Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines

SUMMARY

Regulated deficit irrigation (RDI), an irrigation scheduling technique originally developed for pome and stone fruit orchards, has been adapted successfully for winegrape production. Water deficit is applied during the post-set period of berry development to reduce vegetative growth and, as necessary, berry size of red-winegrape varieties. However, water deficit is avoided during the berry-ripening period, and precise irrigation management is required to ensure minimal competition between ripening berries and vegetative growth. For the variety Shiraz, in particular, this irrigation practice has resulted in significant improvements in wine quality. Partial rootzone drying (PRD) is a new irrigation technique that improves the water use efficiency 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 be always in a dry or drying state while the remainder is irrigated. The wetted and dried sides of the root system are alternated on a 10- to 14-day cycle. PRD irrigation reduced significantly stomatal conductance of vines when compared with vines receiving water to the entire root system. Both systems require high management skills, and accurate monitoring of soil water content is recommended. Drip and other forms of micro-irrigation facilitate the application of RDI and PRD.

There is increasing global demand for high-quality wine and declining demand for wines of lower quality and lower value. Therefore, the challenge facing winegrowers is to improve winegrape quality.

In many regions, in particular in New World vineyards, irrigation is an integral feature of winegrape production. Traditionally, winegrowers have used irrigation maximizes productivity, as is reflected in recommended crop coefficients (FAO, 1977; FAO, 1998). Such coefficients help predict peak water requirement, and therefore are useful in the design stage of vineyard development. However, use of these values will result in water application rates in excess of those that may be optimal for the most appropriate balance between vegetative and reproductive development required for the production of premium quality grapes.

The key to improving winegrape quality in irrigated vineyards is to achieve an appropriate balance between vegetative and reproductive development, as an excess of shoot vigour may
have undesirable consequences for fruit composition. Water stress has a major influence on
shoot growth, and, in general, vegetative growth is more sensitive to water stress than is berry
(fruit) growth. For some wine grape varieties, control of berry size is of importance. However,
irrigation is not the only vineyard practice contributing to an inappropriate balance between
vegetative and reproductive growth. Others include the use of rootstocks that impart high shoot
vigour, improved plant nutrition and soil management, and the tendency to grow vines in cooler
regions, which may favour vegetative growth at the expense of fruit growth. However, in many
localities, the key to achieving the correct balance is irrigation management.

In recent years, the two main approaches for developing practical solutions to manipulate
grapevine vegetative and reproductive growth have been: regulated deficit irrigation (RDI) and
partial rootzone drying (PRD). However, these developments have been possible only as a
consequence of better understanding of physiological responses to water deficit and the
widespread use of drip and other forms of micro-irrigation that enable the precise control of
water application rate and timing. RDI and PRD have become established water management
techniques, both in New and in some Old World regions.

**Regulated Deficit Irrigation**

RDI uses water stress to control vegetative and reproductive growth. It was initially applied in
peach and pear orchards to control growth by imposing water stress at key stages of fruit
development. In an experiment on pear trees (Mitchell et al., 1989), irrigation application was
reduced from 93 percent of the water evaporated from free water surface equivalent to the tree
planting square to either 23 or 46 percent for a period of 19 d between November and December
(southern hemisphere). After rapid fruit growth commenced, irrigation amount was returned to
120 percent. Compared with non-RDI trees, fruit growth was stimulated and vegetative growth
reduced. The effectiveness of the RDI treatments was greater at higher tree density with the
associated increased root competition.

In grapevines, reduced irrigation prior to veraison caused a greater reduction in berry size
than did less irrigation after veraison, compared with control vines (Matthews et al., 1987). Wine
made from fruit of continually drip-irrigated vines was unlike wine from early- or late-
season deficit treatments, and distinctions were evident between ‘early-deficit’ and ‘late-deficit’
wines in appearance, flavour, taste and aroma (Matthews et al., 1990). Tasters of these wines
indicated that ‘late-deficit’ wines had a greater intensity of blackcurrant aroma compared with
‘fully irrigated’ counterparts. The concentrations of anthocyanins and phenolics were higher in
‘deficit’ wines although levels of residual sugar, titratable acid, pH and ethanol were similar to
‘fully irrigated’ wines. The volume of water applied weekly to the least stressed treatment was
about 50 percent of ETo for the site, and the most stressed vines received about 11 percent of
ETo (Matthews and Anderson 1988).

In an experiment on wine grapes, Goodwin and Macrae (1990) reported that reduced irrigation
during defined periods of berry growth after veraison reduced berry fresh and dry weights and
sugar concentration. However, control vines in the experiment were not irrigated at full crop
replacement and, consequently, in comparison to the initial work with RDI on stone and pome
fruit, were deficit irrigated for the whole of the experiment. The question arises as to whether
this practice is actually RDI. Less than full ETo replacement is often practised for the entire
growing season in vineyards where water supply may be limited or in cooler districts where
cropping level needs to be controlled to ensure adequate ripeness levels. In such situations,
irrigation practice should perhaps more correctly, and simply, be termed ‘deficit irrigation.’
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To compare the effects of water stress during berry developmental stages with well-irrigated vines, a large long-term field experiment was established on mature vines near Waikerie in the South Australian Riverland in the Murray-Darling Basin. Water stress treatments were imposed by withholding irrigation during four periods of berry development after flowering of *Vitis vinifera* cv. Shiraz. Control vines were irrigated such that water stress was minimized by regular monitoring of soil water content throughout the growing season and the use of a modern irrigation system that supplied water on demand (McCarthy 1997a, b, 1999, 2000). Coombe and McCarthy (2000) integrated these and previous findings into the figure reproduced here (Figure 1), with the addition of lines representing vegetative growth and the suggested period of water deficit. These findings were:

- Berry growth was most sensitive to water stress during pericarp cell division.
- Higher levels of water stress were needed to reduce berry size compared with vegetative growth.
- A reduction in berry size and, hence cropping level, resulted in earlier fruit maturity.
- Smaller berries resulted in higher anthocyanin concentration.
- Water stress during the early stages of berry ripening may enhance anthocyanin concentration.
- Water stress during the ripening period (post veraison) reduced solute accumulation in berries.
- Accumulation of flavour compounds occurred relatively late in the ripening process and was sensitive to water stress.
- With modern irrigation systems, it was possible to manipulate soil water availability to the degree necessary to influence vegetative and reproductive growth precisely.

Practical application

Many Australian winegrape vineyards normally use soil water monitoring to assist in the implementation of RDI. A variety of proven instrumentation is available. Where soil water content is measured with a neutron probe, for example, the available rootzone soil water content is kept below the irrigation refill line during the period of water deficit. The total available water in the rootzone should not decline by an amount greater than the difference between the full and refill lines (Figure 2). In practice, this may necessitate a light irrigation to prevent excessive water deficit. To control vegetative and reproductive growth, water stress should be limited to the period after fruit set in winegrape vineyards. This strategy is more applicable for red-wine varieties rather than white for which control of berry size and canopy size is considered less important. Monitoring shoot extension or comparing the rate of increase in berry weight with non-stressed vines can assess the effectiveness of the water deficit.
In practice, reduced irrigation application during the post-set period may not achieve the desired outcome. The site may be unresponsive to irrigation due to factors such as:

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

There are various approaches for making sites with high water-holding capacity from winter rainfall responsive to post-set deficit:

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

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

- inability to re-schedule irrigation and application quantities,
- excessive variability in soil water-holding characteristics within each irrigation shift,
- poor distribution uniformity of the irrigation system,
- excessively high soil water availability from furrow and flood irrigation systems,
- general management skills; a more-than-basic understanding of vegetative and berry growth is required in relation to the effects of water abundance or deficit during each stage of vegetative and fruit growth, for example the effect of excessive water stress on floral initiation.

**Conclusions — RDI**

In Australia, numerous vineyards have adopted the concept of applying water stress immediately after fruit set to control vegetative growth, and, in particular for the variety Shiraz, to control berry size. In many instances this practice has resulted in significant improvement in red-wine quality, albeit sometimes at the expense of yield. In addition, experimental work has demonstrated that, contrary to the existing practice in many vineyards, controlled irrigation is recommended to
avoid water stress during the fruit ripening period (post veraison). Minimizing water stress, whilst controlling vegetative growth, has resulted in more rapid ripening and a changed wine flavour profile. The continuance of controlled levels of irrigation during berry ripening is more necessary in drip-irrigated vineyards, where, as a result of drying of deeper soil layers and a reduced wetted soil volume compared with furrow irrigation, drought stress can rapidly develop during periods of high evaporative demand. This is particularly relevant in parts of Australia, United States of America, South America and South Africa, where the ripening period occurs under warm and dry conditions. Maintenance of higher levels of soil water content prior to, and after, harvest is now considered beneficial to post-harvest root growth and ensures vines do not enter dormancy under water stress, a condition that results in susceptibility to damage from cold weather. As a consequence, winegrape growers are now encouraged to use the term ‘strategic irrigation management’ rather than RDI.

**Partial rootzone drying**

PRD uses biochemical responses of plants to water stress to achieve a balance between vegetative and reproductive development. By doing so, it achieves a secondary goal of significant improvement in production per unit of irrigation water applied. It has been a consistent feature of all trials that, even though the irrigation amount was halved, there was no significant reduction in yield due to PRD treatment. This contrasts with RDI experiments, where savings in irrigation application have often been at the expense of yield.

Research into the physiological changes that occur during water stress has led to improved understanding of plant response to stress in terms of chemical signals passing from roots to leaves. The vine’s first line of defence when faced with water shortage is to close its stomata to conserve moisture. One of the principal compounds that elicits this response is abscisic acid. As soil water availability falls following the cessation of irrigation, this acid is synthesized in the drying roots and transported to the leaves in the transpiration stream (Loveys et al., 1999). Stomata respond by reducing aperture, thereby restricting water loss. Improvement in WUE results from partial stomatal closure. However, an inevitable consequence is reduced photosynthesis, as carbon dioxide and water vapour share the stomatal pathway through the leaf surface.

The challenge was to devise ways of controlling the amount of water available to grapevines, to maximize the production of root-derived chemical signals that reduce canopy transpiration, and, therefore, improve WUE. A methodology was developed to permit drying of part of the root system while keeping the remainder well watered. However, early attempts with grapevines were confounded by the transient nature of the response to drying part of the root system. By simply switching the wet and dry sectors of the rootzone on a regular basis, this transient response was overcome (Dry et al., 1996; Dry and Loveys, 1998).

A number of long-term, large-scale field experiments on Shiraz, Cabernet sauvignon, and Riesling, using a range of irrigation methods, have now been completed (Loveys et al., 1997, 1998, 1999; Dry et al., 2000). These included standard drip emitters (2 or 4 litres/h), two per vine in the inter-vine space and placed about 450 mm from the vine trunk (Figure 3) and subsurface drip lines, one on each side of the vine row at a depth of 200-250 mm and 350-400 mm from the centre of the row. In all cases, the intention was to create two wetted zones per vine that could be alternately irrigated on a cycle of approximately two weeks, i.e., while one zone was wetted, the other zone would be dried. Soil moisture sensors installed within each wetted zone assessed whether water applied to one side infiltrated to the other, supposedly dry,
side. In all cases, there was satisfactory separation of wet and dry zones in a range of soil types under field conditions. Partial rootzone drying with furrow/flood irrigation has been successful in experiments with pears and citrus and in commercial vineyards in the Riverina district of New South Wales, Australia (Clancy, 1999), and with other perennial row-crop fruits.

In vines subject to PRD, there were reductions in vegetative growth as measured by pruning weight (Table 1). Much of the reduction in canopy biomass was due to reduced leaf area associated with lateral shoots. Total leaf area of PRD vines was significantly (P<0.05) less, largely the result of reduction in the area of leaves on lateral shoots (Figure 4). In another trial, minimally pruned Riesling vines were subjected to PRD and in July (southern hemisphere) the canes from three control panels (fully irrigated) and three PRD panels were removed and allocated to three length categories. Only the current season’s growth was removed. The PRD treatment resulted in a significant reduction in the weight of canes in the >500-mm-size category and in the total pruning weight. Another measure of canopy density is the amount of light reaching the bunch zone and this figure was consistently higher in PRD than in control vines.

A consistent feature of all trials was that there was no significant reduction in yield due to PRD treatment, even though irrigation amount was halved. As a result, yield per unit of water applied doubled in response to PRD (Table 2). Moreover, there was no effect on berry size in response to a halving of irrigation amount whereas there is usually a significant decrease in berry size in response to a substantial reduction in the amount of irrigation applied (Smart and Coombe, 1983; Williams and Matthews, 1990), particularly with deficit imposed between flowering and veraison (McCarthy, 1997a).

The results of PRD on fruit composition in respect to wine-making attributes indicate that quality is at least maintained if not improved. Some experiments revealed no apparent effect on
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fruit quality as indicated by concentrations of anthocyanins and phenolics in fruit. In these cases, the control vines were well balanced with relatively open canopies: PRD did not substantially alter the canopy microclimate. In earlier experiments, the PRD treatment qualitative changes in the anthocyanin pigments of Cabernet sauvignon. For several seasons and at two sites, the concentration of the derivatives of delphinidin, cyanidin and petunidin in berries from PRD vines increased relatively more than the derivatives of malvidin and peonidin. Furthermore, PRD enhanced the formation of the coumarate forms of anthocyanins. This may be a response to bunch exposure, because shading of Shiraz bunches in a hot climate was found to enhance the proportion of coumarate forms.

Commercial trials have shown that if PRD is applied properly, there should be no significant yield reduction, although irrigation amount may be halved. A critical irrigation management practice with PRD is to ensure adequate rewetting of the dry side. Failure to ensure adequate replenishment of deep soil layers after switching sides may result in water stress, which may significantly reduce berry size during the early stages of berry development. Provided an overall favourable vine water status is maintained with PRD, berry size, and thus yield, will be maintained, despite reductions in water of up to 50 percent of conventional irrigation. A simple indication of whether the soil moisture status of the wet side was adequately maintained is the absence of reduction in berry weight. Similar to RDI, the responsiveness of the site to irrigation determines the successful application of PRD. Where the site is not responsive to irrigation, it is unlikely that part of the rootzone can be dried sufficiently during the initial stages of vegetative growth to control primary and lateral shoot extension. While savings in irrigation application may occur later in the season they may not be sufficient to economically justify the higher capital cost of installing PRD.

Conclusions — PRD

There has been much interest from New World viticultural industries in the PRD concept and its potential for influencing water use, vine vigour and grape quality. The implications for sustainable and profitable winegrape production are, well recognized. The successful adoption of PRD on a large scale has a number of consequences.

A reduction in consumption of water for irrigation is desirable from an economic viewpoint, although market forces will determine whether this ultimately translates to a reduction in district use or to the planting of additional vines or of other crops, to use the water saved. Further restrictions in water availability are probable and, in order to maintain productivity, irrigation

<table>
<thead>
<tr>
<th>Variety/Location/Season</th>
<th>Variable</th>
<th>Control</th>
<th>PRD</th>
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<tbody>
<tr>
<td>Shiraz, Adelaide, 1997–98</td>
<td>Yield (t/ha)</td>
<td>22.6</td>
<td>21.5</td>
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<tr>
<td></td>
<td>Water applied (Ml/ha)</td>
<td>1.4</td>
<td>0.7</td>
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<td></td>
<td>Yield/Ml irrigation</td>
<td>16.1</td>
<td>30.7</td>
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<tr>
<td>Cabernet sauvignon, Adelaide, 1997–98</td>
<td>Yield (t/ha)</td>
<td>15.2</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>Water applied (Ml/ha)</td>
<td>1.4</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Yield/Ml irrigation</td>
<td>10.9</td>
<td>22.0</td>
</tr>
<tr>
<td>Riesling, Waikerie, 1996–97</td>
<td>Yield (t/ha)</td>
<td>29.1</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td>Water applied (Ml/ha)</td>
<td>4.5</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Yield/Ml irrigation</td>
<td>6.4</td>
<td>11.9</td>
</tr>
<tr>
<td>Riesling, Waikerie, 1997–98</td>
<td>Yield (t/ha)</td>
<td>30.6</td>
<td>28.7</td>
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<tr>
<td></td>
<td>Water applied (Ml/ha)</td>
<td>5.2</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Yield/Ml irrigation</td>
<td>5.9</td>
<td>10.9</td>
</tr>
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</table>
practices and WUE will have to improve. Nevertheless, PRD does provide the vineyard manager with an additional management tool for tailoring crop quality to market needs.

The cost of implementing PRD varies depending on the irrigation system employed and whether it is applied to a new or existing vineyard. One of the most successful experiments in these projects utilized a pre-existing irrigation system consisting of two subsurface drip lines, one on each 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 development with the addition of a second drip line may cost about US$100/ha to install. Drip irrigation is in widespread use in vineyards throughout the world and, for example, in Australia a drip irrigation system may constitute half of the capital development cost. The additional outlay of installing PRD, is economical where the cost of irrigation water is high and as water becomes an increasingly valuable and scarce resource. The true environmental cost of irrigation water justifies the cost of implementing PRD.

The evaluation of PRD has progressed beyond the experimental stage with significant areas of PRD installed in vineyards in Australia, New Zealand, Spain, Israel, the United States, and South Africa. To date, most installations have involved a second drip line either above or below ground. Several irrigation-equipment manufacturers are working to eliminate the need to install two separate drip lines and to improve methods of installation and reduce root penetration in buried systems. Further research is underway in Australia to determine the optimum configuration for above- and below-ground installations, such as spacing of ‘on’ and ‘off’ drippers relative to vine spacing.

<table>
<thead>
<tr>
<th>Relevant factors in choosing RDI or PRD as a vineyard management system</th>
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<tbody>
<tr>
<td><strong>RDI</strong></td>
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<tr>
<td>Site must be responsive to irrigation</td>
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<tr>
<td>Can be used with furrow irrigation</td>
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<tr>
<td>Water must be available on demand</td>
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<tr>
<td>Vegetative growth control</td>
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<tr>
<td>Potential for yield loss</td>
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<tr>
<td>Positive effects on grape and wine quality</td>
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<tr>
<td>Marginal water savings</td>
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<tr>
<td>No irrigation hardware modification</td>
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<tr>
<td>Soil water monitoring recommended</td>
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</tbody>
</table>

**GENERAL CONCLUSION**

Table 3 summarizes the factors that determine the choice of RDI and/or PRD as an irrigation method in an individual vineyard.

**REFERENCES**

Clancy, A. 1999. Riverina has the capacity to deliver diverse requirements. *Australian Viticulture* 3: 38-42.


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