SA Wine and Brandy Corporation and Malaysia Airlines

Discussion of results including an analysis of research outcomes compared with the objectives

The primary objective of these projects was to devise an irrigation technique to reduce the vigour of grapevines while maintaining crop yield and quality. The technique had to be simple, cheap to install and operate and be applicable to both new and mature vines. The PRD treatment has achieved these objectives, but as our early experience with the technique grew, it became obvious that the improvement in water use efficiency, which accompanied PRD, was in fact the result which was likely to have the most impact on the expanding viticultural industry in the late 1990's. The potential for PRD to influence winegrape quality has also been a significant factor in the success of this technique. It has been about four years since the first publications appeared describing our initial research (eg. Loveys and Dry, 1996; Dry et al. 1996; Loveys et al. 1997) and since then many commercial trials have been established to test the applicability of PRD in various situations. We may not be aware of the true extent of these trials because they have been established without reference to us. There has also been considerable interest in PRD from overseas and it is possible that the largest area of vines under PRD is in California where a 65ha property has been equipped with PRD irrigation. We are also aware of smaller sites in New Zealand and South Africa. Interest in PRD has also been demonstrated in Europe where the potential benefits of PRD technology have recently been recognised by the European Union's fifth framework programme which has awarded the Environmental Physiology group at Lancaster University £700K to co-ordinate and participate in scientifically evaluating and implementing PRD technology into the European Union and other Mediterranean basin countries. This project will probably constitute the largest focus of activity in evaluating and implementing PRD in the world. It would probably be true to say that PRD is now moving from the experimental to the implementation stage.

The background to the study
(the following text is an adaptation of the Discussion from Peter Dry's thesis)

This study had its origins in the observations of Gowing *et al.* (1990) and others that drying one half of the root system of split-root plants, while maintaining the other half wet, could reduce various components of shoot growth of woody plants, without any associated hydraulic change. Loveys (1991) first proposed the potential of partial root-zone drying for vigour control in grapevines in the context of a discussion on root-derived chemical signals such as ABA. Reduction of grapevine vigour had been successfully achieved by various deficit irrigation

strategies but this was usually associated with a significant reduction in leaf water potential and a negative effect on fruit yield, mainly due to an effect on berry weight (Williams and Matthews 1990). Because of the possible nexus between the negative effect on yield and the perturbation of plant water status, it was thought that a 'partial drying' of the root system whereby there is a reduction in shoot growth, with no associated change in plant water status, may have potential for vigour control in grapevines without a detrimental effect on yield. At the same time, there was a possibility of an improvement in the quality of fruit for winemaking because vigour reduction should lead to more open canopy with better bunch exposure, and the relationship between canopy microclimate and wine quality had been well documented (Smart 1992).

The grapevine was a good candidate for study, not only for the reasons outlined above, but also because experiments with split-root grapevines had shown that half-drying of the root system caused a reduction in stomatal conductance without any associated hydraulic change (Düring 1990; H. Düring and B.R.Loveys, unpublished data). At the same time, an increase in the bulk leaf concentration of ABA in response to half-drying (B.R. Loveys and H. Düring, unpublished data) suggested the involvement of ABA as a putative root signal.

Development of the PRD strategy

These initial experiments successfully demonstrated, for the first time, that half-drying of the root system could significantly reduce shoot growth of grapevines growing under controlled conditions. Furthermore, changes in both shoot growth and stomatal conductance in response to half-drying occurred in the absence of any change in shoot water status suggesting the involvement of a non-hydraulic signal in mediating this response. Shoot growth of half-dried grapevines recovered without any change in soil water content of the dried half of the root system, coincidental with the point at which there was no further decrease in soil water content: this was confirmed by experiments with non-fruiting vines in pots and in the field. It appears to be the first report of this phenomenon for any species.

A single brief period of shoot growth depression during the season is likely to have a marginal benefit for field vines. A significant and long-term reduction in shoot growth is possible if the recovery of shoot growth is minimised. Therefore, the strategy of alternating the irrigation from one half of the root system to the other was tested on both non-fruiting potted vines and fruiting field vines with split-root systems. This strategy was successful in both situations: for potted

vines, alternation of irrigation from one half of the root system to the other every 11 days on average maintained shoot growth at a substantially lower rate than the well-watered control and reduced components of shoot growth by up to 40%. Similarly, with field vines, vegetative growth was substantially reduced. The alternation of irrigation from one side of the vine to the other was timed so that it coincided with the point at which there was no further decrease in SWC on the 'dry' side of the vine: this was successful in limiting the recovery of shoot growth. Furthermore, over three seasons, this strategy resulted in a substantial reduction (up to 50%) in the amount of irrigation applied, without any detrimental effect on fruit yield, but with the bonus of a significant improvement in fruit quality. The reduction in vegetative growth in response to this treatment significantly reduced canopy density and increased bunch exposure.
This strategy has been termed 'partial root-zone drying' rather than 'partial root-zone wetting' because it is the 'drying' which is the functional component of this strategy, ie. the plant appears to be responding to that part of the root system in drying soil. The aim of the strategy is to maintain part of the root system in a drying phase at all times in order to maximise production of the putative signal, so that recovery of shoot growth is minimised.

Leaf water potential

One of the most consistent observations in these experiments was that the changes in shoot growth and gas exchange in response to soil drying were not associated with any significant changes in shoot water status as indicated by Ψ_L. This was the case for both field vines and vines in a controlled environment. Leaf water potential is the most commonly used indicator of shoot water status and some authors have attempted to quantify the degree of water stress in terms of absolute values of Ψ_L (Hsiao 1973). Furthermore, the measurement of Ψ_L has been recommended for irrigation strategies which aim to manipulate grapevine shoot growth (Hardie and Martin 1990; Goodwin and Jerie 1992). However, substantial reductions in shoot growth were achieved with PRD in this study in the absence of any significant change in Ψ_L. Also, McCarthy (1997) found that Ψ_L and soil water status were not correlated in a deficit irrigation experiment. Therefore, the validity of the use of Ψ_L for irrigation scheduling must be questioned.

Symptoms of water stress

The substantial reduction in vegetative growth in response to partial drying was not associated with many of the characteristic symptoms of grapevine water stress, as described by Smart and Coombe (1983) and Williams and Matthews (1990). For example, shoot diameter, berry size and

internode elongation were not greatly affected and these are known to be very sensitive to water deficits. Also, there was no tendril necrosis, abscission of mature leaves or change in leaf colour, nor was there any effect on Ψ_L. On the other hand, some of the responses to partial drying were characteristic of water-stressed vines; however, the magnitude of the response and/or degree of expression of the symptoms were relatively less than with moderate to severe water stress. For example, stomatal conductance was only reduced by 20 to 35% with potted vines and by 12 to 30% with field vines in response to partial drying whereas stomata may almost fully close with severe water stress. The situation with shoot growth rate was similar with a reduction of 30 to 50% for potted vines and 18 to 30% for field vines in response to partial drying whereas severe stress may reduce SGR by 90% relative to the control. Furthermore, the reduction in SGR in response to partial drying was mainly due to a termination of node initiation rather than a reduction in the rate of internode elongation, whereas the latter component of SGR is more typically affected in response to water stress.

The fact that neither expansive growth nor shoot water status were affected significantly by PRD may be important in this context. Expansive growth is considered to be one of the most sensitive of plant processes to development of water deficits and directly affected by shoot water potential (Bradford and Hsiao 1982). Traditionally, effects of low water potential on expansive growth have been attributed to turgor loss but when measurements have been made in regions where cell elongation taking place, turgor often shows little change even though elongation is significantly reduced (Sharp and Davies 1989).

The evidence for ABA as the signal which mediates the response of shoot growth to PRD

The determination of the nature of the putative signal produced in response to partial drying of the root system, and the mechanism by which the signal regulates shoot development and stomatal behaviour, was not one of the main objectives of this study. However, sufficient evidence has been accumulated to suggest that: a) the signal is non-hydraulic; b) the signal is positive in nature; and c) ABA is a likely candidate as the signal.

A chemical signal such as ABA provides a sensitive means of detecting small changes in water status of the soil in the vicinity of each individual root tip (Zhang and Davies 1991). It appears that the grapevine is one of those plants for which the drying of a relatively small proportion of the root system is sufficient to generate a signal which will influence shoot function, even though the bulk of the root system may be in soil of high water content. This is not the case for all plant

species: for example, Gallardo *et al.* (1994) found that it was necessary to dry out the whole of the root system of lupin in order to significantly reduce shoot growth rate.

It may be argued that, even if the signal is produced by drying roots, the flux of the signal from 'dry' roots to shoots will decrease in proportion to the reduced transpirational flow from 'dry' roots as the soil dries. However, transpirational flow from 'dry' roots may be possible due to rehydration of dry roots by 'wet' roots during the night (Saab and Sharp 1989) and this has been confirmed by the results in this study. It is likely that flow from 'dry' roots will be highest in the morning; Jackson *et al.* (1995) suggested that this was the explanation for the relatively high flux of ABA in the morning in droughted conifer seedlings, and they proposed that stomata respond to a 'morning dose' of ABA. Labelled ABA moved from 'dry' roots to the shoots of split-root, half-dried grapevines within 10 hours of application at a time when the water content of soil around the 'dry' roots was relatively low (B. R. Loveys, unpublished data) and we have shown that deuterium-enriched water moves from wet to dry roots once that soil moisture potential around the dry roots falls below about –100kPa.

Recovery of shoot function

Shoot function of half-dried grapevines recovered, relative to fully-watered control vines, without any change in soil water content of the dried half of the root system. This recovery coincided with the point at which there was no further decrease in soil water content, for vines grown in containers and in the field. Recovery of shoot function coincided with an reduction in xylem ABA [X-ABA] for both container and field vines and a reduction in root ABA concentration (Dry *et al.* 1996; Loveys et al. 2000).

The observation that shoot growth could recover without rehydration of the dried half of the root system was important in this study for several reasons. Firstly, it lead to the development of the PRD strategy (with alternation of drying from one part of the root system to the other) because it became necessary to find a means of preventing this recovery if there was to be a significant reduction of shoot growth in the long-term. Secondly, it provided additional evidence for a positive non-hydraulic signal produced by drying roots: if the signal was negative in nature, there would be no recovery because the supply of the signal would not change so long as the soil around the roots remained dry. Recovery can be explained in terms of a positive signal, ie. when there is no further decline in water content and/or matric potential of the soil around the drying roots, there is a decrease in flux of the signal from roots to shoots and thus shoot function rapidly

recovers. However, it is more difficult to explain the recovery in terms of a negative signal such as cytokinins. One possibility is an increased transport of cytokinins to shoots as a result of a stimulation of root activity in the 'wet' part of the root-zone during the late stages of a drying cycle. Davies and Zhang (1991) suggested that "*...positive and negative signals may combine and interact in their effects on shoot processes, perhaps with positive signals dominating in plants in moist soil and negative signals increasing in importance as the soil dries further.*"

The observation that [X-ABA] decreased coincidentally with recovery of shoot function supports the hypothesis that ABA is a positive signal. There are at least two possible explanations to account for this decrease in [X-ABA]:

a) Signal production is maintained in dry roots but transpirational flow from dry roots is low so the flux of the signal from roots to shoots is also low. Khalil and Grace (1993) favour this hypothesis because the 'dry' roots were still accumulating ABA on Day 7 in their experiment. However, ABA content of 'dry' grapevine roots has been found to decrease coincidentally with the recovery of shoot function (Dry *et al.* 1995; Loveys et al. 2000).

b) There are no more fine roots being dried; therefore, production of ABA by that part of the root system ceases. Transpirational flow of water from dry roots to shoots is maintained: for example, day-time sap flow in the 'dry' half of the root system was reduced by no more than ca. 50% relative to the 'wet' half. Therefore, the net result is a diminished export of the signal from roots to shoots. Also, roots in a container of dry soil will remain alive for a relatively long time, so long as they are connected to roots in a container of wet soil, which suggests that the 'dry' roots are supplied with water by the 'wet' roots.

Response to partial drying

The vegetative growth of field vines was substantially reduced in response to partial drying. Most indices of vegetative growth were reduced by up to 30 to 35% relative to the control but lateral shoot growth was the most responsive index of all. Total lateral shoot length per main shoot was reduced by 50 to 66% relative to the control in the Waite experiment, due to a combination of fewer (-28 to -47%) and shorter (-5 to -35%) lateral shoots. It is difficult to draw any firm conclusions about the relative effect of either timing or duration of PRD treatment on these components because there were differences in shoot number per vine, shoot positioning and shoot trimming between seasons, all of which would have influenced the degree of lateral shoot development. The regulation of lateral shoot growth has been a relatively neglected area of viticultural research and is worthy of greater attention, not only because it is an important

determinant of canopy density (Smart 1992) but also because there is the possibility of a direct relationship between lateral shoot development and fruit composition (Jackson and Lombard 1993); however, the mechanism of such a relationship is not known. Paclobutrazol sprayed on hedged Riesling grapevines in the field significantly reduced lateral shoot development (Reynolds et al., 1992); fruit of treated vines had higher TSS than controls and the authors suggested that this response may have been due in part to a reduction in the proportion of photosynthate partitioned to lateral shoots.

In the context of this study, further research is required to determine the mechanism by which a non-hydraulic signal from drying roots may influence lateral shoot development. A possible role for ABA as an inhibitor of lateral bud outgrowth was suggested by Phillips (1975). ABA levels were 50 to 250 times greater in non-growing than growing lateral buds of *Xanthium strumarium* (Tucker and Mansfield 1972, 1973; cited in Phillips 1975); these authors suggested that the high concentration of ABA in lateral buds prevented them from responding to the high levels of endogenous cytokinins in inhibited buds.

The ability of grapevines to regulate leaf area, in response to soil water status, by means of lateral shoot growth may have evolved as a drought-tolerating mechanism. The reduction in main leaf area in response to drought is not reversible in the case of the grapevine because it is associated with termination of main shoot growth; however, lateral shoots may commence or continue growth after main shoots have ceased to grow, in response to favourable soil conditions. Furthermore, because the grapevine has a large number of 'reserve' axillary buds (Mullins *et al.* 1992), several generations of lateral shoots are possible during a single growing season, thus allowing the plant to maximise its carbon-fixing capacity during favourable periods. Therefore, because lateral leaf area component is effectively reversible, it is logical that lateral shoot growth would be particularly responsive to a signal from drying roots.

The drought-tolerating strategy of the grapevine is not based entirely on leaf area control because stomata may also close partially in response to mild soil water deficits. However, shoot growth appeared to respond more rapidly and to a greater degree than stomatal conductance when grapevines were subjected to PRD in this study. The partial closure of stomata in response to PRD may be beneficial because plant water-use efficiency is increased (Düring 1992).

The magnitude of the reduction in vegetative growth of fruiting vines in the field in response to PRD was as great as that which has been achieved in deficit irrigation experiments with a similar reduction in the amount of water applied or similar difference in replacement of Class A Pan evaporation, eg. McCarthy and Staniford (1984); Matthews and Anderson (1988,1989); Goodwin and Jerie (1992); Poni *et al.* (1993); McCarthy (1997). Also, the magnitude of the reduction in vegetative growth was sufficiently large so as to significantly alter the canopy microclimate and thus affect fruit composition. At the start of this study, a slight reduction in yield in response to a substantial decrease in amount of irrigation water was considered to be acceptable so long as there was a concomitant increase in fruit quality. However, I did not anticipate that the amount of irrigation could be halved without any yield penalty at all.

Why does PRD cause a substantial reduction in vegetative growth without any yield penalty? One obvious explanation is that as vegetative growth is inhibited, an increased proportion of carbohydrate is partitioned to reproductive growth. However, this assumes that the total amount of carbon fixed by PRD-treated vines was similar to control vines: it may have been less due to the reduction in leaf area (although the leaves on PRD vines may have been more efficient on average because there would have been a smaller proportion of shaded leaves). Also, the relatively small decrease in stomatal conductance (12 - 30% for field vines) would have had a some effect on carbon fixation. However, Grimes and Williams (1990) found that a reduction in midday g_s of the order of 20% relative to maximum g_s had no effect on the yield of field vines in an irrigation experiment. There is also the possibility that an increased proportion of carbohydrate is partitioned to the roots in response to a reduction in vegetative growth. Root biomass of plants in drying soil may increase relative to well-watered controls and roots may grow deeper (Sharp and Davies 1989). Therefore, one of the potential benefits of PRD may be a stimulation of root growth, resulting in a deeper, more exploitative root system; this may or may not be an advantage, depending on the viticultural situation. There is obviously a need for further research on the effect of PRD on carbon partitioning.

It is likely that one of the keys to the maintenance of fruit yield with PRD, despite the substantial reduction in the amount of irrigation, was the maintenance of berry weight. In deficit irrigation studies, berry weight is usually the most 'responsive' yield component (Williams and Matthews 1990). In this study, the amount of irrigation with PRD was halved; by comparison, a reduction of this magnitude with conventional irrigation would typically result in much smaller berries, particularly because of the timing of the deficit. The timing of PRD in all seasons was such that it

always covered the period between flowering and veraison: berry weight is most sensitive to water deficits during the period immediately after flowering and becomes increasingly resistant thereafter. McCarthy (1997) found that Shiraz berries were two and three times as susceptible to water stress during the post-flowering period as during the pre-veraison and post-veraison periods respectively. Why was there no change in berry weight in response to PRD? Based on the results from deficit irrigation studies, it appears that a relatively large degree of plant and soil water tension must develop before berry weight is affected (as indicated by Ψ_L and soil matric potential respectively). For example, Goodwin and Jerie (1992) found that Chardonnay berry weight was only reduced if the average matric potential of the soil in the root-zone decreased below -300 kPa post-flowering. Similarly, McCarthy (1997) suggested that Shiraz berry weight will only be reduced if the average soil matric potential of the root-zone decreases to -450 kPa or less in the post-flowering period and to -1000 kPa post-veraison. In view of this, the lack of effect of PRD on berry weight may be attributed to the fact that at least half of the root zone of the field vines, ie. the 'wet' side, was maintained at a relatively high level for the whole of the period of berry development.

The other yield components which could have been potentially affected in response to PRD were bunch number per vine and berry number per bunch (fruit set). The former is a consequence of both shoot number per vine and bunch number per shoot (fruitfulness). Shoot number per vine is mainly a function of pruning level and this was the same for both treatments. Both fruit set and fruitfulness are only responsive to severe water stress (Williams and Matthews 1990) and there was no detrimental effect of PRD treatment on these parameters. On the contrary, fruit set and fruitfulness of PRD-treated vines might reasonably be expected to increase in the long-term as a consequence of reduced shoot vigour and improved radiation microclimate of the renewal zone.

Shoot growth and stomatal function recover before the plant-available soil water on the 'dry' side of the vine is completely depleted

In these projects, inhibition of shoot growth appeared to take place in response to a relatively small decrease in matric potential below that at field capacity. If this is the case, this observation would concur with those of Ebel *et al.* (1994) for plants in general, and with van Zyl and Kennedy (1983), Christensen (1975), Hardie and Martin (1990) and others with reference to grapevines. When the soil matric potential decreases below -60 kPa, it becomes increasingly difficult for roots in that soil to extract water (Mitchell and Goodwin 1996). For partially dried plants, it is likely that the total water requirement of the plant becomes increasingly supplied by

the roots in 'wet' soil until a point is reached at which the plant becomes completely dependent on those 'wet' roots. This stage is reached before the plant-available water (between -10 and -1500kPa) has been fully extracted by the 'dry' roots, ie. when the soil of the 'dry' root-zone is at a relatively high matric potential. For example, in the pot experiments conducted on the Waite campus, SWC of the 'dry' pot of half-dried plants did not ever decrease lower than 7% in the soil mix used for those experiments: this represents a matric potential of ca. -100 kPa. Similarly, for field vines, the SWC at 20 and 40cm depths on the 'dry' side of the vine did not decrease lower than 22 and 19% respectively, ie. a matric potential range of -100 to -77 kPa. By comparison, much lower matric potentials (-1,000 kPa or less) have been recorded in irrigation experiments where the whole root-zone has been dried and vines have been severely stressed (McCarthy 1997). Therefore, recovery of shoot function appears to take place when the soil of the 'dry' part of the root-zone has a relatively high matric potential, which is probably not much lower than the matric potential at which shoot growth is inhibited in the first instance.

The previous discussion was written with the assumption that non-hydraulic signals are produced by drying roots in response to changes in soil water potential rather than soil water content. Although this may seem to be a reasonable assumption, it was not one of the aims of this study to investigate the nature of the relationship between soil water potential and vine response. This is an area for future research, not only in the context of partial drying but also in terms of the general response of grapevines to water stress.

There is also a need for further research to determine the most appropriate indicators for irrigation scheduling when the PRD strategy is employed. If measurements of soil water status (either volumetric or matric potential) are used, which part of the root-zone is most appropriate? On the other hand, should the timing be based on plant indicators because they are able to integrate the effects of the 'wet' and 'dry' parts of the root systems? Hardie and Martin (1990) recommended the use of de-fruited shoots on field vines for the implementation of their irrigation strategy, presumably because such shoots are more sensitive to changes in soil water status than shoots with bunches. Measurements of the rate of shoot growth every two or three days on several de-fruited vines in a vineyard may provide an economical indication of the recovery of shoot growth and thus be used to schedule the alternation of drying from one side to the other.

Reduction in the amount of irrigation with PRD

The amount of irrigation water applied to PRD-treated vines was substantially reduced relative to the control vines in all field experiments. For example, during the 1995/96 season in the Waite experiment, the control vines received 1.34 ML/ha while the PRD-treated vines received 0.7 ML/ha, ie. the amount of irrigation was effectively halved. It could be argued that a reduction of similar magnitude, but applied by conventional means (ie. 0.7 ML/ha, with both sides irrigated as for the control), would have produced a similar reduction in vegetative growth as achieved in this study. While the results from other irrigation deficit experiments would tend to support that proposition with respect to vegetative growth, a reduction in the amount of irrigation water of this magnitude in such experiments have, to my knowledge, always been associated with significant reductions in fruit yield. For example, a 50% reduction in the amount of water applied resulted in a decrease in yield of the order of 15 to 50% (Freeman 1984; McCarthy and Staniford 1984; Matthews and Anderson 1988,1989; Grimes and Williams 1990; Goodwin and Jerie 1992; Poni *et al.* 1993; McCarthy 1997). It is difficult to make exact comparisons with other experiments because it is not always possible to determine if the controls in those experiments had been irrigated at an optimal level: if the controls had been over-irrigated then a halving of the amount of water applied may have had no effect on yield. For example, Freeman (1984) examined the relationship between fruit yield and crop factor (= proportion of Class A Pan evaporation applied as irrigation, plus rainfall) in a long-term field experiment with Shiraz grapevines. There was no yield response for a change in crop factor over the range from 0.9 to 0.3; however, a reduction in irrigation amount equivalent to a change in crop factor from 0.3 to 0.15 resulted in a halving of yield. The control vines in the Waite experiment were certainly not over-irrigated: the actual amount of irrigation water applied in all seasons was less than that applied to commercial vineyards in a nearby region with similar growing season rainfall and comparable yield per hectare. Furthermore, the calculated crop factors for the irrigation period in 1995/96 for the Waite experiment were 0.26 and 0.18 for control and PRD-treated vines respectively. By comparison, in the Shiraz irrigation experiment reported in McCarthy and Staniford (1984), the crop factor calculated for the control vines was 0.36; a reduction in irrigation amount equivalent to a change in crop factor from 0.36 to 0.22 resulted in 22% lower yield.

Therefore, it is highly likely that, had a third treatment been included with the same amount of water per vine as PRD-treated vines, ie. 0.7 ML/ha in 1995/96, but applied both sides of the vine as for the control vines, the yield of that treatment would have been significantly reduced relative to both PRD-treated and control vines. This prediction was supported by subsequent experiments

which showed that at low water application rates, PRD vines actually had higher yields and biomass accumulation (as measured by pruning weights) than control vines when both treatments received the same amount of water.

This study was commenced with the main aim of achieving vine balance through control of shoot vigour. However, the water conservation potential of the partial root-zone drying technique may prove to be more important from an environmental perspective. Irrigated horticultural crops occupy approximately 250,000ha in Australia, and major problems are likely to be encountered in sustaining water supply to these crops in future, particularly with the current expansion of vineyards. Furthermore, current irrigation practice can be damaging to the environment through depletion of ground water reserves, rising water tables, and salinity and nutrient leaching. There is potential for this new technique to be refined and developed for a wide range of horticultural crops, thus leading to major reductions in water use.

The Role of Cytokinins

The experiments in these projects have tended to emphasise the potential role of ABA as a root signal. However, the fact that lateral shoot growth was one of the major components of shoot growth affected in response to PRD suggests that the potential role of cytokinins should also be investigated and experiments carried out in CSH95-3 showed that levels of zeatin and zeatin-riboside were reduced in roots during the PRD drying cycle. Furthermore, levels of these cytokinins in shoot tips and subtending buds were also reduced in PRD vines.

Cytokinins are known to have an important role in the promotion of budburst and lateral branching (Phillips 1975). Intact plants may respond to applied cytokinin by formation of new buds (Little 1985) and burst of lateral buds may be induced by cytokinin application ((Phillips 1975, Li and Bangerth 1992). Various studies have shown a correlation between endogenous cytokinin levels and bud development. For example, the concentration of cytokinins in xylem increases just before and during budburst of apple (Tromp and Ovaa 1990) and coincides with outgrowth of axillary buds in rose plants (Dieleman et al. 1997). The level of cytokinins in buds increased during the period of active bud development of *Picea abies* (Chen et al. 1996) and the induction of new lateral bud primordia in *Pinus radiata* (Taylor et al. 1984). The level of cytokinins appears to play an important role in the establishment of differences in bud size and thereby architecture of the tree crown of *Picea abies* (Bollmark et al. 1995).

It is widely accepted that cytokinins can be produced in root tips and transported via the xylem to shoots (Skene 1975). Root-derived cytokinins transported to buds appear to be involved in induction of budburst (Letham 1994). Lateral shoot production of peach seedlings was inhibited by removal of 50% of the root system but this effect could be reversed by exogenous application of the cytokinin 6-benzylaminopurine (Richards and Rowe 1977).

Optimum levels of soil moisture and macronutrients promote cytokinin biosynthesis in plants (Mullins et al. 1992; Jackson 1993). Reduced xylem transport of cytokinins to shoots has been detected in droughted plants of some species (Livne and Vaadia 1972) but there was no correlation between soil drying and concentration of cytokinins in xylem sap of almond trees (Fusseder et al. 1992). Davies et al. (1986) speculated that reduced leaf extension of maize in a split-root experiment may be the result of a reduced supply of cytokinins from roots in response to soil drying. However, according to Davies et al. (1994), there have not been any reports of studies in which the flux of cytokinins has been quantified and compared to changes in growth induced by drought.

Evidence for cytokinins as root signals was provided by Meinzer *et al.* (1991) for sugarcane and Fusseder *et al.* (1992) for almond respectively. However, Gowing *et al.* (1993) doubted a central role for these compounds in the signalling process. They argued that, unless the roots dry out significantly, the reduction in the flux of cytokinins will be very small and it is unlikely that shoots could detect and respond to anything but a substantial change in cytokinin supply. Nevertheless, the possibility of an interaction between ABA and cytokinins cannot be dismissed. Cytokinins are known to modify stomatal response to ABA: exogenous application of cytokinin can override ABA-mediated stomatal closure in maize (Blackman and Davies 1985). Therefore, there is a possibility of an interacting effect of ABA and cytokinins on growth, as suggested by Davies et al. (1994). Future research could test the hypothesis that the reduction in lateral shoot growth in response to PRD is the result of a decreased supply of cytokinins caused by root drying.

In the case of the grapevine, there is strong evidence that cytokinins play an important role in the regulation of reproductive development (Mullins et al. 1992), starting with the promotion of fruitfulness of latent buds (Srinivasan and Mullins 1981) and finishing with maintenance of the berries as a strong sink for sugar (Hoad et al. 1977). The xylem sap of the grapevine contains high cytokinin activity during budburst and flowering (Skeene and Kerridge 1967). Therefore, a reduced supply of cytokinins caused by soil drying may be expected to have a negative effect on

fruit yield and quality. On the other hand, it is also known that bud fruitfulness is strongly regulated by radiation and temperature, and the effect of these factors on fruitfulness is thought to be mediated by cytokinins (Srinivasan and Mullins 1981). PRD reduces shoot vigour and improves the radiation microclimate of the buds of the renewal zone (= the basal portion of the mature shoot which is retained at pruning). Therefore, the potential negative effect of PRD (via an effect of soil drying) on fruit yield may be counteracted by the positive effect (via an effect of microclimate).

Possibilities for future research

Grapevine shoot vigour is strongly correlated with the supply of nitrogen (N) to the plant (Mullins et al. 1992): one of the most obvious symptoms of N deficiency is a reduction in shoot vigour. It is possible that the reduction in vegetative growth in response to PRD may be due, in part, to a reduction in the availability of N to shoots. In turn, this may be a consequence of either reduced uptake of N from the soil or changes in partitioning of N within the plant. Araujo et al. (1995) found that irrigation method affected the partitioning of N with *Vitis vinifera* cv. Thompson Seedless (syn. Sultana): N concentration of fruit and roots was significantly lower with drip irrigation than with furrow irrigation. The authors attributed this difference to the effect of irrigation method on relative size of the root system. Therefore, the effect of PRD on partitioning of N is worthy of future investigation.

Much of the water used for irrigation of horticultural crops in Australia has low to moderate salinity. Grapevines are classified as moderately sensitive to salinity based on yield and foliar symptoms (Williams and Matthews 1990). The effect of PRD on uptake of chloride should be investigated because both irrigation method and irrigation strategy may affect the concentration of chloride in leaves and fruit (Boland et al. 1993).

The field experiments of this study have focused on the effects of PRD on winegrapes. However, it is likely that this strategy will also be useful if applied to both drying and table-grape vineyards. Drying and table-grapes are mainly produced in intensively-irrigated vineyards in southern Australia and California, and Sultana is the most important cultivar for both end-uses (Dry and Smart 1988). A large proportion of Sultana is grafted to the nematode-resistant rootstock cultivar Ramsey in Australia and this combination tends to be excessively vigorous under the growing conditions of the Murray-Darling basin. Lighter pruning, eg. nil or minimal pruning (Clingeleffer 1983) cannot be used to reduce shoot vigour with either end-use because this practice reduces

berry size and this is an important quality parameter with these products. In fact, pruning tends to be relatively severe in order to maximise berry size and cultivars such as Sultana are generally cane-pruned because they have low fertility of basal buds. Therefore, PRD has the advantage that shoot vigour of drying and table-grapes may be reduced without any detrimental effect on berry size; furthermore, water may be conserved as with winegrapes.

Implications and recommendations

There has been much interest from the Australian viticultural industry in the PRD concept and its potential for influencing water use efficiency, vine vigour and grape quality. The implications for sustainable and profitable winegrape production are therefore well recognised. The research team has been involved collectively in many public lectures, workshops and seminars to promote the PRD technique. Furthermore PRD has been included as a module in the "Water Management for Grape Production: Research to Practice" workshops. In all of the written and oral presentations the research team has tried to present as much background information as possible to allow readers and listeners to devise their own ways of implementing PRD, rather than follow a series of set recommendations. This seems to have been quite a successful approach, although it may have had the slightly undesirable effect of dislocating the extension of the project from the adoption. Consequently, we have not been able to fully keep track of the degree of adoption in Australia.

The successful adoption of PRD on a large scale will have a number of consequences which may be summarised as follows:

- A reduction in consumption of water for irrigation is obviously desirable from an economic viewpoint, although whether this ultimately translates to a reduction in district use or the planting of additional vines, or other crops, to use the water saved will be determined by market forces. Nevertheless, PRD does provide an additional management tool for the vineyard manager with which to tailor crop quality to market needs.
- The cost of implementation of PRD will vary depending on the irrigation system employed and whether it is being applied to a new or existing vineyard. One of the most successful experiments carried out in these projects utilised a pre-existing irrigation system consisting of two sub-surface drip lines, one on either side of the row. In this case the implementation cost was restricted to a few valves to allow switching water from one side to the other. At the other end of the cost scale a new

development with the addition of a second drip line may cost about $2000/ha to install.

Intellectual property arising from the research (such as commercially significant developments, patents applied for or granted, licences, etc.)

The intellectual property arising from the research has been mainly in the form of knowledge about the physiological and biochemical changes associated with the application of the technique and has been largely disclosed in the form of publications.

Technical summary of all information developed as a part of the research

All the technical information generated in this project is summarised in the abstracts of the published papers. Additional information is contained in Appendices 1 and 2.

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