IRRIGATION INSIGHTS
NUMBER 4

REGULATED DEFICIT IRRIGATION

AND

PARTIAL ROOTZONE DRYING

An information package on
two new irrigation methods
for high-input horticulture

NATIONAL PROGRAM FOR
Sustainable Irrigation

REGULATED DEFICIT IRRIGATION

AND

PARTIAL ROOTZONE DRYING

An overview of principles and applications

by

Paul E. Kriedemann
Adjunct Professor, National Wine and Grape Industry Centre
Charles Sturt University Wagga Wagga NSW and
Visiting Fellow, Research School of Biological Sciences,
Australian National University, Canberra ACT

and

Ian Goodwin
Senior Irrigation Scientist
Department of Primary Industries
Tatura, Victoria

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GPO Box 2182
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Phone: 02 6257 3379
Fax: 02 6257 3420
Email: <public@lwa.gov.au>

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PREFACE

This information package was commissioned by the National Program for Sustainable Irrigation, a program of Land & Water Australia, the Cooperative Research Centre for Viticulture and the Grape and Wine Research and Development Corporation to provide an overview of the background, current developments and future prospects for implementing regulated deficit irrigation and partial rootzone drying.

In preparing this *Irrigation Insights* both authors consulted with researchers and growers, visited a number of sites where the systems were being used and participated in seminars on water use and management of horticultural crops. Meetings took place in Mildura and Adelaide, and were sponsored by the Cooperative Research Centre for Viticulture, the Australian Society for Viticulture and Oenology, the Grape and Wine Research and Development Corporation and CSIRO Plant Industry (Horticulture Unit).

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Richard Wells, Grapegrower and NPIRD Steering Committee member, Merbein, Victoria

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CHAPTER 1

PERSPECTIVES

"Business as usual" is no longer an option for irrigation horticulture in Australia. Rather, in coming decades, a combination of financial realities, environmental factors and ethical sensibilities will affect both access to the water resource and how excess groundwater from irrigated orchards and vineyards is disposed of. These enterprises will need to grow crops using much less applied water than at present.

Water-efficient irrigation methods are now available, and will be crucial in doing this. In the future these methods will be closely tailored to the water needs of horticultural crops, which will be monitored to ensure water use efficiency. Regulated deficit irrigation and partial rootzone drying have great potential to contribute to an increasingly water-efficient horticulture.

Profitability and competition for water

By definition, sustainable irrigation uses no more water than is available on a recurring basis from rainfall over a catchment at a national level (i.e. allowing for catchment-to-catchment diversions). Schemes based on groundwater are in effect drawing on stored 'capital' from previous decades, centuries or even millennia (fossil water). Once that stock of groundwater is depleted to the point of uneconomical pumping or is rendered saline, it will be access to a recurring supply of fresh water that dictates long-term prospects for sustainability.

The total area devoted to agriculture in Australia is about 465 million hectares, of which only 2 million hectares is irrigated. At least three quarters of that 2 million hectares lies within the Murray-Darling Basin, which covers about one million square kilometres, accounts for about 70% of irrigation water use, produces about 40% of Australia's gross agricultural income, and is responsible for 56% of Australia's fruit production. In gross terms, about $5 billion is earned through irrigation for dairy, rice, cotton, beef, wine and horticulture.

In the Murray-Darling Basin competition for water from both urban and rural users is increasing. This is in a context where average annual flow is now almost 90% committed, and where allocations to irrigators have been capped. As suggested by Smith and Maheshwari (2002), "New developments should be allowed, provided the water is purchased from existing developments or obtained through increases in WUE".

In this situation, regulated deficit irrigation and partial rootzone drying are irrigation methods that will enable further expansion of irrigated horticulture by improving the efficiency with which orchard and vineyard irrigators use their entitlements, and in so doing, these new irrigation methods will help sustain returns to irrigators (see Table 1).

Much has been achieved worldwide, including in Australia, over the past 30 years with respect to storing and distributing irrigation water more efficiently, as well as improving application methods (from flood to overhead sprinkler to low level sprinkler, microjet and drip). As an example, irrigation application rates on citrus orchards in the South Australian Riverland have fallen between 30 to 40% over the past twenty years, and trends are similar in other horticultural areas within the Murray-Darling Basin.

Added to this development in getting water from source to crop more effectively, and in minimising unproductive losses from evaporation from wet soil and deep drainage, water use efficiency by horticultural species has also been improved. Research in Australia starting around the mid 1970s put a totally new complexion on potential water use efficiency by perennial crop plants under irrigation (expressed as crop yield per ML of water applied). Savings of

Table 1. A comparison of gross margin estimates for different irrigation enterprises in the Kerang-Swan Hill area where horticultural produce is marketed for fresh fruit rather than processing. (Based on data in Downs and Sime 1999; Downs and Montecillo 2001.)

COMMODITY	GROSS MARGIN ($/ML IRRIGATION)
Apples	2,714
Apricots	2,031
Peaches	1,624
Plums	2,084
Rockmelons	1,645
Sultanas	1,049
Tomatoes	2,965
Wine grapes	2,802
Zucchini	210
Barley	86
Lucerne hay	64
Maize grain	123
Oats	116
Rice	60-84
Sunflowers	12
Wheat	73
Milk	206-282

from 20 to 30% have been documented under regulated deficit irrigation, and even greater improvements reported for partial rootzone drying (conservatively between 30 and 50% with reports of even greater improvements as discussed in Chapter 3). As well, that improvement in water use efficiency has not caused a loss in fruit quality, rather quality of both wine grapes and tree crops has been consistently improved under both forms of deficit irrigation.

A snapshot of regulated deficit irrigation and partial rootzone drying

Regulated deficit irrigation and partial rootzone drying are designed to limit vegetative vigour and improve water use efficiency in perennial crop plants such as grapevines and fruit trees. This shift in crop management, compared with traditional irrigation methods which use more water, is a feature common to both regulated deficit irrigation and partial rootzone drying. These two methods of irrigation do, however, differ fundamentally in two key respects. With regulated deficit irrigation water application is manipulated over time whereas, with partial rootzone drying irrigation, water is manipulated over space.

With regulated deficit irrigation a water deficit is applied in an orchard or vineyard in a closely controlled way over a critical period, i.e. after fruitset and up to veraison. By contrast, partial rootzone drying relies on separating alternating dry and moist roots and necessitates dual dripper lines that can be operated independently or some other irrigation system that can produce the desired pattern of soil wetting.

Partial rootzone drying can be targeted to a particular tree or grapevine growth phase but would usually be maintained during an entire growing season.

Although the way the two systems work differs significantly, the ultimate outcomes of regulated deficit irrigation and partial rootzone drying are similar in that they limit vegetative growth and enhance water use efficiency for crop production. With both irrigation methods, canopy growth is constrained in favour of crop development. A smaller canopy allows more light to enter the tree or vine and this enhances initiation and differentiation of fruit buds. This means that water use efficiency for crop production is improved while cropping potential for the next season is not necessarily affected.

Key features of regulated deficit irrigation (RDI) and partial rootzone drying (PRD) that highlight some key distinctions between them are as follows:

RDI	**PRD**
Validated on both fruit crops and wine grapes	Validated for wine grapes potential for fruit crops
Irrigation savings assured	Irrigation savings assured
Fruit crops maintain final size and yield	Potential for fruit crops and research continues
Wine grapes produce smaller berries with reduced yield	Wine grapes maintain berry size and yield
RDI timing critical	PRD timing flexible
Improved quality in wine grapes and fruit crops	Potential for improved quality via reduced vigour in wine grapes
Reduced vegetative vigour conducive to improved cropping	Reduced vegetative vigour conducive to improved cropping
Deficit irrigation where only uppermost profile is re-wetted	Deficit irrigation where deeper wet/dry zones are spatially separated

Observations to date indicate that both regulated deficit irrigation and partial rootzone drying are realistic options for long-term management of perennial crop plants.

Towards a definition of regulated deficit irrigation and partial rootzone drying

(courtesy Jim Hardie, Cooperative Research Centre for Viticulture, Adelaide SA)

Regulated deficit irrigation. Regulated deficit irrigation is the practice of using irrigation to maintain plant water status **within prescribed limits of deficit with respect to maximum water potential** for a prescribed part or parts of the seasonal cycle of plant development. The aim in doing this is to control reproductive growth and development, vegetative growth and/or improve water use efficiency.

It follows that the re-wetting frequency under regulated deficit irrigation should be determined by detection or prediction of **a decrease in plant water potential below a prescribed limit.** Ideally this should be measured in terms of plant water potential but in practice, for convenience and cost saving, this may be inferred from soil moisture depletion or estimates of plant water use based on evaporative conditions or measurement of sap flow.

Partial rootzone drying. Partial rootzone drying is the practice of using irrigation to alternately wet and dry (at least) two spatially prescribed parts of the plant root system to **simultaneously** maintain plant water status at maximum water potential and control vegetative growth for prescribed parts of the seasonal cycle of plant development. The reason for doing this is to control vegetative growth or improve water use efficiency or both while maintaining reproductive growth and development.

It follows that the re-wetting frequency under partial rootzone drying should be determined by detection or prediction of completion in extraction of soil water from the drying side. In practice this can be identified from soil moisture depletion or estimates of plant water use based on evaporative conditions or measurement of sap flow.

The strict test for regulated deficit irrigation or partial rootzone drying implementation rests in the actual values for plant water potential against the fully watered state.

The test for whether partial rootzone drying has caused observed responses seems to depend on whether or not reproductive growth, berry or fruit size or weight has been decreased because this seems unlikely if maximum turgor is maintained. The experimental evidence from partial rootzone drying pot trials in controlled conditions reveals this as a defining feature.

In practice it is likely that partial rootzone drying will involve a degree of deficit i.e. submaximal plant water potential, because of factors related to the application of water to maintain maximum plant water potential throughout the wetting cycle as follows:

- insufficient re-watering frequency
- insufficient water application
- insufficient infiltration
- insufficient size of the wetted zone relative to canopy size and evaporative demand.

Two issues arise concerning partial rootzone drying application:

- What is the allowable or desirable limit for any departure from the fully watered state?
- What are the consequences of regional differences in vapour pressure deficits as they impact on the daily range of plant water potential of plants under partial rootzone drying regimes?

In relation to water deficit strategies in general, a barrier to implementation, apart from lack of convenient plant based measures of water potential, appears to be the lack of broad recognition that plant stress is a quantifiable continuum and that any attempt to regulate the deficit to achieve plant responses must involve defining, measuring and controlling the stress within prescribed limits. Satisfactory implementation of deficit strategies in warm areas i.e. high vapour pressure deficit, generally requires responsive watering systems and soils with high infiltration rates.

Deficit irrigation in viticulture. In viticulture, the concept of water deficit irrigation has its origins in Mediterranean wine grape growing, which relies mainly on seasonal drawdown of soil moisture replenished by winter rainfall. Under those conditions, relieving a deficit by irrigation to avoid the effects of summer drought sometimes caused delays in achieving the desired sugar concentration while at other times ripening was advanced.

Those instances of an irrigation-induced delay in ripening strengthened the case for seasonal water deficits. In western Europe, irrigation was banned by regulation in many regions, and there was much debate among wine grape producers as a result, particularly those striving to establish vineyards in the 'New World'. This apparent paradox of irrigation sometimes hastening and sometimes slowing ripening rate, and sometimes making no difference at all, led to a series of irrigation studies to define the extent to which deficits should be relieved in terms of irrigation practices within local contexts. Most studies confirmed the delaying effects of minimal water deficits on a harvest that was based on sugar concentration. This delay was usually caused by a relative increase in berry size or berry number or both, depending on the size of the deficit imposed.

However, recognising that growth stage and regional site factors such as soil, rainfall and evaporative demand would govern irrigation responses, and seeking to devise a general irrigation strategy that avoided the uncertainty that comes with using indirect measures of vine water status such as soil water content, or estimates of transpiration, a researcher named Hardie (1985) sought to define grapevine responses in terms of plant water potential.

Drawing on pot studies and field studies and the general responses of plants to water deficits, Hardie presented tentative recommendations for a generalised deficit strategy in 1985. In the absence of convenient, non-destructive, full range measures of vine water potential the strategy is based on critical limits of soil water potential necessary to regulate vine water potential within prescribed limits.

The term *regulated deficit irrigation* was coined by a team of researchers based at Tatura, Victoria and led by David Chalmers to describe the application of water deficit strategies based on orchard evapotranspiration relative to water loss from an evaporimeter. These strategies were developed by them for use in peach and pear production to maximise fruit biomass through redeploying photo-assimilate from shoot growth. The term was later applied to wine grape production where the priority was not maximising fruit biomass, but achieving a prescribed concentration of sugar for alcoholic fermentation and other fruit quality attributes related to the sensory qualities of wine produced from those grapes. Any improvement in irrigation water use efficiency was perceived as a bonus, but was not the original motivating factor for adoption of regulated deficit irrigation.

Note. “Deficit irrigation” is used here in a generic sense. By allowing a water deficit to develop in a strategic fashion, regulated deficit irrigation imposes a **plant deficit** during a proscribed stage in crop growth and development. Partial rootzone drying on the other hand, imposes a **soil deficit** within alternating sides of a rootzone, but plants so managed should remain turgid.

CHAPTER 2

REGULATED DEFICIT IRRIGATION

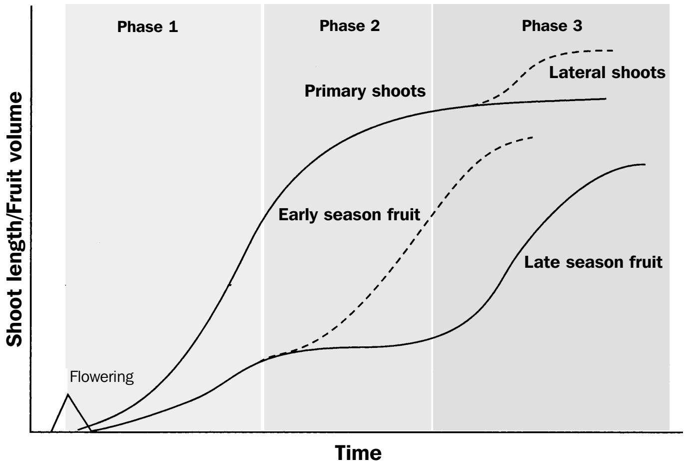
Regulated deficit irrigation was first coined as a term during the 1970s at Tatura in Victoria, and was subsequently applied in the 1980s on high-density orchards of peaches and pears in the Goulburn Valley (grown mainly for canning). Researchers discovered that water deficit constrained shoot growth when shoots and fruits were competing for photo-assimilates. Shoots would normally be growing rapidly during early summer, and fruits that had set successfully would be in their slow growth phase (see Figure 1). Under mild stress, canopy growth was contained while fruit yield was unaffected.

Regulated deficit irrigation for pome and stonefruits

Regulated deficit irrigation has been developed according to demands of plants for water and photo-assimilates throughout different growth stages.

Stonefruit are amongst the orchard crops that are responsive to regulated deficit irrigation. It is worthwhile looking at how stonefruit grow and develop (Figure 1) as a way of describing how regulated deficit irrigation is applied in orchards.

Figure 1. Stonefruit growth stages emphasising flowering ahead of shoot growth and fruit enlargement in three phases. Regulated deficit irrigation is released and full irrigation restored ahead of the onset in Phase 3 (based on B G Coombe, unpublished data.)



Flowering occurs before leaves and shoots expand, and then fruit enlarge in a three-phase growth curve. In the Goulburn Valley, phases one, two and three last about 68, 50 and 56 days respectively for the canning peach variety Golden Queen.

Fruit growth during Phase 1 is the result of a combination of rapid cell division and moderate cell enlargement. Growth during Phase 3 is due entirely to the enlargement of existing cells. In the peach variety Golden Queen, as much as three quarters of the increase in fruit volume occurs during Phase 3. During Phase 2 fruit growth slows and fruit don't compete with shoots and leaves for photo-assimilates. As a result it is during this time that shoots grow rapidly and canopy expansion is at its maximum.

David Chalmers and a number of other researchers based at Tatura (see Mitchell *et al* 1989) realised that Phase 2 provided an opportunity to limit tree vigour as a result of water deficit, while not jeopardising fruit yield in the process.

There were two other benefits of doing this. First, a smaller canopy meant that sunlight penetration was increased and initiation of fruiting buds for next season was enhanced. Second, smaller canopies for a given crop load also meant that orchard water use efficiency was improved. For example, transpiration from peach trees was reduced by half during regulated deficit irrigation as a result of both stomatal conductance and leaf area being reduced. Water use continued to be 30% lower than that of trees on standard irrigation because of the smaller leaf area following the deficit period. Taken collectively, total irrigation for the season was reduced by as much as 2 ML/ha, which represents a 25 to 30% reduction in irrigation water use compared to traditional methods.

There was extra benefit from regulated deficit irrigation in early summer. Fruit from regulated deficit irrigation trees were not smaller. In fact there were instances when fruit size actually increased. Grapevines (as discussed later) do not behave this way, and berries are commonly smaller after regulated deficit irrigation.

More research explained why. Early stages of fruit growth are sustained by cell division, and during those stages young fruits are less sensitive to moisture stress compared to young foliage. While early fruit growth could be diminished to some extent by early summer regulated deficit irrigation (RDI phase in Figure 3), shoot growth was much reduced.

During later stages of fruit growth (mid January to harvest), cell enlargement takes over as the main driver of fruit growth, but by then shoot extension slows for other reasons, including competition with fruits for photo-assimilates. In a regulated deficit irrigation orchard, full irrigation is restored at that later stage, and turgor-driven enlargement of fruit tissues proceeds (Figure 2). This can happen more quickly than normal because osmotically-active materials have accumulated in fruits during the regulated deficit irrigation phase. Peter Jerie and other researchers at Tatura measured pear growth continuously with transducers and a data logger in 1989, and they recorded similar daily fruit growth between regulated deficit irrigation and full irrigation. In both treatments, fruit shrank during the day then expanded rapidly in late afternoon, followed by slower but steady growth overnight. Fruit osmotic pressure was 2400 kPa (2.4 MPa) in trees on regulated deficit irrigation, but only 1700 kPa (1.7 MPa) in trees on full irrigation. This increase in pressure explains the enhanced growth of pear fruits (Figure 2) once regulated deficit irrigation is discontinued in favour of full irrigation.

Any minor restriction on fruit enlargement during its earlier phase is then offset by enhanced growth during its later cell enlargement phase. Regulated deficit irrigation thus provides a way of limiting vegetative vigour and improving crop water use efficiency, while sustaining or even enhancing reproductive development.

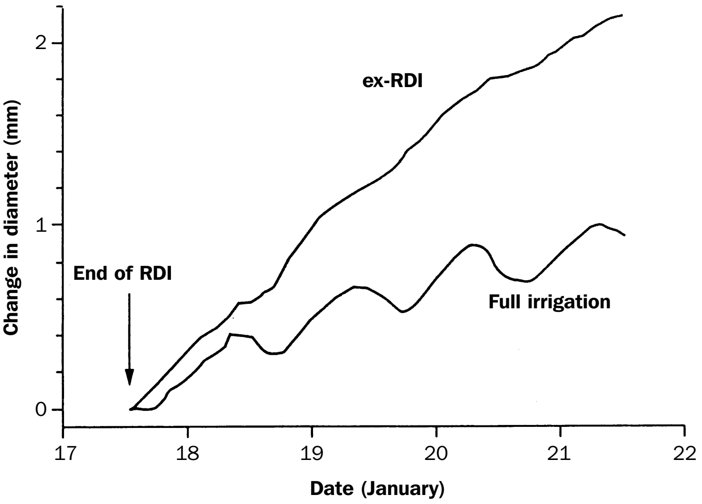


Figure 2. Daily growth of pear fruits over four days after changing from regulated deficit irrigation to full irrigation (ex-RDI) compared with continuous full irrigation. Fluctuations on full irrigation reflect the daily rhythm of variation of water potential within the soil-plant-atmosphere continuum. Fruit growth surges following full irrigation is restored after regulated deficit irrigation as a result of turgor generated from an accumulation of osmotically-active materials in fruit on trees previously subjected to regulated deficit irrigation (based on Jerie *et al.*, 1989).

Fruit growth in pears (Figure 3) follows an approximately exponential pattern for fresh mass increase over time, whereas peach fruit growth occurs in two phases with a lag in fresh mass increase around the time of stone hardening (Figure 4). Pears reach the greatest final mass, and this is consistent with their generally higher productivity (typically 50 and 90 t/ha for peaches and pears respectively under favourable conditions in the Goulburn Valley).

In contrast to fruit growth curves for pears with their early slow phase, and for peaches with their mid-point slow phase, apples maintain a steady increase in volume from set to harvest (Figure 5). Apple trees are thus less suited to regulated deficit irrigation because at no stage is vigorous shoot growth clearly associated with reduced fruit growth.

Some effects of water deficit on shoot growth and cropping in Cox's Orange Pippin apple have been described. However, only general guidelines for apple orchard management with regulated deficit irrigation have been published which recommend that soil moisture tension between budburst and harvest be maintained between 8 and 40 kPa. Regulated deficit irrigation has yet to have much of an impact on apple production, but some benefit from regulated deficit irrigation-controlled cropping is possible while returns to growers are linked to fruit size. For example, *cv.* Pink Lady fetches around $3000/t for fresh (dessert) fruit, compared with around $400/t for oversize juice fruit.

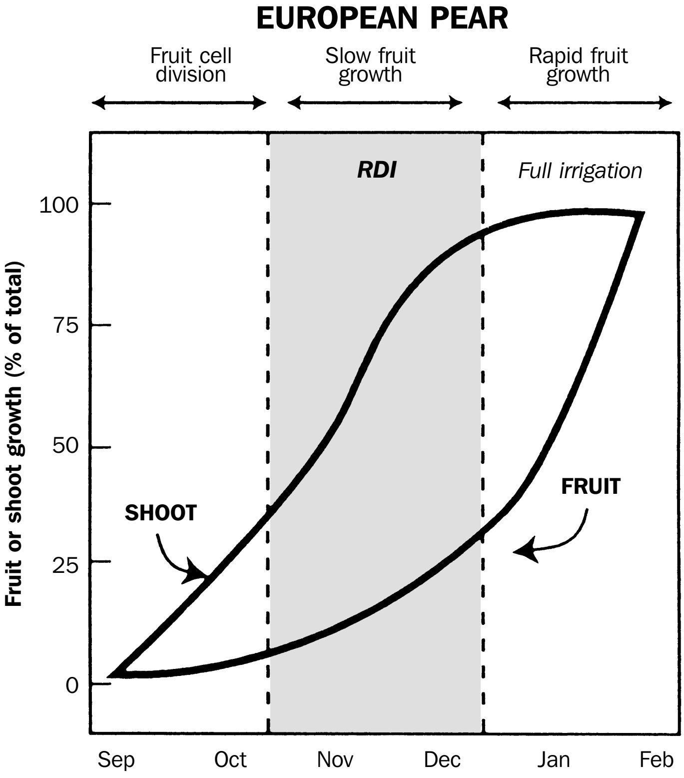


Figure 3. The progress of shoot extension and fruit growth on pear trees in the Goulburn Valley in Victoria. Regulated deficit irrigation is applied during the slow fruit growth phase (based on Goodwin and Boland, FAO, 2002).

The distinctive stages of shoot and fruit growth in peaches and pears (figures 3 and 4) make these two crops responsive to regulated deficit irrigation. Deficit irrigation is used to limit shoot growth when fruits are firmly attached but are growing only slowly (onset of stone hardening in peaches, and midway between bloom and harvest for pears). In both cases, water stress during this mid phase does not affect final fruit size, but it does slow vegetative growth. Benefits include a smaller canopy with better penetration of sunlight and thus flower bud initiation, plus reduced whole-tree transpiration.

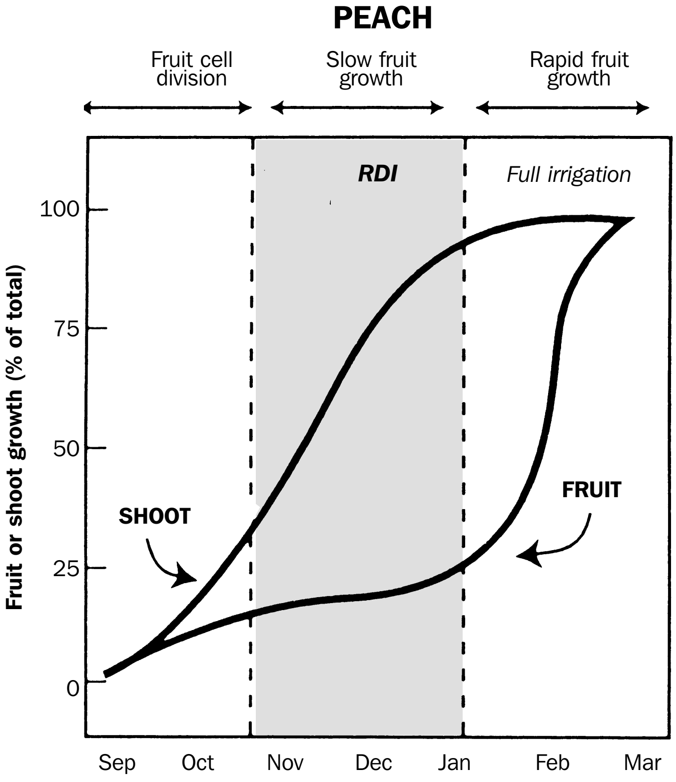


Figure 4. The comparative progress of shoot extension and fruit growth on peach trees in the Goulburn Valley in Victoria. Regulated deficit irrigation is applied during the slow growth phase (based on Goodwin and Boland, FAO, 2002).

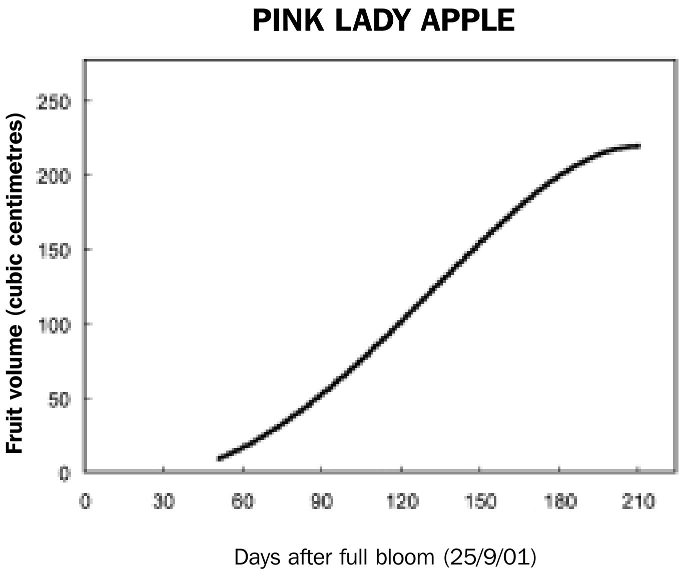


Figure 5. Growth curve for an apple fruit (variety Pink Lady) in the Goulburn Valley of northern Victoria (Mark O'Connell and Ian Goodwin unpublished data, 2001-2002 season). Fruit growth is initially slow (immediately after set) but soon increases rapidly, staying high for most of the growing season. Fruit growth typically slows as fruit ripen. Regulated deficit irrigation will reduce final fruit size and such reduction can be useful for the fresh fruit market (especially when crop load is low, and over-sized fruit is a likely outcome). In this present case, irrigation was stopped around 182 days following full bloom in an attempt to reduce fruit size at harvest.

These benefits act to improve water use efficiency (WUE), expressed in terms of fruit yield per unit of irrigation water applied. For example, Mitchell and Chalmers (1982) reported a WUE increase in Goulburn Valley peach orchards from around 4.9 to about 8.0 t/ML as a result of regulated deficit irrigation in canning peaches that yielded 48 t/ha. Corresponding data for William Bon Chretien pears showed that WUE increased from 12.5 to 22 t/ML in orchards yielding around 90 t/ha. Translated to savings in irrigation water, peaches on regulated deficit irrigation save 3 ML/ha while pears would save 2 ML/ha. Even greater savings have been reported for peaches in China where irrigation was reduced from 3.0 to 1.4 ML/ha without sacrificing yield.

Recommendations for managing regulated deficit irrigation in peaches

A detailed regime of irrigation management for peach production has been devised, and is summarised below. See also Figure 6 on moisture release curves for a sandy loam and a light clay that will enable conversion from soil water tension to volumetric soil water content.

Period 1 - from flowering to stone hardening. Fruit cell division is active and tree canopy is developing. Maintain soil water tension between 8 and 40 kPa.

Period 2 - from the start of stone hardening to 6 to 8 weeks before harvest. Fruit growth is slow and shoot growth is potentially rapid. Regulated deficit irrigation can be applied. To reduce vegetative vigour, withhold irrigation until soil water tension reaches 200 kPa.

Period 3 - final 6 to 8 weeks harvest. Fruit are now growing rapidly, and must generate a substantial positive turgor to achieve full volume by harvest. Restore irrigation, and maintain soil water tension between 8 and 40 kPa.

Period 4 - post-harvest phase. Tree water use is greatly diminished, and irrigation can be greatly reduced. Allow soil water tension to reach 200 kPa.

As an aid to irrigation scheduling, suggested crop factors are summarised below and represent the fraction of pan evaporation that should be applied as irrigation water.

CROP FACTORS FOR SCHEDULING IRRIGATION FOR PEACHES

	FLOWERING	FRUIT GROWTH STATUS			POST-HARVEST
		Stage 1	Stage 2	Stage 3	
Standard irrigation	0.4	0.4	0.6	1.0-1.2	0.6
Regulated deficit irrigation	0.4	0.4	0.3	1.0-1.2	0.3

Crop factors are an approximate guide only, and soil water should be monitored to check irrigation effectiveness for particular sites. In the example above for peaches, crop factors are calling for replacement of about 30% of pan evaporation during regulated deficit irrigation. In pear orchards, that figure can be reduced to about 20%.

Recommendations for scheduling irrigation for peach and pear orchards

Successful regulated deficit irrigation hinges largely on effective irrigation scheduling. Soil water deficit must be monitored and managed in a way that ensures tree growth is limited during critical phases but sustained for the season as a whole. Recommendations for doing this are as follows:

General techniques

1. Measure fruit and shoot growth to determine the regulated deficit irrigation period for fruit species/varieties in an orchard.
2. Excavate one side of a tree to determine root distribution, including information on rootzone width and depth.
3. Determine the wetting pattern of the irrigation system and estimate wetted rootzone.
4. Develop a season irrigation plan for run time and interval based on soil type, wetting pattern and average pan evaporation.

5. Install soil water sensors (preferred measure is soil water tension using gypsum blocks at 30 cm and bottom of rootzone in shallow soil, at 30 cm, 60 cm and bottom of rootzone in deep soil).

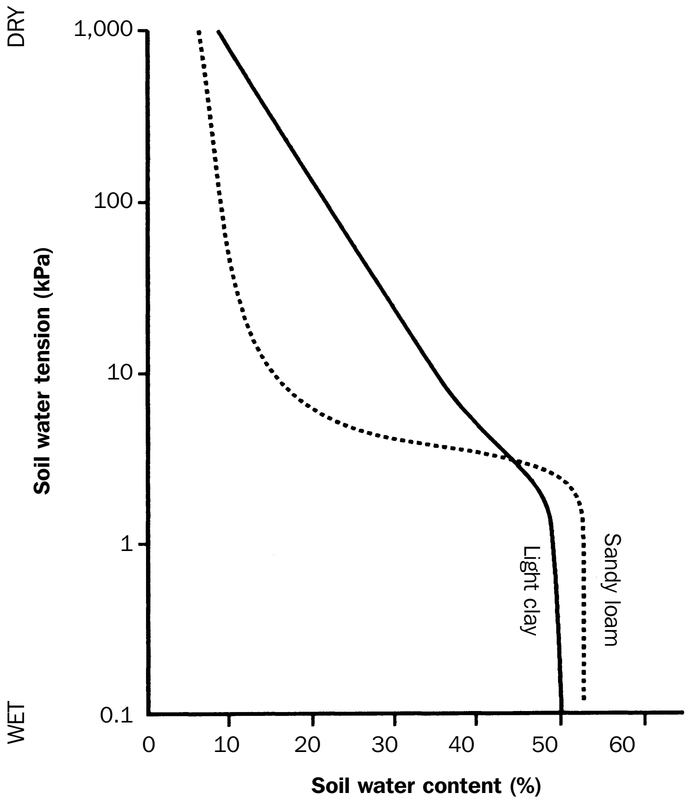
During regulated deficit irrigation period

1. Measure and record soil water tension and irrigate when the entire rootzone dries out to a minimum of 200 kPa.
2. Irrigate to wet the top 30 cm of the rootzone.
3. Measure and record soil water 6 to 12 hours after irrigation and, if necessary, adjust the amount applied in previous irrigations to wet soil to 30 cm depth.
4. Irrigate when the wetted rootzone soil at 30 cm depth dries out to 200 kPa.
5. Measure pan evaporation between irrigations, and irrigate in future years based on this cumulative evaporation.

During rapid fruit growth

1. Irrigate to wet at least the top 60 cm of rootzone.
2. Measure and record soil suction 6 to 12 hours after irrigation and, if the soil is drier than 30 kPa (sandy soil) or 50 kPa (clay soil) at 60 cm, apply more irrigation.
3. Irrigate when the wetted rootzone soil water tension at 30 cm depth dries out to 30 or 50 kPa.
4. Measure pan evaporation between irrigations, and irrigate in future years based on this cumulative evaporation.

Figure 6. Generalised water release curves for contrasting soils (sandy loam compared with a light clay). Starting with a wet soil (around 50% volumetric soil water content and soil water tension 0 to 2 kPa) and allowing water extraction by transpiring plants to proceed, both soils fall to wilting point at about 10% volumetric soil water and 1000 kPa soil water tension. The light clay shows a steady (near linear) increase in tension with decrease in volumetric water-content over that range. Soil water tension in the sandy soil initially changes little with loss of volumetric soil water, but then increased dramatically with further extraction of water below a volumetric content of around 20%. Onset of plant water tension is thus more abrupt on a sandy loam than on a light clay (based on Mitchell and Goodwin 1996).



Case study

Peaches in the Goulburn Valley

As part of an extension program in the Goulburn Valley, sites were established on growers' properties to demonstrate regulated deficit irrigation. Growers were interested in controlling vegetative vigour in high-density orchards and saving water. One site consisted of 6-year-old Golden Queen peach trees on Tatura Trellis irrigated with 45 L/hr microjets (one every second tree). Thirty trees (3 rows each of ten trees) received normal irrigation and thirty received deficit irrigation (also 3 rows of ten trees). Measurements recorded to indicate water use efficiency and vigour control included water applied, soil water (tensiometers and gypsum blocks), butt diameter and fruit growth.

Regulated deficit irrigation was applied from the first week of November to the last week of December to provide about 40% of pan evaporation while control trees received full irrigation. Soil tension was maintained at between about 0 and 65 kPa on the control treatment and between 0 and 200 kPa on the regulated deficit irrigation treatment. For the rest of the season, soil suction was maintained between 0 and 50 kPa on all of the trees.

Fruit growth was measured over the season (120 fruit per treatment). There was no difference in fruit size between the regulated deficit irrigation-treated trees and the controls. Tree butt size was used as an indicator of vigour. Overall, the butt diameters of the thirty trees irrigated under the regulated deficit irrigation strategy were smaller at the end of the season. The grower also noted reduced tree vigour, with more fruiting wood established.

Less water was applied under regulated deficit irrigation management compared to normal irrigation, with a saving of 2.3 ML/ha. Total irrigation for the control was 7.9 ML/ha, compared with 5.6 ML/ha under regulated deficit irrigation.

Regulated deficit irrigation for wine grapes

Deficit irrigation is now established practice for at least half of the area planted to red wine varieties in Australia. Even though pioneering work on viticultural application of regulated deficit irrigation was done with Gewurztraminer and Chardonnay, white varieties are generally less likely candidates for regulated deficit irrigation because of the current pricing policy for harvested fruit (summer 2002). Red grape returns to growers are driven by colour, °Brix and tonnage. Any bonuses offered are based on °Brix and other quality attributes such as colour that are enhanced under regulated deficit irrigation.

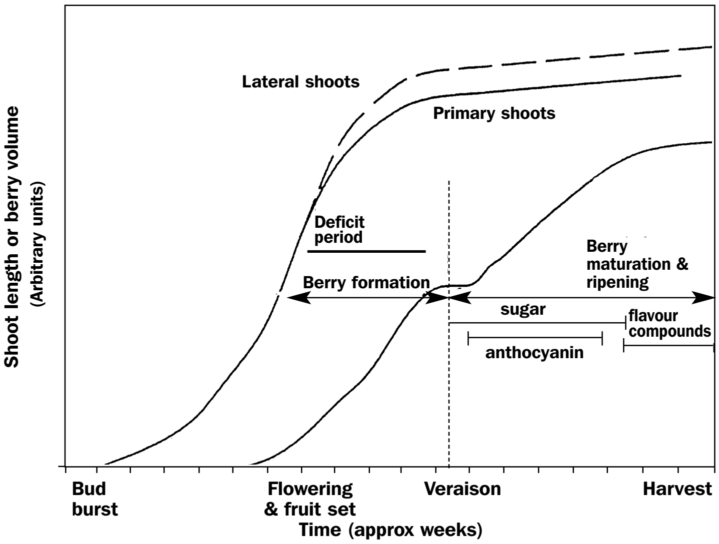
By contrast, yields from white varieties of wine grapes can be reduced by regulated deficit irrigation, with only a moderate trade-off in the form of increased °Brix, so there is less incentive to adopt deficit irrigation even though some of the highest value white wine varieties such as Riesling from Clare Valley (SA) and Semillon from the Hunter region (NSW) are either dry-grown or partly dry-grown. Another exception is Chardonnay where wines can benefit from more tannin (ex seeds) and from skin-derived constituents that lend structure.

As an added incentive for adopting regulated deficit irrigation for red varieties in hot climates, deficit irrigation between fruitset and veraison (berry softening and onset of sugar accumulation) usually accelerates ripening and improves colour provided maximum daily temperatures during ripening are not extreme. As a general rule, the sooner a red variety reaches maturity and is harvested, the better the wine, so the economic implications of successfully applied regulated deficit irrigation for growers and red wine makers are clear.

In peach and pear orchards, water is withheld during a prescribed phase of fruit and shoot growth. A soil water deficit is allowed to develop from about 6 weeks after flowering to about 6 weeks before harvest. Such a schedule would not generally suit grapevines, rather timing needs to be related to berry formation versus berry maturation and ripening (see Figure 7). Adapting regulated deficit irrigation from orchards to vineyards requires an appreciation of key differences in growth stages between fruit trees and grapevines.

Springtime budburst in a stonefruit orchard is a time of flowering, whereas springtime budburst in a vineyard involves mainly vegetative growth (there are important developmental processes

Figure 7. Grapevine growth stages emphasising shoot growth ahead of flowering, and with fruit enlargement in three phases. Regulated deficit irrigation is imposed so that vine stress builds up after flowering; full irrigation is restored just before veraison (see veraison in Figure 10). (Based on B.G. Coombe, unpublished data.)



underway in grapevine buds during spring, but these are not visible). In fruit trees, current season reproductive development precedes vegetative growth, whereas budburst, shoot emergence and rapid extension all precede current season reproductive development in grapevines (Figure 7). To gain benefit from applying regulated deficit irrigation, irrigation management must be linked to vine growth stages and not simply be calendar driven.

Unlike fruit trees, flowering in grapevines follows shoot growth by some weeks, and shoots are still growing strongly (though slowing) during the critical phases of flower fertilisation and fruitset. Like fruit growth in orchards, berry enlargement on grapevines has two phases of active growth separated by a lag phase, referred to in Figure 7 as berry formation and berry maturation/ripening. Veraison signals the end of berry formation. During berry formation, volume increase is a result of active cell division plus some enlargement of those cells.

During maturation, berry volume increase is entirely a result of cell enlargement. However, plant water stress around flowering and fruitset can cause flower and berry abscission. Even though withholding irrigation during early stages of berry formation is often the only way a viticulturist can restrict shoot growth, this strategy is risky, especially in warmer areas. A safer option is to manage irrigation in a way that leads to grapevine moisture stress developing full intensity midway through berry formation, and at about the time lateral shoot growth becomes active (see 'Deficit period' in Figure 7).

Developing a regulated deficit irrigation strategy for grapevines

In 1990 Hardie and Martin developed a conceptual framework for imposing just enough vine-water tension to slow shoot growth without a similar loss in photosynthetic carbon gain. A 'target zone' of leaf water tension between about 500 and 900 kPa was envisaged (i.e. leaf water potential between −0.5 MPa and −0.9 MPa) where shoot growth had virtually stopped, but leaf photosynthesis was little affected (within a temperature range of 20 to 35°C). Generic guidelines were devised to maintain vine moisture status within the 'target zone' to make them 'independent of specific vineyard characteristics'. Their soil-water management strategy was as follows:

Budburst – flowering
Winter and spring rain usually predominates. Ensure soil water tension does not exceed 30 kPa. Avoid waterlogging.

Flowering – fruitset
Maintain soil water tension around 10 kPa throughout the rootzone.

Fruit set – veraison
Allow rootzone soil water tension to increase to a maximum of 80 kPa (i.e. the limit of the tensiometer range). If irrigation is necessary, wet no more than 25% of the rootzone to 10 kPa.

Veraison – harvest
If irrigation water is readily available, maintain rootzone soil water tension at 80 kPa. If water is scarce, allow rootzone soil water tension to increase to a maximum of 200 kPa. (Instrumentation additional to tensiometers needed).

Harvest – leaf fall
Autumn rain usually predominates. Avoid rootzone soil water tension greater than 200 kPa.

Dormancy
Winter rain is usually predominant. Avoid soil water tension greater than 200 kPa. If rootzone soil water tension is greater than 30 kPa shortly before budburst, thoroughly wet the rootzone to 10 kPa. Avoid waterlogging.

Qualifications were added to these guidelines such as the following:

- collecting soil moisture data from the driest and wettest parts of each vineyard so that averages could be made over the whole vineyard
- maintaining soil moisture tension in the 60 to 80 kPa range to restrain growth under high evaporative conditions on sandy soils
- allowing soil water tension to reach from 100 to 200 kPa to restrain growth under mild evaporative conditions on well structured soils with a wide range of vine-available moisture.

This strategy was used by Hardie and Martin to successfully regulate shoot and berry growth for Gewurztraminer across extremes of the climatic spectrum. Average vineyard yield increased 60% over four seasons, and across a wide range of Australian viticultural environments. Locations ranged from cool to very hot, on soils that varied from heavy clays to light sands. Planting densities ranged from 1,323 to 5,882 vines/ha, and pruning systems varied from single cane to minimal pruning. Trickle irrigation was the favoured system, but under-vine sprinkler, over-vine sprinkler, furrow and flood irrigation were all used successfully.

Goodwin and Jerie further developed management guidelines for deficit irrigation and set about designing regulated deficit irrigation treatments and measurement protocols for three situations that covered a wide range of site conditions in cool climates, namely:

- Chardonnay growing in a deep sandy loam at Seppelt's Barooga vineyard
- Cabernet Sauvignon growing in a shallow granitic sand overlying a sandy clay at Mt Helen vineyard
- Cabernet Sauvignon growing in a shallow sandy loam overlying a clay at Dromana Estate on Mornington Peninsula.

At each site, irrigation was withheld to impose moisture stress over three treatment periods, as follows:

1. budburst to veraison
2. one month starting at veraison
3. starting one month after veraison, and maintained till harvest.

Regulated deficit irrigation grapevines were compared with fully-watered controls (all trickle irrigated) and data collated over 5 years.

In general terms, vine yields were most affected by regulated deficit irrigation during period 2 (after veraison) whereas shoot extension, and thus canopy volume, was most affected by regulated deficit irrigation during period 1 (before veraison). Overall, regulated deficit irrigation before veraison reduced shoot growth, increased berry pH and decreased titratable acidity, but the impact of stress during period 1 on fruitset was significant with berry number on regulated deficit irrigation-managed vines reaching only 75% of fully-irrigated controls. By contrast, regulated deficit irrigation during period 2 or 3 had no impact on berry number at harvest. Post-veraison regulated deficit irrigation reduced yields, °Brix and titratable acidity, while late-season regulated deficit irrigation (period 3) also reduced °Brix and titratable acidity.

Unlimited water has long been known to delay ripening, but the converse does not necessarily apply and, contrary to anecdotal information at that time, late-season moisture stress neither hastened ripening nor enhanced °Brix at harvest. Indeed, Goodwin and Jerie concluded that ‘the greater the water stress post veraison, the greater the reduction in yield and soluble solids’. McCarthy reached the same conclusion from his later experiments on Shiraz at Waikerie in South Australia (discussed later in this chapter).

Regulated deficit irrigation during either period 1 or period 2 caused grapevines in central Victoria to produce smaller berries but there was some improvement in quality when much less water was applied. Based on this and their research experience with stone- and pome fruit, Goodwin and Jerie devised guidelines for irrigation management in regulated deficit irrigation vineyards under cool to warm climate conditions at Barooga in Victoria.

Their recommendations emphasised evaporative conditions and soil moisture monitoring, compared with the emphasis on vine water status of Hardie and Martin, and were as follows:

- In soils with a coarse textured A horizon, such as at Dromana Estate or Mt Helen, impose regulated deficit irrigation by withholding irrigation until soil water tension in the mid-zone of the grapevine root system has dried out to about 100 kPa (measured with gypsum blocks), and then replace only 20 to 25% of pan evaporation for the duration of regulated deficit irrigation.

- On heavier soils such as a fine-textured clay loam, allow the mid rootzone to dry down to about 200 kPa. In either situation, apply only enough irrigation to wet down to the mid rootzone. Deeper soil can stay dry.

- Manage successive cycles of irrigation so that about the same volume of soil is being re-wetted each time. This ensures that the same population of vine roots experience the wetting-drying cycles. Roots sustained in this way will stay healthy and thus remain effective absorbers of soil water from the wetted zone. Vineyard water savings under regulated deficit irrigation were about 30%.

Regulated deficit irrigation viticulture in a hot climate is more exacting, and there is less margin for error in terms of gauging the intensity and duration of the imposed soil moisture stress. Recognising a need for a detailed assessment of grapevine response to regulated deficit irrigation in a hot climate, Michael McCarthy conducted research into growth and productivity of *Vitis vinifera* L. *cv*. Shiraz under irrigation near Waikerie in South Australia over three growing seasons, i.e. 1992-3, 1993-4 and 1994-5. Key outcomes are summarised briefly below (see also Figure 8).

McCarthy's research involved a comprehensive set of irrigation treatments along with soil moisture monitoring and measurements of grapevine response. The site was a mature vineyard, previously irrigated with overhead sprinklers but converted to full-cover microjets.

This vineyard was on a deep porous soil suited to rapid vine growth, and experienced dry and warm to hot summers. The experiment comprised nine replicates of 8 irrigation treatments, as follows:1. fully irrigated, 2. regulated deficit irrigation after flowering, 3. regulated deficit irrigation before veraison, 4. regulated deficit irrigation after veraison, 5. regulated deficit irrigation before harvest, 6. regulated deficit irrigation between flowering and veraison, 7. regulated deficit irrigation between veraison and harvest, and 8. non-irrigated.

The depth of water applied to fully irrigated vines during a growing season ranged between 550 and 602 mm. Regulated deficit irrigation grapevines received 240 mm less in 1994-5. Average rootzone soil water tensions under fully irrigated grapevines were never higher than 30 kPa, while soil water tensions for regulated deficit irrigation vines were around 1000 kPa and above. Midday leaf water tensions on those stressed vines were around 1400 kPa (leaf water potential of – 1.4 MPa). Daily patterns of leaf water tension and stomatal conductance were also affected.

Water stress between flowering and veraison restricted shoot growth with shoots between 15 and 30 cm shorter than fully irrigated vines. Shoots on non-irrigated vines (1994-5) were from 30 to 40 cm shorter, and pruning weights were only about 30% of those from fully-irrigated vines. McCarthy reported, "…Surprisingly, there was no effect of water deficit treatment on the date of budburst, percent budburst, fruitfulness, anthesis date or veraison".

The effects of regulated deficit irrigation treatment on berry growth were most obvious in 1994-5. In summarising outcomes from this season, McCarthy reports: "…water stress between anthesis and veraison reduced berry weight relative to fully irrigated by about 17 percent by the end of the stress period compared to about a 5 percent reduction in berry weight when irrigation was withheld between veraison and maturity…There was no compensatory increase in berry weight when normal irrigation was resumed in either of these treatments. Water stress during the period before harvest had no effect on berry weight. The reduction in berry size (Figure 8) was correlated with average rootzone soil matric potential and a soil water stress index."

This trial established that a well designed and carefully monitored irrigation system offers:

- substantial savings in irrigation water
- the potential for applying deficits in a strategic way to limit unwanted shoot growth
- improved wine quality as a result of smaller berries.

Berry size at harvest was shown to be most sensitive to water deficit after flowering. It was also shown that the intensity of deficit needed to achieve this would reduce shoot growth. One key condition in implementing regulated deficit irrigation was that soil water must be measured at least twice a week to ensure precise timing of irrigation water application.

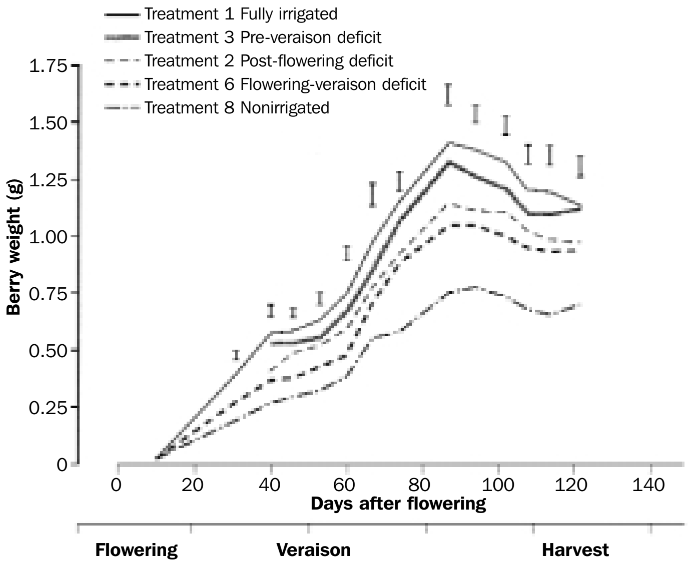


Figure 8. Outcomes from selected regulated deficit irrigation treatments on Shiraz grapevines at Waikerie during the 1994-95 growing season (based on McCarthy 1997b).

An apparent paradox regarding grapevine moisture stress and ripening was also addressed. In striving to reach minimum maturity levels from highly productive vineyards in the Murray-Darling Basin, growers often withhold irrigation before harvest in the belief that water stress will enhance maturity through higher sugar levels. Based on experiences with Shiraz, McCarthy advises, “Data from the Waikerie experiment indicates that any enhancement of juice °Brix from water stress before harvest may be due to berry shrivel and not increased solute content per berry”.

With growers encouraged by these initial positive results, regulated deficit irrigation viticulture on deep sandy soils of the South Australian Riverland continued to expand. By 1993-94, regulated deficit irrigation was becoming established practice and was drawing on additional results from large scale trials with varieties such as Shiraz at Waikerie (on own roots) and Ruby Cabernet (grafted to Ramsey rootstock). A number of Cooperative Research Centre for Viticulture-sponsored *Research to Practice* workshops followed, and by 2002 management guidelines had been further refined for both Riverland and Sunraysia vineyards.

Regulated deficit irrigation is now becoming a more common management practice in Sunraysia, and the slightly reduced yields are more than offset by improved quality. Once that improvement in quality (with red varieties) is recognised in contractual arrangements, financial returns should be higher.

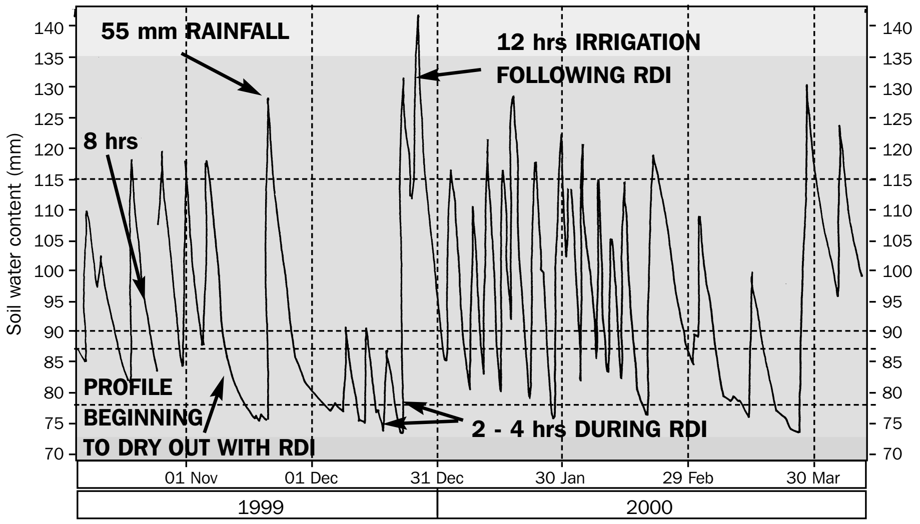
Vineyard irrigation systems for regulated deficit irrigation

A drip irrigation system, though not essential, will help with regulated deficit irrigation management, and best practice calls for closely spaced emitters (from 50 to 60 cm apart) to ensure that all vines receive some water during deficit phases. Shown in Figure 9 is an example of monitored changes in soil moisture under drip irrigation, where the soil profile (a deep sandy loam) initially took seven days to dry (early November), and a further five days to re-dry after 55 mm of rain.

Such an early return to deficit after rain is one of the main advantages of using a dripper system for regulated deficit irrigation. The transpiring vines draw on a smaller volume of wetted soil compared to either full-cover sprinkler irrigation or some form of surface flow, and thus enter a stress condition more quickly.

In this example, grapevines would have been returned to a stress condition (readily-available water exhausted) once soil moisture content fell to below about 80 mm (volumetric soil moisture content summed over a depth of from 20 to 80 cm). A series of brief irrigations (2 to 4 hours during regulated deficit irrigation) did not push soil water content above the full point. A 12-hour irrigation period was necessary to re-wet the entire profile following the regulated deficit irrigation period that ends just before veraison.

Figure 9. A representative example of changes in soil water content (mm of summed moisture from 20 to 80 cm deep) under a Shiraz vineyard in Sunraysia (1999 – 2000 growing season). Unpublished data courtesy Jeremy Giddings, Agricultural Research and Advisory Station, Dareton, NSW Agriculture.



Most soil types will be hard to wet after regulated deficit irrigation, and about double the volume of a regular irrigation will be necessary to fully restore profile moisture. A quick succession of close irrigation cycles (to the point of run off) is often required.

In contrast to drip, full-cover sprinklers result in a greater wetted root volume. Vines managed this way take longer to reach a deficit state compared with drip systems. As a result, vineyards with full-cover irrigation will take longer to dry down in spring (seasonal conditions permitting), so irrigation needs to be withheld earlier if regulated deficit irrigation is to take effect soon after fruitset.

Soil type

Soil type is an issue with regulated deficit irrigation. Sandy loams dry and re-wet more readily than clay soils, and are generally easier to manage. Although a clay soil has theoretically a greater range of plant-available moisture (see Figure 6, page 11), root growth can be slower. Total length of roots per unit volume of soil is thus reduced and a smaller fraction of plant-available soil water is actually extracted. Consequently, there is a much greater discrepancy between plant-**available**, as opposed to plant-**extractable** soil water in a clay soil compared to a sandy soil.

In addition, grapevine root systems tend to form a much shallower rootzone on a clay soil, so irrigation must be managed precisely to reduce the margin for error. As with any regulated deficit irrigation regime, apply only enough stress to slow down vegetative growth in early spring, or after berry set. Do not sustain stress beyond veraison, especially if hot dry weather is expected. Contrary to popular belief, Mike McCarthy's early experience with Shiraz at Waikerie implies that berries will not ripen more quickly, colour development will not be enhanced, and sugar accumulation will be impaired if moisture stress continues beyond veraison. Subsequent experience (2001 - 2002) showed colour increased in proportion to berry size reduction.

Scions and rootstock

Scions and rootstocks differ in their sensitivity to regulated deficit irrigation. Scion varieties grafted to Ramsey tend to grow quickly, and regulated deficit irrigation is a useful way to control that growth, even when applied in early spring to contain canopy volume. Scion varieties grafted to Schwarzmann, Kober 5BB (clone Teleki 5A) and K5132 can be less tolerant of drought stress, but are responsive to regulated deficit irrigation on well structured deep soils. Scions on Ruggeri and Paulsen grow less quickly than those grafted to Ramsey, and are thus easier to manage with regulated deficit irrigation.

There are critical differences in scion sensitivity. Most regulated deficit irrigation research has been on Shiraz vines, a variety which has been consistently responsive to deficit irrigation. Given the rapid growth of Shiraz vines, deficit irrigation can be used to good effect to contain canopy growth (as at Karadoc). Once tendrils drop, or basal leaves die and fall, water stress is relieved in good time for flowering and fruitset. Regulated deficit irrigation can then be introduced after fruitset and until veraison. Well managed Shiraz vineyards under regulated deficit irrigation in Sunraysia have yielded 35 t/ha of high quality fruit. Ironically, overcropping then becomes an issue, and Shiraz grapevines managed with regulated deficit irrigation might fall into decline. If this happens, grapevine vigour can be restored with full irrigation for a single growing season every 3 to 4 years.

Cabernet Sauvignon, as grown in Sunraysia, must be more carefully managed compared with Shiraz because visible symptoms are masked, and tendrils are not dropped as readily. Unlike Shiraz, shoots on Cabernet Sauvignon continue to grow during regulated deficit irrigation (although at a reduced rate), so that soil water monitoring is more critical. Cabernet Sauvignon fruitset can be as much as 10 days later than Shiraz, and water stress after fruitset does not need to be as long or intense to be effective. If berries do shrivel as a result of too much stress, volume recovery is less likely compared with fruit on Shiraz grapevines.

Ruby Cabernet is a naturally high-yielding variety, and regulated deficit irrigation can be used successfully to reduce crop loads and accelerate ripening. This follows the principle outlined earlier that faster maturation of wine grapes in hot climates favours higher quality. Earlier ripening also brings Ruby Cabernet into line with harvest dates for other red wine varieties.

Merlot is regarded as a weaker variety in hot climates such as experienced in Sunraysia, and it is less responsive to regulated deficit irrigation. Criteria appropriate for Shiraz (such as tendril abscission) are not applicable to Merlot. Based on anecdotal reports, Merlot fails to recover once cumulative moisture stress has resulted in loss of tendrils.

Similarly, Grenache is less favored for regulated deficit irrigation management, but for different reasons. Regulated deficit irrigation applied to Grenache can result in bunch stem death and heavy loss of set berries. In addition, shoots intended for next season's canes can fail to lignify, and eventually die. Regulated deficit irrigation is not recommended for this variety.

CASE STUDIES

Regulated deficit irrigation viticulture in Western Australia

Regulated deficit irrigation is practised widely in Western Australian viticulture with 50% of red wine varieties being grown under this system on an area basis, particularly in those regions with a reliably dry growing season. Rain in late spring and sometimes early summer, on top of winter rain, keeps soil profiles wet in southwest areas such as southern Margaret River, Pemberton and Denmark, and makes those areas less suited to deficit irrigation. Grapevines in those regions generally experience only occasional water stress between fruitset and veraison, thus limiting prospects for successful regulated deficit irrigation. Where deficit irrigation is practised, growers use covercrops that use a lot of moisture to de-water vineyard profiles.

By contrast, rainfall is lower in late spring and early summer in the north Margaret River and inland Great Southern and Swan regions so vines there are more responsive to regulated deficit irrigation. Many growers have used regulated deficit irrigation successfully, except those on sandy soils where low waterholding capacity makes the risk of severe drought stress too great. Notwithstanding those limitations, Neil Lantzke, from Agriculture WA, has collected some useful experiences from his regulated deficit irrigation demonstration plots on properties in the Mooliabeenee area. His aim was to help growers adopt improved practices that would enhance grape quality by managing a regime of deficit irrigation according to soil water sensors and long-term evaporation data. One case study from his June 2002 interim report is outlined below.

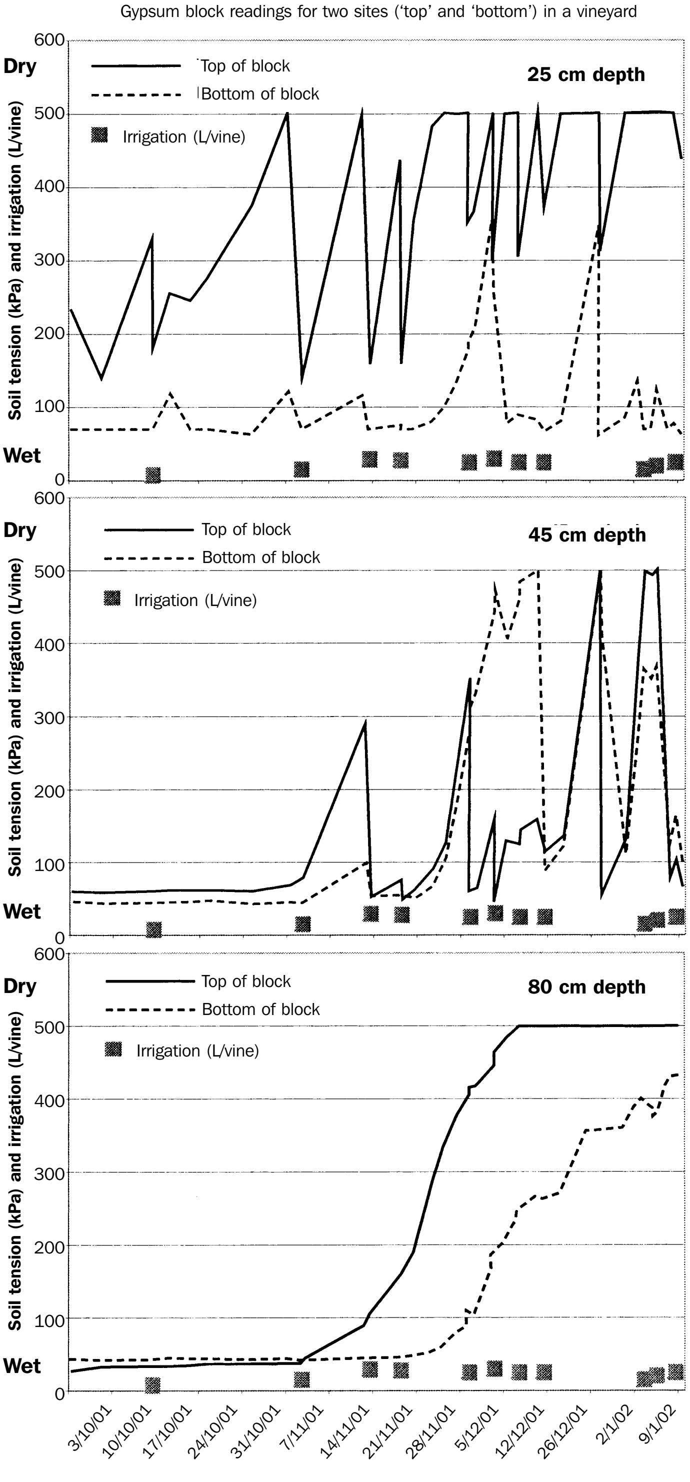
Mooliabeenee, WA

The demonstration vineyard had been established for 4 years on a gentle slope (about 5%) with rows of Shiraz (own roots) running across the slope. The loam soil graded into clay at depth and was derived from granitic rock. There was no discernible watertable. Soil pits revealed abundant feeder roots down to 1.5 m, with occasional structural roots to 2 m. Irrigation water was taken from a farm dam, and distributed with 2.5 L/hr drippers at a 100 kPa from a single line. In-row spacing between vines was 2 m, with two drippers evenly spaced per vine. Irrigation was withheld early in the season except for two fertigation applications in mid October and early November. Measured irrigation started 21 November and was applied until the third week of February 2002. A total of 1 ML/ha was provided during the 2001-2002 growing season. Gypsum block soil-water sensors were installed at three depths (25, 45 and 80 cm). Changes in soil water over time during the early part of the 2001-2002 season at two locations (up-slope and down-slope) are summarised in Figure 10.

Regulated deficit irrigation demonstration site for Shiraz grapevines (own roots) from the Mooliabeenee irrigation study. Photo courtesy Neil Lantzke, Agriculture WA, South Perth.

Consistent with a shallow soil, up-slope sensors showed that rootzone soil water was reduced early. Eighty centimetre values were affected by mid November, reaching ‘dryness’ (soil water tension of 500 kPa) a month later. By contrast, down-slope sensors did not reach ‘dryness’ till early January. Soil water sensors at 25 cm responded to each irrigation, showing especially big changes on the shallow soil up-slope. Data from 45 cm follow those same general trends, showing a relaxation of soil water tension with irrigation, although the time course of tension build up and subsequent relaxation sometimes differed greatly between up-slope and down-slope sensors.

Figure 10. Soil water changes in a regulated deficit irrigation vineyard from 3/10/2001 to 9/1/2002. Soil water tensions were taken from gypsum blocks buried at 25, 45 and 80 cm depth (top of block and bottom of block). At 25 cm depth, dynamic changes in response to vineyard evapotranspiration and irrigation are especially evident at the top of this vineyard. Soil water tension traces for 80 cm depth show that grapevines are drawing water from depth over the entire growing season, and that extractable reserves are already largely exhausted (tension 500 kPa) by mid December at the top of this vineyard. (Unpublished data courtesy Neil Lantzke, Agriculture WA, South Perth.)



Irrigation was discontinued in late February when dam water became limiting. Subsurface layers (80 cm) then stayed dry until the end of observations in late May despite rain in mid April (a total of 40.5 mm fell between 16 and 23 April 2002). Clearly, transpiring vines had extracted a lot of water from soil layers down to 80 cm at both locations, although soil pits dug afterwards to two metres revealed both structural roots and a moist substratum that would have allowed water extraction from even deeper layers in the soil profile.

Measured against expectations, regulated deficit irrigation, as practised on this WA vineyard, was a success. Vines were free of water stress during flowering and fruitset, drawing on subsurface water reserves built up after the previous winter-spring rains. The regulated deficit irrigation schedule succeeded in drying the profile before veraison, and restricted vegetative growth.

Measured irrigation started 21 November and continued through veraison at a rate equivalent to about 25% of vineyard evapotranspiration until mid February when irrigation water from the farm dam became limiting.

Yields varied according to position (top *vs*. bottom of the slope) and highlight how difficult it is to manage irrigation in a vineyard with soils that differ markedly in their waterholding capacity. Data summarised below (Table 2) show the differences recorded in yield, but also emphasise that apart from a small difference in colour, there was no significant trade-off between yield and berry attributes due to differences in vine performance.

Table 2. Western Australia Shiraz regulated deficit irrigation demonstration site.

LOCATION IN VINEYARD	YIELD (t/ha)	°BRIX	pH	TA* (g/L)	COLOUR† (mg/g)
Top of slope	5.5	25.2	4.15	3.4	1.44
Bottom of slope	10.0	25.5	4.14	3.3	1.28

*TA. Titratable acidity and is expressed as tartaric acid g/L of juice
†Colour is expressed as mg anthocyanin/g berry fresh weight.

Further reading: Jim Campbell-Clause and Diana Fisher (1999), *Irrigation techniques for winegrapes* (Western Australia Agriculture Farmnote No 66/99).

Hanwood, Murrumbidgee Irrigation Area, New South Wales

This field trial was set up in McWilliams' vineyard on a heavy clay loam previously used for rice growing, and with an aquitard (impervious layer) at 40 to 50 cm. Shiraz grapevines (own roots) were established in 1994 and trained onto a single wire cordon and mechanically pruned. The trial was drip irrigated using 3 L/hr drippers and soil water monitored regularly with a neutron moisture meter. Treatments started in spring 2000 and consisted of three different irrigation methods (standard drip, regulated deficit irrigation and partial rootzone drying) in combination with three rates of nitrogen application:

- 40 kg N/ha between bloom and veraison
- a split application of 20 kg between bloom and veraison followed by a further 20 kg between harvest and leaf fall
- 40 kg between harvest and leaf fall (all treatments are repeated six times and within a total area of 1.2 ha).

Results from regulated deficit irrigation treatments are summarised in Table 3 on page 23 and in Table 4 on page 24.

Neutron probe readings from standard drip irrigation and regulated deficit irrigation-treated grapevines confirm that irrigation was withheld from regulated deficit irrigation grapevines from early October 2001 and was restored in early January 2002. Grapes were harvested from the regulated deficit irrigation x N treatments on 1 March 2002, and from the Standard drip x N treatments on 15 March 2002.

Harvest data for the 2001-2002 growing season (Table 3) show that regulated deficit irrigation led to reduced yield, reduced canopy size (inferred from pruning weights), and smaller berries but increased levels of anthocyanin per unit berry fresh weight. Bunches were smaller and looser and less vulnerable to bunch rots. There were no clear interactions between irrigation treatment and mode of N application, so that data from N treatments has been averaged in making overall comparisons of yield and wateruse between irrigation treatments (Table 4).

Irrigation water was applied with under-vine drippers (3 L/hr) with three emitters on each side of each vine (in-row single dripper line for standard drip treatment and regulated deficit irrigation, but dual and independent dripper lines for partial rootzone drying).

Table 3. Yield, pruning weights and berry composition for Shiraz grapevines (own roots) in response to irrigation and nitrogen addition to a heavy clay soil at Hanwood (MIA) for 2001-2002.

IRRIGATION TREATMENT	N MODE	YIELD (kg/vine)	PRUNING (kg/vine)	°BRIX	BERRY WT (g/berry)	COLOUR* (mg/g)*
Standard	40+0	20.29	3.29	22.62	1.55	0.82
	20+20	20.24	3.37	23.17	1.52	0.94
	0+40	21.91	2.85	22.87	1.48	0.88
Partial rootzone drying	40+0	16.40	2.22	22.22	1.42	0.95
	20+20	16.73	2.41	22.45	1.41	0.97
	0+40	15.16	2.22	22.38	1.50	1.01
Regulated deficit irrigation	40+0	11.45	3.06	21.93	1.17	0.95
	20+20	12.34	2.84	22.53	1.18	1.06
	0+40	10.44	2.74	22.50	1.20	1.10

*Colour is expressed as mg anthocyanins/g berry fresh weight.

Note: N mode refers to fertiliser nitrogen addition where 40+0 = 40 kg N/ha between bloom and veraison, 20+20 = a split application of 20 kg between bloom and veraison followed by a further 20 kg between harvest and leaf fall, and 0+40 = 40 kg between harvest and leaf fall. All treatments are replicated six times and within a total area of 1.2 ha. (Unpublished data courtesy Jessica Wade, Bruno Holzapfel and Kerry DeGaris, National Wine and Grape Industry Centre, Charles Sturt University, Wagga Wagga NSW.)

Productivity and irrigation water use efficiency (Table 4) show that yield was reduced from 21.2 t/ha under standard drip irrigation, to 12.4 t/ha under regulated deficit irrigation. That substantial reduction in yield cannot be attributed solely to smaller berries (Table 3) and must have resulted in part from smaller bunches (with fewer berries per bunch) or fewer bunches per vine or both. Generally smaller and looser bunches under regulated deficit irrigation have been reported, and greater variability in bunch size has also been noted. Irrigation water use efficiency was also much reduced from an average of 3.90 t/ML under standard drip irrigation, down to 2.77 t/ML under regulated deficit irrigation.

Total irrigation applied under regulated deficit irrigation was around 80% of the amount supplied under standard drip irrigation, and should have been enough to maintain productivity. It was noted that canopy growth under regulated deficit irrigation was maintained at 91% of the standard drip irrigation treatment (as inferred from average pruning weights for standard and regulated deficit irrigation in Table 3) and yet yield dropped to about 60%. Presumably, profile moisture during spring and early summer was enough to sustain shoot growth, but then

Table 4. Yield, irrigation and apparent irrigation water use efficiency for Shiraz grapevines (own roots) on a heavy clay soil at Hanwood (MIA) for 2001-2002 (Data averaged across all N treatments).

IRRIGATION TREATMENT	YIELD (t/ha)	WATER APPLICATION (ML/ha)	IRRIGATION WATER USE (t/ML)
Standard drip	21.20	5.44	3.90
Partial rootzone drying	18.70	3.38	5.22
Regulated deficit irrigation	12.40	4.48	2.77

the regulated deficit irrigation grapevines endured excessive stress at critical times during their cropping cycle and yield was greatly reduced as a result. One possible explanation is that because soil water under deficit irrigation was not fully restored to control levels (corresponding to standard drip treatment) until about 20 February and regulated deficit irrigation grapes were subsequently harvested on 1 March, these grapevines experienced soil water deficit for too long into their post-veraison growth and ripening phase. As implied in Table 3, regulated deficit irrigation is not without risk. Regulated deficit irrigation does not mean **no** irrigation. As defined earlier, irrigation frequency under regulated deficit irrigation should be determined by a decrease in water potential below a set limit. In this case study (Table 4) that limit was exceeded.

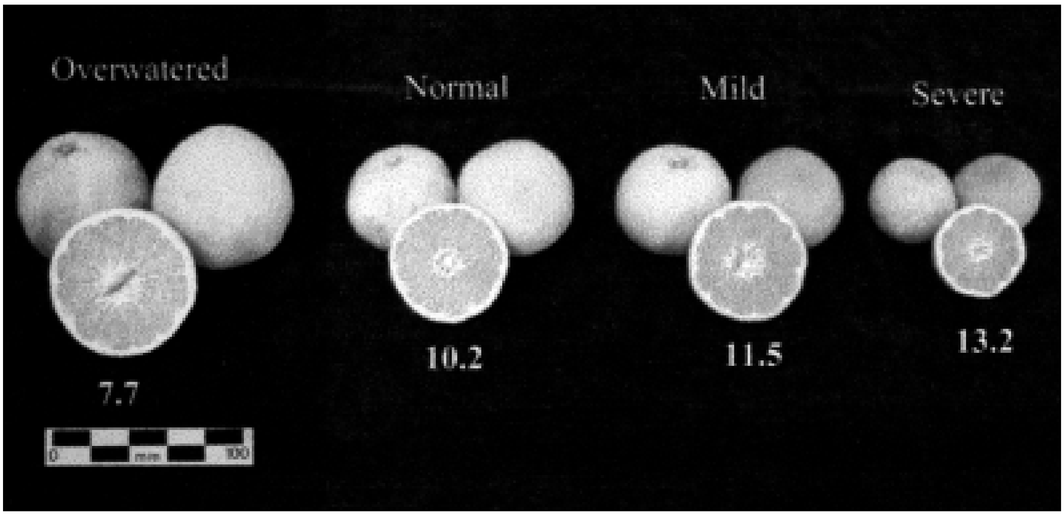
Regulated deficit irrigation for Okitsu Satsuma mandarin

Deficit irrigation can be used to regulate the growth and cropping of some citrus (lemons, oranges and mandarins). Okitsu Satsuma mandarin, a variety newly introduced from Japan, is a good example of this. It commonly sets fruit parthenocarpically, i.e. without fertilisation, on about 30% of flowers and readily over-crops, resulting in some biennial bearing. While trees are normally routinely thinned to smooth out year-to-year variation in productivity, a high percentage fruitset also predisposes the variety to crop regulation with regulated deficit irrigation because set fruit are unlikely to shed when they are moderately moisture stressed.

Trials by NSW Agriculture at Dareton by Graeme Sanderson in January 2002 provide useful insights on the response of this variety to orchard irrigation management.

Graeme Sanderson in the citrus trial area of the Agricultural Research and Advisory Station, Dareton (NSW Agriculture). Photo: Neil Lantzke, Agriculture WA, Perth.

Okitsu Satsuma mandarins exported from New Zealand to Japan are required to have an ideal fruit size of between 55 and 65 mm diameter at 10 °Brix (with a bonus paid for fruit with total soluble solids ≥ 10 °Brix). This standard can be achieved with regulated deficit irrigation under Australian growing conditions. In the NSW Agriculture trials, over-watering (see photo below) produced a large puffy fruit with reduced °Brix (70 mm diameter and 7.7 °Brix). Either normal irrigation or mild regulated deficit irrigation resulted in fruit of desirable characteristics (65 and 62 mm respectively, with 10.2 °Brix) while severe water stress produced sweeter fruit (13.2 °Brix) that were undersize (52 mm diameter). Fruit from over-watered trees was both unpalatable and unmarketable; normal drip or mild stress (regulated deficit irrigation) produced fruit that was both palatable and marketable; and severe stress produced fruit that was palatable but unmarketable on grounds of small size and high content of fruit acid (1.3%).



Okitsu Satsuma mandarins from the Dareton regulated deficit irrigation trial. Photo: Graeme Sanderson, Agricultural Research and Advisory Station, Dareton, NSW Agriculture.

In Sunraysia, South Australia, Okitsu Satsuma mandarin grows so that fruit are firmly set by mid-January and trees can be then managed with regulated deficit irrigation. In the same set of trials, irrigation water was supplied through microsprinklers that wetted the entire orchard floor that was kept bare with herbicide.

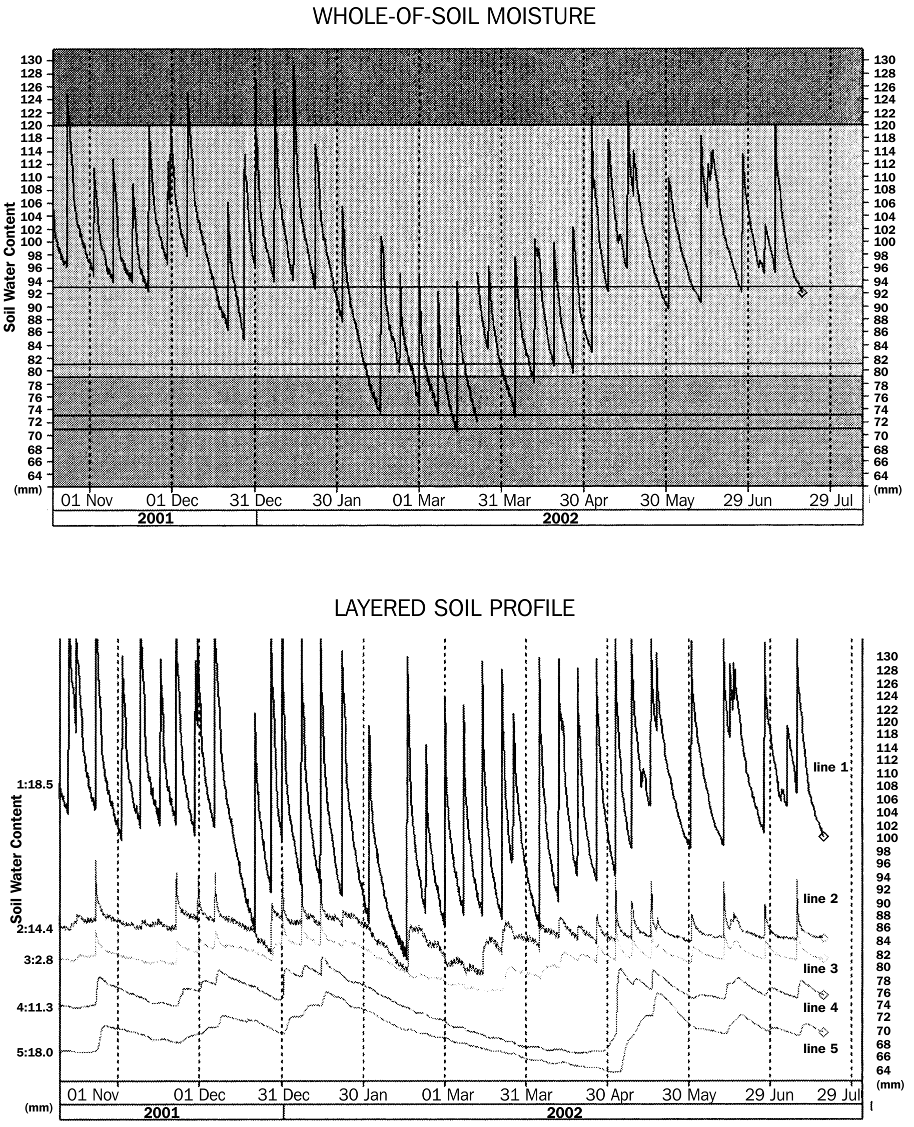
In a typical regulated deficit irrigation cycle (Figure 11) irrigation is reduced, and soil water is extracted through tree transpiration until soil water reserves within the rootzone fall to between 75 and 80 mm (estimated volumetric water content summed 0 - 80 cm depth). That level of soil water corresponds to a pre-dawn leaf water tension of 600 to 800 kPa (equivalent to a leaf water potential of –0.6 to –0.8 MPa). Under summer conditions in Sunraysia, pre-dawn leaf water tension of around 800 kPa is a prelude to severe stress, and was taken as a safety limit for the Dareton trial.

Another visible indicator of impending water stress in mandarin trees at Dareton was a loss of leaf lustre. Soft broad leaves (e.g. grapevine) visibly wilt, but mandarin leaves are structurally resilient compared to grapes and take on a less reflective appearance at leaf water tension around 600 to 800 kPa in early morning (Satsuma on trifoliata rootstock in a light sandy soil).

However, under severe stress at Dareton, mandarin leaves do then visibly wilt (leaf turgor lost) but partially recover after each irrigation. Severe stress during summer would be fatal for trees in hot inland irrigation districts such as Sunraysia. By way of comparison, Okitsu Satsuma mandarin is also grown in Japan under deficit irrigation where pre-dawn leaf water tension (inferred from trial results) would rarely be higher than about 1200 kPa(–1.2 MPa).

About ten cycles of soil wetting and drying between late January and late April were needed for effective regulated deficit irrigation for Okitsu Satsuma mandarin (Figure 11) at Dareton. Fruit were harvested in early May. By extending mild stress up to harvest, final size was contained and flavour was enhanced through an increase in sugar and fruit acid contents.

Figure 11. Cyclical patterns of soil water content over a growing season where regulated deficit irrigation was applied to Okitsu Satsuma mandarins grown at the Agricultural Research and Advisory Station Dareton, NSW Agriculture (unpublished data provided by Graeme Sanderson).



Varying soil water cyclically in this mandarin orchard over an entire growing season (November 2001 – June 2002 in Figure 11b) shows wide changes for the top 10 cm (line 1) but only moderate variation at 30 cm (line 2) and at 50 cm (line 3) in response to successive cycles of moisture extraction and subsequent irrigation. Notably, during regulated deficit irrigation trees are also extracting water from a great depth on this deep sandy loam as implied by a steady downward trend in soil water content at 80 cm (line 4) and at 110 cm (line 5) from mid January to early May. Restoring full irrigation in early May (three-hour runs increased to six hours at that time, and equivalent to an increase from 17 to 34 mm) has clearly enabled water to penetrate to the lower rootzone thereby recharging the profile down to 110 cm (and possibly lower).

CHAPTER 3

PARTIAL ROOTZONE DRYING

Partial rootzone drying grew out of experiments on drought stress in grapevines managed by Brian Loveys from CSIRO Plant Industry. The potential of this research for reducing irrigation water use was gradually realised and work has continued in the last decade to translate the results from research to practice.

Beginnings

In 1990, John Possingham drew Brian Loveys' attention to a row of grapevines next to a line of trees at Blewitt Springs in South Australia. These grapevines had failed to grow vigorously. In explaining this failure to thrive, drought stress was discounted because the vines were irrigated often. Partial drying of the grapevine's root system in response to the demands of the roots of the eucalypts seemed more plausible. While these slower-growing vines showed no other evidence of drought stress, it was surmised that the partially-dry root system had resulted in stomatal closure, and slower growth in vines that stayed turgid.

While it was known that applying the hormone abscisic acid[†] (ABA) to turgid leaves closed stomata, and while drought-stressed plants were known to generate massive amounts of ABA, this connection between the hormone and the functioning of stomata was a feature of drought-stressed plants. Plants not affected by drought stress but still making ABA, which resulted in some stomatal closure, and thus slower growth, didn't seem to make sense. Put another way, it seemed that production of ABA and stomatal physiology could not be separated from drought disruption to plant water relations. Evidence of a functional separation between plant hydraulics and hormone physiology was lacking.

Coincidentally, three researchers, Gowing, Davies and Jones, working at the same time at the University of Lancaster with apple trees, provided evidence of this functional separation in a report published in 1990 and called, 'A positive root-sourced signal as indicator of soil drying in apple, *Malus x domestica* Borkh'.

The paper described how withdrawing water from one side of small apple trees with split root systems gave a stomatal response that was independent of any reduction in leaf water potential, and that removing those drying roots relieved the closing response. Strengthening their case even further, ABA applied externally to turgid plants mimicked the dry-roots effect on stomatal conductance. This showed that a partially dry root system was enough to trigger stomatal closure in a turgid plant.

Pursuing these leads with grapevines, researchers in Adelaide led by Brian Loveys and including Peter Dry, University of Adelaide, and Michael McCarthy, South Australia Research and Development Institute Nuriootpa, devised grafted and own-rooted plants with a split root system. One side was allowed to dry, while the other side was irrigated. In this way, grapevines remained turgid, but were also subject to the physiological influence of stress-related substances derived from the drought-stressed side. The researchers noted that recovery in shoot growth appeared to 'anticipate' dry-pot re-watering (similar to an internal rhythm that had become entrained by a constant schedule of wet/dry).

A picture emerged that ABA did accumulate in the roots of the drying side of the rootzone, and was then either swept into shoots following irrigation of that same side; or could spread into the other side. Alternating cycles of wetting and drying between these two sides thus

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[†] abscisic acid is a drought related plant stress hormone.

provided grapevines with both enough moisture and a recurring surge of ABA. That surge resulted in reduced water loss (partial stomatal closure), and restricted shoot extension. The group went on to show that reduced cytokinin[†] levels (relative to ABA) in xylem sap entering shoots were probably responsible for reducing shoot growth.

In one particular set of experiments, where the split root systems of potted grapevines carrying bunches were wetted and dried alternately, the researchers noticed that shoot growth was greatly reduced but without any adverse effect on fruit growth and development. That important observation led eventually to present-day field trials where entire vineyards are maintained under a drip irrigation system that wets alternating sides of the in-row root system. Results over the past 5 years or so have confirmed the wide applicability of this irrigation method. Substantial savings in irrigation have been documented, while plant growth has been contained on high input vineyards. Comparing partial rootzone drying irrigation with conventional irrigation practice for a given region, irrigation water use efficiency for cropping has virtually doubled in some situations (see Table 4, page 24).

Since this initial work in 1990 a comprehensive outline of underlying physiology and practical applications of what has become known as partial rootzone drying has been developed. As summarised in Loveys *et al.* (2000):

> 'Using this knowledge, we have been able to develop a commercially viable irrigation system for grapevines which had 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 partial rootzone drying 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'.

APPLICATIONS

Some of the practical applications of partial rootzone drying are discussed in this section.

Vineyard applications

In a typical partial rootzone drying installation (Figure 12), dual supply pipes provide irrigation water to alternate sides that are switched from drying to wetting every 10 to 14 days (Figure 13). During each interval, water must be supplied to the wetted side to ensure water lost as transpiration is replenished, and thus avoid serious reduction in soil water availability on the wetted side. Should the vine's entire root system become dry the partial rootzone drying effect is lost, and yield can be reduced. Under a well-managed partial rootzone drying regime, roots on the nominally dry side remain healthy and are able to draw water (hydraulically) from the wet roots.

A number of field trials are presently underway in commercial vineyards. Those in South Australia are based on varieties such as Shiraz, Cabernet Sauvignon and Riesling. Both own-rooted and grafted vines (Ramsey rootstock) are used. Trial vineyards were established 5 to 10 years ago at a planting density of between 1750 and 2500 vines per hectare, and were trained

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[†] Cytokinins are plant hormones that stimulate cell division and promote functions such as bud formation and germination.

to a simple vertical trellis. Existing irrigation systems were modified to provide a pair of drippers per vine, which can be run independently. Water supply to the fully irrigated control vines is conservative and ranges from 0.7 ML/ha per season around Adelaide to 5 ML/ha per season for hot inland sites near Waikerie (see Table 5, page 31).

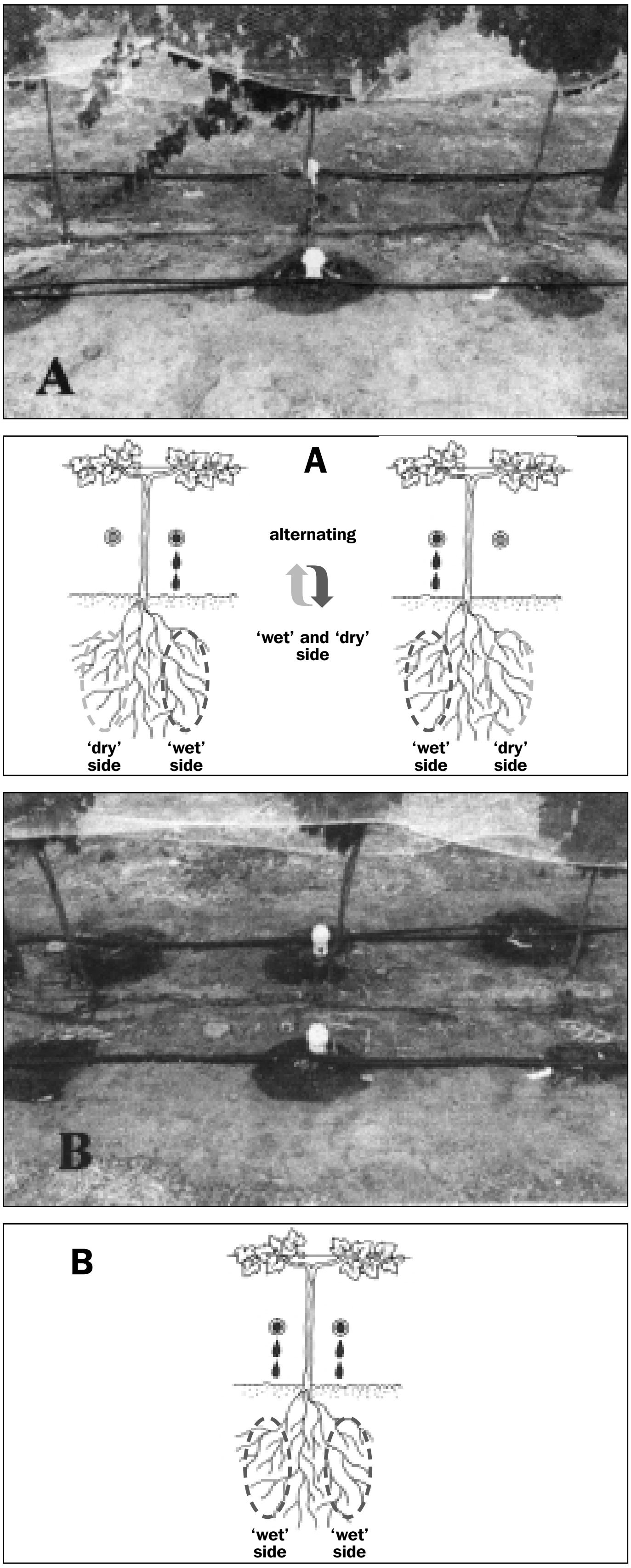
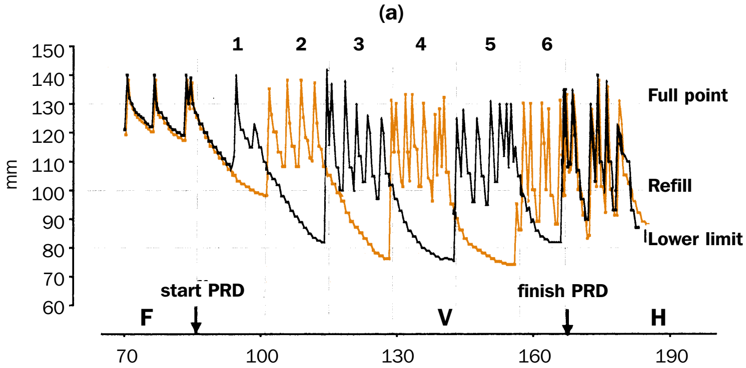


Figure 12. A partial rootzone drying installation in a research vineyard. Split-root vines (Cabernet Sauvignon) were established with roots arranged either side of a plastic membrane that ran the length of each row. Wet patches associated with active drippers are evident. In A, wet patches are evident on just one side; in B, wet patches are evident on both sides. In A, wet sides and dry sides alternated (as shown in the lower panel) while control vines (B) received water on both sides at each irrigation. Photos: Manfred Stoll, University of Adelaide, Waite Campus.

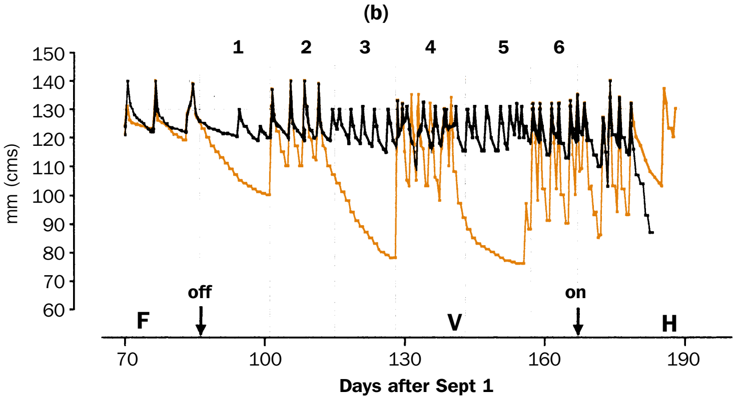
Figure 13. Changes in volumetric soil water content (in mm and summed for 15 to 55 cm depth) under Cabernet Sauvignon on Ramsey rootstock during the 1994-95 growing season in a research vineyard.

F = Flowering
V = Veraison
H = Harvest



The numbers 1 to 6 represent drying periods. One side of the PRD vine was not irrigated from Day 86 until Day 100.

(a) shows the western (red) and eastern (black) sides of partial rootzone drying vines, illustrating that the wet side dries down only to about 100 mm before being rewetted, whereas the dry side is allowed to dry down to about 80 mm before being switched to a wetting regime, and held between 140 and 100 mm water.



(b) data for the dry side of a partial rootzone drying treatment (red) shows that water extraction leaves behind only about 80 mm; the top line represents the much reduced amplitude of soil water changes under a control vine (black) where volumetric soil water content varies between 115 and 130 mm (courtesy Peter Dry, University of Adelaide, Waite Campus).

Field-grown Cabernet Sauvignon is representative of those trials (see bottom panel, Table 5), and berries ripened normally. Briefly, °Brix was 23.05 for partial rootzone drying compared with 22.9 for control vines, pH was unaffected, fresh weight per berry was essentially the same at around 1 g, and yield was comparable at 22.4 t/ha for partial rootzone drying compared with 23.6 t/ha for control vines.

Most striking is water use. Partial rootzone drying vines received a total of 0.35 ML/ha for that growing season, compared to 0.70 ML for control vines. Given their similar yields, that difference in irrigation level translates to a major difference in irrigation water use efficiency, about 33.6 t/ML for fully irrigated vines compared with 63.9 t/ML for partial rootzone drying vines (bottom panel in Table 5). Even allowing for an average input of 100 mm from rain (assumed to be 50% effective in Table 5), total water use efficiency is still greatly improved by partial rootzone drying.

More extensive trials in different regions of Australia show that yield is not adversely affected by partial rootzone drying, and that irrigation water use efficiency is consistently higher under a partial rootzone drying regime. Improvements in water use efficiency were recorded as follows:

- for Shiraz at McLaren Vale, 86%
- for Shiraz in Sunraysia, 55%
- for Shiraz at Langhorne Creek, 76%
- for Riesling in the SA Riverland, 90%.

Table 5. Yield, irrigation quantities and water use efficiencies for grapevines in field trials in South Australia.

VARIETY LOCATION (SEASON)	**YIELD (t/ha)**		**IRRIGATION (ML/ha)**		**WATER USE EFFICIENCY (t/ML)**	
	STD	**PRD**	**STD**	**PRD**	**STD**	**PRD**
Shiraz Adelaide 1997-98	22.6	21.5	1.4	0.7	16.1	30.7
Cab Sav* Adelaide 1997-98	15.2	15.4	1.4	0.7	10.9	22.0
Riesling Waikerie 1996-97	29.1	28.9	4.5	2.4	6.4	11.9
Riesling Waikerie 1997-98	30.6	28.7	5.2	2.6	5.9	10.9
Shiraz McLaren Vale	20.3	19.0	1.53	0.77	13.3	24.7
Shiraz Sunraysia	29.0	26.9	7.42	4.45	3.9	6.1
Shiraz Padthaway	13.3	9.6	3.9	2.2	3.4	4.4
Shiraz Langhorne Creek	12.3	13.3	3.2	2.0	3.8	6.7
Riesling SA Riverland	37.7	37.0	5.5	2.8	6.9	13.1
Cab Sav* Adelaide	23.6	22.4	0.70	0.35	33.6	63.9
(incl rain)†			(1.20	0.85)	(19.7	26.4)
Shiraz Adelaide	17.3	19.7	0.46	0.46	37.7	42.7

STD = fully irrigated control vines (standard irrigation)
PRD = partial rootzone drying

Top panel: Dry *et al*. 2001 *J Int Sci Vigne* 35 (3) 129-139; middle panel: Dry *et al*. 2000 *Australian Grapegrower and Winemaker Annual* Technical Issue pp. 35-39; bottom panel: Loveys *et al*. 2000 *Acta Hort* 537, 187-199.
*Cab Sav = Cabernet Sauvignon.
†(include rain) refers to 100 mm of rain assumed to be 50% effective and thus equivalent to 50 mm of irrigation or 0.5 ML/ha.

Grapevines growing on deep sandy loam soils are especially suited to partial rootzone drying, and the 90% improvement in irrigation water use efficiency by Riesling grapes in the SA Riverland is a good example. Given the deficit irrigation under partial rootzone drying (2.8 ML compared with 5.5 ML for control vines), a question arises as to whether this 90% improvement is because of partial rootzone drying in itself, or whether deficit irrigation encourages vines to draw more, unmonitored, water from sub-soil layers. Any contribution from such additional water (not included in calculations of irrigation water use efficiency) would then cause an apparent increase in irrigation water use efficiency under partial rootzone drying.

Notwithstanding this technicality in calculating the apparent efficiency of irrigation water use, the actual amount of irrigation applied with partial rootzone drying is still much less than with conventional irrigation. In effect, this unmonitored subsoil water that may have been accessed through partial rootzone drying would have been totally lost under conventional irrigation, and possibly would have become a further accession to groundwater.

While some contribution from subsoil water under deficit irrigation has been assumed for the Nuriootpa trial with Chardonnay (discussed later in connection with Table 9, page 43), this is not the case with Riesling grapes at Oxford Landing (Waikerie) in the SA Riverland (Table 5, page 31). The reason for this is that the vineyard, which is managed as minimally pruned Riesling on Ramsey rootstock, has groundwater at 1.8 to 2.1 m. This groundwater is highly saline (3.45 to 3.6 dS/m) so that if vines were drawing water from that depth they would be exposed to salt.

These trial vines were maintained under partial rootzone drying for three years before leaves and petioles were sampled on 8 February 2000. They received about 55% of the quantity of irrigation supplied to control (standard irrigated) vines, i.e. 5 to 7 ML/ha. Yields were high, varying between 29 and 40 t/ha, and there was never any significant difference in yield from partial rootzone drying and control vines.

Leaf petiole chloride was 0.134 % dry mass in the control vines compared with 0.148 % dry mass in the partial rootzone drying vines. Leaf lamina chloride was 0.04 and 0.05 % dry mass for the control and partial rootzone drying vines respectively. These minor differences were not statistically significant and are evidence that these high-yielding vines at Waikerie were not drawing on groundwater to any extent.

Ramsey is a salt-excluding rootstock, but given the length of this experiment, cumulative potential evapotranspiration for a reference crop (ET_o) from that site of at least 1000 mm per season and the highly saline groundwater, even a salt-excluding rootstock would not have been a total barrier to chloride uptake. The trial continues.

In contrast to grapevines on deep sandy loam soils in the SA Riverland, the improvement in water use efficiency for Shiraz at Padthaway (middle panel in Table 5) was only modest at 29%, and the yield relatively poor. An unknown number of uncontrolled stress cycles were probably involved and have been attributed to inadequate filling of deeper soil layers after switching from dry to wet.

Such episodes would have been especially damaging if they coincided with early stages in berry development (see Figure 7, page 13). Smaller berry size under partial rootzone drying recorded for this site implies that soil moisture reserves on the wet side were not adequately maintained.

Partial rootzone drying can also have a positive effect on fruit and wine quality, and outcomes for some key indicators for Cabernet Sauvignon were summarised by Dry *et al.* in 2001. They provided data for 1994-95 and 1996-97. °Brix was virtually identical for control and partial rootzone drying vines in both years and, against that background, changes in other berry constituents are worth noting.

As they explained:

> “berries from partial rootzone drying-treated vines had significantly lower juice pH and higher berry anthocyanins and phenolics than controls when the bunches on partial rootzone drying vines were much better exposed than those on controls in the 1994-95 season”.

On that occasion, total anthocyanins were 0.89 and 1.28 mg/berry; a statistically significant difference at $P<0.01$, while anthocyanin concentration was 1.19 and 1.72 mg/g berry fresh weight for control and partial rootzone drying respectively, a statistically significant difference at $P<0.05$.

Consistent with general experience, those partial rootzone drying grapevines had a smaller canopy volume, so that bunches were more exposed to sunlight, and certain berry constituents are affected. Berries from partial rootzone drying Cabernet Sauvignon retained higher acidity in 1994-5, as well as much more anthocyanins on both a per berry and a mass basis. Therefore, partial rootzone drying had a positive effect on the synthesis or accumulation or both of secondary metabolites. Anthocyanin levels were little affected by partial rootzone drying in the 1996-7 season, when bunch exposure was not much different, although wine made from that fruit rated more highly for aroma than wine from control fruit.

Questions now arise as to the viticultural implications of this change in grapevine physiology and canopy dynamics for irrigated vineyards. A number of projects are already in progress to address issues such as total vineyard water use, water use efficiency for cropping, grape yield relative to canopy surface area, implications for berry nitrogen physiology, and alternative approaches to pruning and trellising. Partial rootzone drying effects on berry constituents at harvest, especially sugar and amino acid composition, soil-water and salt relations, and biological indicators of drought stress are also being studied.

CASE STUDIES

Initial research on partial rootzone drying in Adelaide used container-grown grapevines with split roots. This research provided new knowledge about measuring root-derived signals and the way in which root signals led to restricted shoot growth and changed how stomata functioned. Higher transpiration efficiency (leaf and whole shoot level) was one critical outcome of those changes in vine physiology.

Application of those findings to grapevines in a vineyard was first based on purpose built vine rows where grapevines were established on a split root system either side of a dividing membrane. These rows were carefully engineered to enable rapid re-wetting and were comprehensively instrumented for soil moisture monitoring at various depths. Using that system, previous experience with pot-grown vines was confirmed, and some examples of differences in irrigation management between partial rootzone drying vines and those on standard irrigation are given in Figure 14, page 35.

Practical implementation of partial rootzone drying was the next logical step to large-scale implementation and validation of this new irrigation method for commercial viticulture, and a series of field trials was established. Experiences to date on some of those sites are discussed over page.

Sunraysia, northwest Victoria

Wingara Wine Group, Karadoc

A 6.5 ha block of Shiraz grafted to Schwarzmann rootstock was established in 1994 in this extensive, 350 ha vineyard. Within that block, a trial site was established in 1998 to compare vine performance under a variety of treatments including standard drip, partial rootzone drying and subsurface emitters, in combination with different pruning regimes. A number of treatments are running concurrently, and some key outcomes from two of those treatments to do with vine productivity and water use (1998-2002) for mechanically-pruned vines with above-ground emitters, are presented in this section.

The trial site is on a deep sandy loam topsoil overlaying a clay-loam subsoil within an undulating landscape that was used originally for dryland cereals before being converted to irrigated horticulture, especially citrus and viticulture. The site is naturally well drained, closely managed, and the dripper irrigation system rigorously maintained. The vineyard environment is monitored continuously with a weather station. Daily potential evapotranspiration for a reference crop is calculated from data generated by the Sunraysia Rural Water Authority weather station. This information complements irrigation scheduling decisions that are based largely on regular monitoring of rootzone soil water status.

Vine rows run east-west, and partial rootzone drying is imposed by alternating water supply through dripper lines on the north and south sides of individual vine rows. Figure 14 illustrates the cyclical patterns of rootzone drying and re-wetting in this partial rootzone drying installation. Representative traces for soil water (expressed as mm of water per metre depth of soil at 0 to 90 and 100 to 110 cm) are also shown. North-side rootzone and south-side rootzone show a clear and alternating pattern of drying and re-wetting cycles. Re-wetting starts once the drying side approaches the lower limit of readily available water.

Inter-row grapevine spacing is 3 m, in-row spacing is 1.8 m with 75 cm between drippers. Standard drip irrigation (Treatment 1; Std) is equipped with 3.5 L/hr emitters so that hourly output is equivalent to (3.5 L/hr x (1.8 ÷0.75 drippers) ÷ (3.0 m x 1.8 m) = 1.55 L/hr/m^2 = 1.55 mm/hr (because 1 mm is equivalent to 1 L /m^2).

Partial rootzone drying rows (Treatment 2; partial rootzone drying) are equipped with two dripper lines that carry 4.0 L/hr drippers spaced at 75 cm in alternating inter-vine spaces and 15 cm separating the outer most drippers from the vine stems. Hourly output is equivalent to (4.0 L/hr x 3 drippers)÷ (3.0 m x 1.8 m)÷ 2 (to allow for alternating operation) = 1.11 mm/hr.

Irrigation rates for partial rootzone drying grapevines are about 60% of those for standard (Std) irrigation, but this is not initiated until around mid to late November, and usually just before the onset of flowering. The Karadoc trial site usually emerges from winter with a 1/2 to 3/4 charged soil profile, and early spring growth (rapid shoot extension) draws on that stored water and any spring rain. If there has not been enough winter-early spring rain, a supplementary irrigation is applied just after budburst. If spring is unusually hot, an irrigation equivalent to only 0.5 to 1.5 mm/day is applied to stop vine stress and keep shoots growing at a steady rate.

When partial rootzone drying is first initiated at around the time of flowering, only enough water is applied to keep the alternating rootzones wetted down to about 20 cm (equal to an application of 2.5 to 3.0 mm/day for the 7- to 8-day cycle).

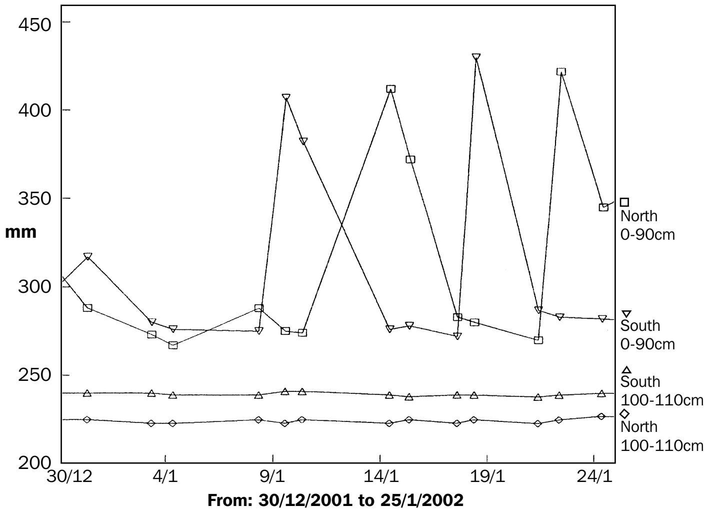


Figure 14. Successful partial rootzone drying in a commercial vineyard. Volumetric soil water content (mm per metre of soil) has been inferred from monitoring with a neutron probe. Partial rootzone drying impact on cyclical variation in soil water became apparent around 9 January. Thereafter, north 0 to 90 cm and south 0 to 90 cm readings stayed discrete and in strict opposition as required in partial rootzone drying. As inferred from the steady values for soil water at 100 to 110 cm, these grapevines were not drawing water from deeper layers within the soil profile. See text for further details (unpublished data courtesy Craig Thornton, Wingara Wine Group, Karadoc).

Partial rootzone drying cycling time

In the original partial rootzone drying installations in generally mild environments around Adelaide and southeast South Australia the length of drying and re-wetting cycles was initially set at around 10 to 14 days, but was sometimes reduced to 5 days in mid summer. By contrast, a combination of higher vineyard evapotranspiration and a more limited range of available moisture in the deep sandy loams at Karadoc resulted in a decision to reduce the length of the partial rootzone drying cycle during most of summer to a maximum of 7 to 8 days, and even shorter (4 to 5 days) under extreme conditions.

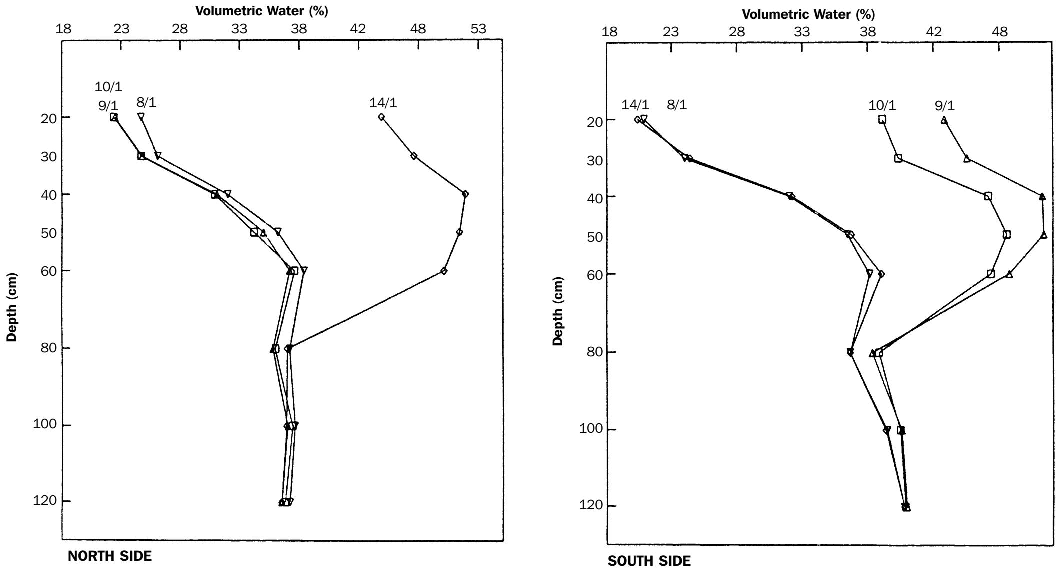
Partial rootzone drying is then maintained during flowering and fruitset and until berries grow to pea size. Providing 'adequate' irrigation during this period is intended to reduce both terminal and lateral growth, and at the same time keep vines turgid for fruit development. In striking this balance, close attention is paid to weather forecasts, and water is always applied before expected hot spells. Conversely, application rate is stepped down during cool or overcast weather.

With veraison, application rate is stepped up from the previous equivalent of 2.5 to 3.0 mm/day to around 4.5 to 5.0 mm/day, and this is maintained through to harvest. Partial rootzone drying is then discontinued and enough irrigation water applied to recharge the profile ahead of autumn-winter. Because rain is expected during those cooler months, only enough supplementary water is added to wet the soil profile to around 80 to 100 cm.

In Figure 14, successive drying and re-wetting cycles from 9 January 2002 show a clear displacement between north side and south side with no serious overlap. Equally important for effective partial rootzone drying, the depth to which each side of the vine rootzone is re-wetted by successive irrigations corresponds with the depth to which vine roots had previously extracted soil moisture (Figure 15). Put another way, volumetric water content of the mid rootzone (40 to 50 cm deep) varies in a highly dynamic way from around 50% (wet) to 20% (dry), but moisture content stays unchanged at 80 cm and below.

As required for both regulated deficit irrigation and partial rootzone drying, only enough water is being applied during successive irrigations to re-wet the same population of roots. Applied water is thus being absorbed to best effect by an existing population of roots that are kept healthy by regular re-wetting, and they remain effective for extraction of soil water. As an extra bonus, lateral growth of roots is limited to this wetted volume. While some roots have strayed towards inter-row centres, inspection pits show the main mat of roots in association with the dripper outlets.

Figure 15. Changes with time and at different depths under partial rootzone drying grapevines at the Wingara Wine Group vineyard. Grapevines are shown to have extracted soil water from the north side starting 8 January to reach a minimum soil water around 10 January and were subsequently irrigated again to restore maximum soil water by 14 January. In strict contrast, south side roots had been restored to full water on 9 January, and were approaching their minimum soil water content by 14 January. That routine continued for the duration of partial rootzone drying, and as noted earlier (Figure 13, page 30), these dynamic changes in rootzone water content did not extend any deeper than about 80 cm. Both frequency and amount of partial rootzone drying irrigation was being matched with grapevine evapotranspiration (unpublished data, courtesy Craig Thornton, Wingara Wine Group, Karadoc).



Comparing standard drip irrigation with aboveground partial rootzone drying, water applied was approximately halved, but yield was reduced only marginally (Table 6, page 37 top panel); berry acidity was maintained; and sugar accumulation was sustained, and even improved slightly by partial rootzone drying in 1999, 2001 and 2002 (Table 6 bottom panel). For those harvests where data are available, berry colour and phenolics content (berry weight basis) were also increased by partial rootzone drying in 2000, 2001 and 2002. Taking harvest data from 2002 as indicative of other years, smaller berries at harvest could have contributed to that higher concentration under partial rootzone drying. Mean fresh weight per berry from the 2002 harvest was recorded (CSIRO trial site data) as 1.12 g under standard drip irrigation compared with 0.90 g under partial rootzone drying.

With yields maintained, and irrigation halved under partial rootzone drying, water use efficiency was improved significantly with only a minor trade-off in yield per hectare. Quality indicators (Table 6 bottom panel) were actually enhanced under partial rootzone drying. Measured against viticultural expectations and irrigation water use efficiency, the Wingara trial is a major success, and a model for producing Shiraz grapes under partial rootzone drying in a hot climate on light soils. Observations of grape yield, berry composition and water use by these Shiraz vines at Karadoc (Table 6) showed that vineyard productivity under standard drip irrigation (water applied + rain was about equal to half the potential evapotranspiration from a reference crop) ranged from around 17 t/ha up to almost 30 t/ha according to season, and thus confirmed expert vineyard management.

Table 6. Wingara data Karadoc (Shiraz on Schwarzmann rootstock).

YEAR OF HARVEST	YIELD (t/ha)		IRRIGATION APPLIED (ML/ha)		WATER USE EFFICIENCY (t/ML)	
	STD	PRD	STD	PRD	STD	PRD
1998	28.98	24.87	7.42	4.04	3.91	6.16
1999	17.6	14.6	—	—	—	—
2000	28.35	23.33	6.13	3.07	4.62	7.61
2001	20.98	16.05	6.34	3.64	3.31	4.41
2002	16.68	15.05	4.59	2.62	3.63	5.74

YEAR OF HARVEST	°BRIX		pH		TA (g/L)		COLOUR (mg/g)	
	STD	PRD	STD	PRD	STD	PRD	STD	PRD
1998	23.7	23.7	3.80	3.63	5.60	6.00	—	—
1999	22.9	24.2	4.15	4.06	4.3	4.6	—	—
2000	24.7	23.7	4.1	4.2	3.3	3.1	0.90	1.01
2001	25.9	26.1	4.37	4.29	2.9	3.0	1.15	1.47
2002	24.4	24.0	3.60	3.60	4.5	4.8	1.80	2.06

TA = titratable acidity and is expressed as grams of dihydrogen tartrate per litre of juice (g/L)
Colour is expressed as mg anthocyanin/g berry fresh wt (mg/g)
— data not available.
Unpublished information courtesy Craig Thornton, Wingara Wine Group. Colour data for 2000-2002 harvest years from CSIRO Plant Industry (Horticulture Research Unit Merbein, and Department of Natural Resources and Environment, Agriculture Victoria, Sunraysia Horticultural Centre trial sites.

Margaret River, southwest Western Australia

Voyager Estate

This vineyard south of Margaret River comprises eight-year-old Shiraz vines at a density of 1666 vines/ha on their own roots, and on a typical gravelly soil (loamy sand overlying a gravelly clay) that is favoured for viticulture in southwest WA. Average annual rainfall is about 1200 mm so that in any year less than 1 ML/ha need be applied to sustain commercial vine production. Long-term average monthly rainfall during a growing season (October – April) amounts to: 72, 47, 22, 15, 11, 28 and 72 mm for those seven months respectively.

During the trial season in 2000-2001, part of Voyager Estate was set up with ten rows of partial rootzone drying alternating with ten rows of conventional drip irrigation. Consistent with standard practice, 0.50 ML/ha was applied to conventional sections, and 0.32 ML/ha was applied to partial rootzone drying sections. Rootzone moisture had been fully charged following a wet winter-spring in 2000, and irrigation did not begin until about two weeks before veraison, i.e. on 5 January 2002. Gypsum blocks were installed at 30, 60 and 90 cm, and irrigation was triggered once rootzone moisture tension exceeded 200 kPa. During the 2002 summer, 312 L/vine was applied with standard irrigation, and 193 L/vine to partial rootzone drying irrigated vines.

Partial rootzone drying trial in a commercial vineyard (Voyager Estate WA) using 8-year-old Shiraz grapevines (own roots). Photograph: Neil Lantzke, Agriculture WA, South Perth.

Data for vine growth, yield and berry composition (Table 7, page 39) show that canopy growth (indicated by pruning weights) had been limited by partial rootzone drying (pruning weight of 1.56 kg/vine from partial rootzone drying treatments compared with 1.86 kg/vine from standard drip irrigation).

Grape yield was not affected much (3.25 kg/vine under partial rootzone drying compared with 3.34 kg/vine under standard drip irrigation) while berry quality attributes had been enhanced. Comparing partial rootzone drying with standard drip irrigation the following was noted:

- weight per berry was slightly reduced (1.43 *vs.* 1.60 g/berry)
- °Brix had been increased (24.0 *vs.* 23.3)
- colour was slightly improved (1.85 *vs.* 1.81 mg anthocyanin/g fr wt)
- phenolics were slightly increased (3.28 *vs.* 3.22 mg/g fr wt for partial rootzone drying and Std respectively).

Compatible with viticultural goals in southwest WA, grape yields from the trial site were modest and, converted from a per-vine to a per-hectare basis, vines on the standard regime of drip irrigation cropped at 7.4 t/ha, whereas those on partial rootzone drying cropped at 7.2 t/ha. Since irrigation applied during the 2002 ripening season was equivalent to 0.50 ML/ha for standard drip irrigation and 0.32 ML/ha for partial rootzone drying, irrigation water use efficiency was thus 14.8 and 22.5 t/ML for standard drip and partial rootzone drying respectively.

It is not clear whether this increase in grape quality and apparent water use efficiency was a genuine response to partial rootzone drying or more a direct consequence of deficit irrigation. Soil water measurements based on gypsum blocks (data not shown) did not establish a clear pattern of drying/re-wetting cycles on alternating sides within the vine row (set up as in Figure 17, page 52). Since effective partial rootzone drying calls for a clear spatial separation between drying/re-wetting zones, outcomes from the Voyager trial must remain ambiguous.

Langhorne Creek, southeast South Australia

Orlando vineyards

These trial sites are set in a technically sophisticated vineyard on a variety of soil types. Soils are either alluvial clay loams or deep sandy loams that allow vine roots to penetrate to at

Table 7. Voyager Estate, Western Australia

PARTIAL ROOTZONE DRYING TRIAL SHIRAZ (OWN ROOTS) 2000-2001 SEASON

IRRIGATION MODE	**STD**	**PRD**
Yield (t/ha)	7.4	7.2
(kg/vine)	3.34	3.25
Irrigation- (ML/ha)	0.50	0.32
(L/vine)	312	193
Irrigation water use efficiency (t/ML)	14.8	22.5
Pruning wt (kg/vine)	1.86	1.56
Berry wt (g/berry)	1.60	1.43
°Brix	23.3	24.0
Colour (anthocyanin) (mg/g fr wt)	1.81	1.85
Phenolics (mg/g fr wt)	3.22	3.28

Unpublished data courtesy Neil Lantzke and Sue Wills, Agriculture WA, South Perth

least 1.5 m, or sandy loams over dense clay layer or calcareous layer allowing root penetration to about 0.6 to 1.0 m.

Infiltration rates can be low on alluvial soils and those with a dense clay layer once they have dried compared with sandy loams, which tend to have high infiltration rates. According to John Kennedy, Orlando Wyndham Viticulturist at Langhorne Creek,

> “We usually have low infiltration rates with low RAWs on soils with dense clay layers, however, we can also have low infiltration rates on alluvial soils once they have dried out, although they do hold a lot of water. High infiltration rates are a feature of the sandy loams with deep topsoils. Partial rootzone drying appears to me to be more successful on soil types that allow for high infiltration rates and deep rootzones. Partial rootzone drying is less successful at this point on soils with low infiltration rates. Note, however, that rootzone depth does not necessarily dictate infiltration rate. Low infiltration can be associated with either shallow rootzones, or in other cases with a deep rootzone.”

Once vines had been established on this site at Langhorne Creek, soil pits revealed that most roots (about 95%) had grown in the top 60 to 90 cm on high infiltration sandy loam soils, compared with the top 30 to 50 cm on soils with dense clay layers. Rootzone soil-water reserves differed accordingly. The more permeable silt-loams allowed higher infiltration rates, and water from 2 L/hr drippers commonly reached sixty centimetres after 6 hours. The dense clay layer in some profiles was a barrier to deep infiltration. The total volume of readily available water to vine roots on those dense clay soils (30 to 50 mm) is much less than is available on silt loams (60 to 80 mm) so that any margin for error in scheduling irrigation is reduced accordingly.

Trial outcomes. Clonal selections of Cabernet Sauvignon (3.5 ha) and Shiraz (4.7 ha) had been established in 1999 (on own roots) under partial rootzone drying irrigation. Positive experiences on this trial site have meant that the area under partial rootzone drying is to be increased to a total of 56 ha with 23 ha devoted to Cabernet Sauvignon, 22 ha to Shiraz, and 11 ha to Merlot. As mentioned in Chapter 2, Merlot is generally regarded as more sensitive to soil-moisture stress, and might prove less suited to partial rootzone drying as well.

One important practical issue to emerge at Langhorne Creek by the end of the first partial rootzone drying season (1999-2000) was that alternating emitters associated with each of the two dripper lines had become misaligned, i.e. they were too close to achieve the necessary spatial separation between drying and re-wetting zones. The dripper lines had stretched during installation and uneven lengthwise contraction over subsequent months brought some emitters closer together and others further apart in the rows.

Knowing that effective partial rootzone drying relies on a clear and sustained separation of drying and re-wetting zones (1.2 m at Langhorne Creek), the original system that was based on two separate parallel pipes (as has been universal practice to date, see Figure 12, page 29) is to be replaced by a single twin-core dripper line along the length of the vine row. This line will be aligned with vine trunks, and in-line drippers delivering 2 L/hr and pressure compensated for vineyard uniformity will be installed strategically along its length. Spacing between drippers will ensure a 6 m separation between the centres of alternating wet and dry zones.

Outcomes from the 2001-2002 season at Langhorne Creek have proved especially instructive (Table 8), and have enabled some critical comparisons between the two cultivars on the two soil types. These are as follows:

- Partial rootzone drying improvement of apparent water use efficiency is more obvious on the more porous soil in both varieties of vines.
- Efficiency values for Cabernet Sauvignon in the silt-loam soil with high infiltration rate were almost doubled under partial rootzone drying compared with standard drip irrigation (11.07 *vs* 6.66 t/ML).
- Water use efficiency of Shiraz on the silt-loam with a medium infiltration rate increased by 47% under partial rootzone drying compared with standard drip irrigation (5.47 versus 3.72 t/ML in Table 8).

The improvements in apparent water use efficiency were associated with only barely noticeable effects on berry size (see g/berry in Table 8) and related indicators of quality (data not shown).

Table 8. Results from Langhorne Creek.

GRAPE VARIETY	**IRRIGATION INFILTRATION RATE**	**IRRIGATION WATER USE EFFICIENCY (t/ML)**		**TOPSOIL DEPTH (mm)**		**SOIL MOISTURE (mm RAW)**		**ROOTZONE DEPTH (mm)**		**BERRY WT (g/berry)**	
		STD	**PRD**	**STD**	**PRD**	**STD**	**PRD**	**STD**	**PRD**	**STD**	**PRD**
Cab Sav	Low A	5.51	6.66	656	900	76	80	1178	1278	0.92	0.72
	Low B	5.83	5.05	370	350	57	50	920	860	1.04	0.88
	High	6.66	11.07	417	1300	59	84	958	1500	1.11	1.09
Shiraz	Low	2.31	2.54	180	460	43	59	720	1020	1.24	0.93
	Medium	3.72	5.47	533	500	42	52	733	860	1.10	1.07

Cab Sav = Cabernet Sauvignon
mm RAW = readily-available soil moisture within the grapevine rootzone expressed as mm of water
Low A and Low B refer to two separate sites where soils showed low rates of irrigation water infiltration. Irrigation water use efficiency (t/ML) was derived from water applied (ML/ha) ÷ yield (t/ha).

A comparison of Cabernet Sauvignon 'A' and 'B' in Table 8 shows how soils with a low infiltration rate or shallow rooting depth or both are not conducive to successful partial rootzone drying.

In 'A', topsoil depth was about 660 to 900 mm, readily-available soil water (RAW in Table 8) was about 76 to 80 mm and rootzones were between 1.18 and 1.28 m deep. The soil was characteristic of an alluvial floodplain, and was very hard to re-wet once it was thoroughly dry. Water use efficiency increased from 5.51 to 6.66 t/ML, ie. an increase of 21% due to partial rootzone drying.

By contrast, in Cabernet Sauvignon on soil 'B':

- topsoil depth was only 370 and 350 mm (for Std and partial rootzone drying respectively)
- readily-available soil water (RAW in Table 8) was also less at 57 and 50 mm (for Std and partial rootzone drying respectively)
- rootzones extended downwards to only 920 and 860 mm (for Std and partial rootzone drying respectively).

This 'Low B' soil had a dense clay layer which slowed water penetration. Based on yield data and records of trial site irrigation, water use efficiency actually decreased by about 13% under partial rootzone drying compared with standard drip irrigation.

There is a question as to whether poor penetration of irrigation water was counteractive to partial rootzone drying and whether deep roots contributed to the strong positive effects of partial rootzone drying on apparent water use efficiency by Cabernet Sauvignon on a high infiltration rate soil in Table 8. The large increase in water use efficiency from 6.66 t/ML under Std irrigation to 11.07 t/ML under partial rootzone drying was associated with a topsoil depth of 1.30 m, readily available water of 84 mm and a rooting depth of 1.50 m.

As John Kennedy explained, "Cabernet Sauvignon on conventional drip irrigation, and with an apparent water use efficiency of only 6.66 t/ML, may have been disadvantaged, relative to partial rootzone drying vines, by a topsoil depth of around 420 mm, of readily-available water of only 59 mm and a rooting depth of about 960 mm".

Data on vineyard productivity and water use over several seasons will be needed for any critical interpretation of partial rootzone drying effects on apparent water use efficiency at Langhorne Creek, especially where soils vary so widely in water-holding capacity, rootzone depth and permeability. Devising a partial rootzone drying regime that improves irrigation water use efficiency on soils with low to medium permeability is likely to be challenging.

Barossa Valley, South Australia

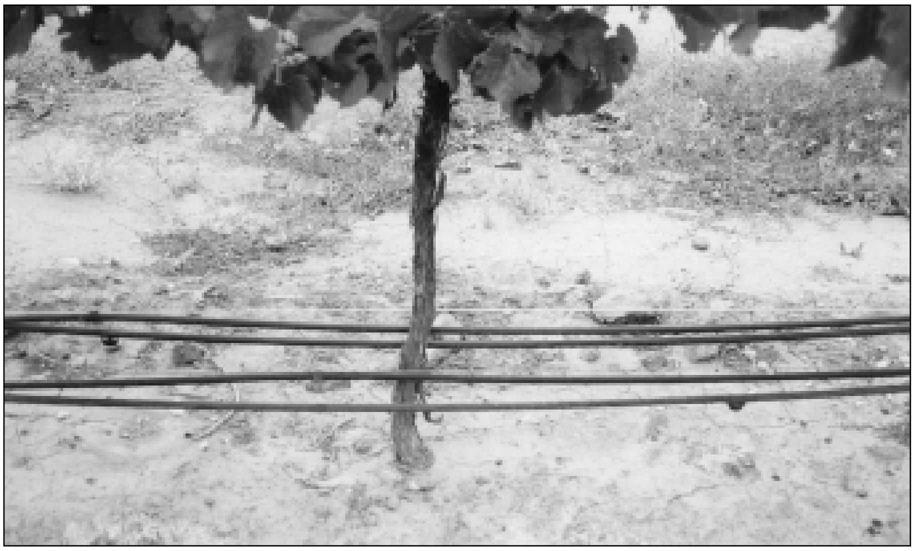
CRC for Viticulture/SARDI trial, Nuriootpa

The Barossa Valley of South Australia is characterised by winter-spring rains and summer drought. Previously regarded as a region of low vine vigour and thus low yield, near-universal adoption of drip irrigation over the past 30 years has virtually doubled yields. Given that yield response to supplementary water, irrigation for viticulture is common. However, with restrictions on extracting groundwater (1 ML/ha season) plus a cap on supplies from the Murray-Darling system, further expansion of viticulture as well as continuing economic viability of some existing vineyards will hinge on more efficient use of presently-available irrigation water.

The SARDI trial at Nuriootpa was established against this background, and at a time when increases in water use efficiency driven by partial rootzone drying were first publicised. In assessing the practical implications of those reports, Michael McCarthy and Shannon Pudney decided to address the critical issue of whether large increases in water use efficiency by partial rootzone drying vines were due to a qualitative change in vine physiology or simply the result of improved extraction of soil water from deeper layers under deficit irrigation. Implications of their trial findings for a special 'partial rootzone drying effect' are discussed over the page.

Their test site was a section within a Chardonnay vineyard (planted in 1985 on own roots) established on a Light Pass fine sandy loam, and irrigated with drippers (either 2 or 4 L/hr). A total of five treatments x three replicates were devised to test the combined impact of irrigation mode which consisted of standard fixed drippers *vs* alternating outlets as in partial rootzone drying (see photo below for general features of dripper lines).

Seasonal volume of irrigation, and water quality are summarised in Table 9, page 43. Murray River water salinity was 0.6 dS/m, local bore water was 2.8 dS/m. Outcomes from three of these treatments (on mains water) over two growing seasons, 2000-2001 and 2001-2002, are reported here.



Combined deficit irrigation and partial rootzone drying trial site at SARDI, Nuriootpa using Chardonnay (own roots) and showing 2L/hr partial rootzone drying dripper locations (1 metre apart, and 50 cm on either side of each vine stem). Photograph: Shannon Pudney, SARDI/CRCV, Plant Science Centre, Waite Campus, University of Adelaide.

Those three treatments are referred to in Table 9 as '4Std', '2Std' and '2PRD'. The 4Std treatment means one standard (fixed) dripper per vine that delivers 4L/hr; 2Std means one standard (fixed) dripper per vine that delivers 2L/hr; and 2PRD means one standard dripper on each side of a vine, each of which is fed by two separate dripper lines (identified in Figure 20, page 59) that alternated between successive irrigations. The 2PRD treatment was designed to deliver the same total amount of water per growing season as 2Std, and half as much water as 4Std.

Data on total irrigation water delivered to these three treatments (Table 9) confirm that vines on 4Std received twice as much irrigation water as either of the other two treatments, while vines on 2Std received the same total amount of water as 2PRD.

In effect, 2Std and 2PRD were two different forms of deficit irrigation compared with the conventional application rate of 4Std. Comparisons of vine performance across these three treatments should then establish for this particular trial site whether deficit irrigation results in an increase in water use efficiency, and whether there is a special partial rootzone drying effect.

The 2000-2001 growing season was both hot and dry whereas 2001-2002 was mild by comparison. Consequently, yields in 2000-2001 were lower in all treatments. Grapes ripened faster in the summer of 2001, and were harvested by 27 February at 23.7 °Brix on average. The ripening season in 2002 was cooler, yields were higher from all treatments and grapes were harvested by 19 March at 23.9 °Brix on average.

Yields of Chardonnay grapes from the Nuriootpa trial (Table 9) confirmed that vine productivity was well maintained under both 2PRD and 2Std deficit irrigation compared with the fully irrigated treatment 4Std for both growing seasons and that water use efficiency had been doubled as a result. Equally significant, and especially relevant to the question of a special partial rootzone drying effect on water use efficiency, both modes of deficit irrigation returned similar values in both seasons.

Table 9. A summary of yield and irrigation water use efficiency by Chardonnay grapes at Nuriootpa for harvest years 2001 and 2002 under three irrigation treatments.

	YIELD (t/ha)			**IRRIGATION (ML/ha)**			**IRRIGATION WATER USE (t/ML)**		
Treatment	4Std	2Std	2PRD	4Std	2Std	2PRD	4Std	2Std	2PRD
2001	10.1	10.5	9.1	1.0	0.5	0.5	9.8	20.2	17.5
2002	13.3	12.3	12.3	1.8	0.9	0.9	7.3	13.6	13.6

Treatment codes: 4Std means one standard (fixed) dripper per vine that delivers 4 L/hr; 2Std means one standard (fixed) dripper per vine that delivers 2 L/hr. 2PRD means one standard dripper on each side of a vine, each of which is fed by a separate dripper line and alternating between successive irrigations. 2PRD delivered the same total amount.

Notwithstanding a slight difference in water use efficiency between 2PRD and 2Std in 2000-2001, both forms of deficit irrigation resulted in a greatly improved value for irrigation water use efficiency compared with the fully irrigated treatment 4Std.

In trying to explain this improvement in water use efficiency by grapevines on either 2PRD or 2Std, a question arises as to whether grapevines on deficit irrigation were drawing on subsoil water more than grapevines on full irrigation (i.e. 4Std). Preliminary data on changes in soil water from 11 December 2001 to 21 March 2002 (capacitance probes) gave this impression. More subsoil water seemed to be extracted under both forms of deficit irrigation compared with the 4Std treatment, but this was not confirmed by gypsum block data and must therefore remain speculative.

Such consumption of subsoil water, had it occurred, would have contributed to an increase in estimates of irrigation water use efficiency compared with values for full-irrigation vines which appeared not to have drawn on soil water from deeper layers to the same extent (preliminary data from capacitance probes). The direction of any effect from this unmetered source of water on calculations of water use efficiency is self-evident, but the extent of any such effect must remain notional until quantified. One immediate task is to resolve whether any extra subsoil water was extracted by the deficit irrigation treatments at Nuriootpa (compared with 4Std), and if so, recalculate water use efficiency.

Hanwood, Murrumbidgee Irrigation Area, NSW

This field trial combined three irrigation treatments (standard dripper, regulated deficit irrigation and partial rootzone drying) with three modes of nitrogen application, and has already been discussed in connection with regulated deficit irrigation effects (see Chapter 2). There were no clear interactions between irrigation treatment and mode of nitrogen application, so that data for irrigation treatment outcomes have been averaged across nitrogen treatments, and are outlined below.

In contrast to the reduction in both yield and irrigation water use efficiency under regulated deficit irrigation (Table 10, below), partial rootzone drying produced an increase in irrigation water use efficiency from 3.90 t/ML under standard drip to 5.22 t/ML under partial rootzone drying. This was accompanied by only a moderate yield penalty (21.20 t/ha under standard drip down to 18.70 t/ha under partial rootzone drying).

Table 10. Yield, irrigation and apparent irrigation water use efficiency for Shiraz grapevines (own roots) on a heavy clay soil at Hanwood (MIA) for 2001/2002.

IRRIGATION TREATMENT	**YIELD (t/ha)**	**WATER APPLICATION (ML/ha)**	**IRRIGATION WATER USE (t/ML)**
Standard drip	21.20	5.44	3.90
PRD	18.70	3.38	5.22
RDI	12.40	4.48	2.77

Note: Irrigation water was applied via under-vine drippers (3 L/hr) with three emitters on each side of each vine (in-row single dripper line for standard drip treatment and RDI, but dual and independent dripper lines for PRD). (Unpublished data courtesy Jessica Wade, Bruno Holzapfel and Kerry DeGaris, National Wine and Grape Industry Centre, Charles Sturt University, Wagga Wagga NSW.)

Compared with standard drip irrigation, partial rootzone drying grapevines:

- were also less vigorous (2.28 compared with 3.17 kg prunings/vine)
- were harvested a week earlier (8 March compared with 15 March 2002)
- had slightly smaller berries (1.44 compared with 1.52 g fresh wt/berry) with about the same °Brix (22.35 compared with 22.89) but with slightly more colour (0.98 compared with 0.88 mg anthocyanin/g berry fresh weight).

These partial rootzone drying outcomes are generally consistent with findings from other successful trial sites, and were presumably driven by alternating wet and dry sides during critical phases of grapevine canopy growth and reproductive development. Data on variation in soil moisture (summed over the top 70 cm of the soil profile in Figure 16) show moist soil on both sides by late October that was drawn down equally until late November, when side 2 was irrigated, and the wet and dry alternation between side 1 and side 2 began. Strict alternation was lost during mid January, but was regained to some extent during mid February, and consolidated during March around harvest time. Both sides were restored to springtime levels by mid April, after harvest.

Summed over the 2001-2002 growing season, these Shiraz grapevines returned a 34% improvement in irrigation water use efficiency (t/ML) and, together with vine growth, harvest data and berry composition, imply a positive response to partial rootzone drying. This modest improvement in irrigation water use may have been improved if wet and dry sides had been strictly alternated for the entire season, but given the inertia known to be associated with re-wetting a heavy clay soil, plus a tendency for runoff from under-vine drippers due to in-row mounding on this particular trial site, even a modest positive response is an achievement.

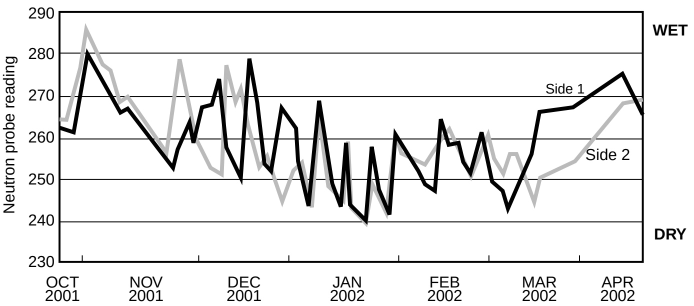


Figure 16. Seasonal variation in rootzone water status (arbitrary values from a neutron moisture meter) for Shiraz grapevines (aged 7 years), on own roots for the 2001/2002 growing season and irrigated according to a regime of partial rootzone drying. Note the alternation in drying/re-wetting patterns on side 1 versus side 2 during December 2001. (Unpublished data courtesy Jessica Wade *et al.,* National Wine and Grape Industry Centre, Charles Sturt University, Wagga Wagga NSW).

In-row neutron access probes down to 100 cm gave no suggestion of improved extraction directly under vines but grapevine roots are known to reach 80 cm on this Hanwood clay so that lateral growth may have enabled extraction of subsoil water from inter-row spaces. Moreover, such inter-row extraction may have been enhanced under either form of deficit irrigation (regulated deficit irrigation and partial rootzone drying) compared with standard drip irrigation, but in the absence of complementary data on seasonal changes in the subsoil water of inter-row spaces, such possibilities remain pure speculation.

Goulburn Valley, Victoria - pears

Pear orchards in the Goulburn Valley are noted for their high productivity. They commonly return 75 to 85 t/ha, with some crops of canning varieties exceeding 90 t. These high yields have been traditionally achieved by using luxury irrigation, with associated consequences for groundwater accession. Because of this, orchards in the Goulburn Valley were early candidates for irrigation management using regulated deficit irrigation and subsequent trials have included partial rootzone drying.

In the 1998-99 growing season, partial rootzone drying was trialled in a commercial orchard near Tatura on a clay-loam soil. The results confirmed an increase in apparent irrigation water use efficiency when compared with conventional flood irrigation.

In this trial there were four irrigation cycles during the season, and water was carefully applied in three ways, as follows:

- standard flood irrigation (STD) where the entire section was flooded
- fixed partial rootzone drying (FPRD), where only the west side of each tree line received water
- alternate partial rootzone drying (APRD), where flood irrigation was applied alternately to west and east sides of the tree line.

Orchard floor management was based on a grass sward with a herbicide strip along tree lines. In-row spacing between trees was 3.1 m, rows were spaced at 5.8 m. Seventy millimetres of rain fell just before the growing season (thoroughly wetting the soil profile), and a further one hundred and seventy two millimetres fell during the growing season.

Taking 1 November 1998 as the trial starting date, irrigation was applied on days 39, 60, 77 and 98. Observations were made until day 165, and the trial was then harvested. The orchard environment was closely monitored in great detail, and soil moisture observations (from 0 to 110 cm deep) were comprehensive enough to put together a soil moisture balance sheet under the various treatments (see Table 11, below). Groundwater was probably being extracted by trees on deficit irrigation (especially APRD) where some hydraulic lift was identified using a Gopher capacitance probe from detailed measurement of changes in rootzone soil water.

Total crop evapotranspiration over the trial period was slightly more than total water input (irrigation + rainfall) for all treatments. Such a difference implies that there was either a mild deficit or a depletion of soil water in all cases, but particularly in FPRD, and especially when total crop evapotranspiration is compared with irrigation input. Irrigation productivity (fruit yield/irrigation supply in Table 12) is thus highest for FPRD.

Table 11. A summary of water input and water consumed by pear trees (Goulburn Valley trial) maintained under one of three different irrigation treatments.

IRRIGATION TREATMENT	IRRIGATION APPLIED (mm)	RAIN (mm)	TOTAL INPUT (mm)	ORCHARD ET (mm)
STD	291	172	463	479
FPRD	141	172	313	343
APRD	223	172	395	424

STD = standard flood irrigation, FPRD = fixed partial rootzone drying, and APRD = alternate partial rootzone drying. Orchard evapotranspiration (orchard ET) was inferred from comprehensive measurements of soil moisture using a Gopher capacitance probe. (Based on Kang *et al.* 2002.)

Table 12. A summary of productivity and apparent water-use efficiency by pear trees Goulburn Valley trial) maintained under one of three different irrigation treatments.

IRRIGATION TREATMENT	PEAR YIELD (t/ha)	FRUIT YIELD/ WATER CONSUMED (t/ML)	FRUIT YIELD/ IRRIGATION APPLIED (t/ML)
STD	81.3	16.97	27.93
FPRD	85.3	24.83	60.48
APRD	79.0	18.62	35.41

STD = standard flood irrigation, FPRD = fixed partial rootzone drying, and APRD = alternate partial rootzone drying. Orchard evapotranspiration (orchard ET) was inferred from comprehensive measurements of soil moisture using a Gopher capacitance probe. (Based on Kang *et al.* 2002.)

Taking rainfall into account, and expressing yield in terms of water consumed (fruit yield/water consumed in Table 12), treatment FPRD is still outstanding.

FPRD thus ‘worked’ as a deficit irrigation treatment, sustaining a similar (even higher) yield compared with conventional flood irrigation (STD in Table 12), not necessarily through a change in water-use efficiency itself but possibly by ‘forcing’ trees to access more groundwater than did trees on STD.

The small improvement in water use efficiency under the APRD treatment (Table 12) must also be viewed against this same background. Soil water content, which was measured as changes in profile water during the trial, did increase under both FPI and API treatments and would have contributed to an apparent improvement in irrigation water use efficiency.

Any change in tree physiology due to a partial rootzone drying effect is also unlikely in this trial. The eastern and western sides of each tree row were alternated around a 20-day duty cycle, which was possibly too long for a partial rootzone drying response. In addition, and counter to generation of a 'true' partial rootzone drying effect (see Chapter 4), the nominally 'dry' side still held a deal of readily available water when irrigation water was reapplied, and thus may not have been dry enough for long enough to have generated critical root signals.

Despite those qualifications on interpretation of treatment outcomes, the trial demonstrated that deficit irrigation can be applied to a pear orchard with good effect. Irrigation water use efficiency was improved during a growing season where trees had access to subsurface moisture that had built up during winter and early spring and was thus available to supplement irrigation applied during the growing season. A different outcome would be expected after a dry winter and early spring where orchard evapotranspiration would thus depend on current application during the growing season.

Kang *et al.* (2002) also noted in this same context "that the complete water requirements of a pear tree could be met by supplying only half of the rootzone with water, and pear trees are able to modify their spatial patterns of water uptake in response to different levels of available water in their rootzone".

Of special relevance to FPRD and APRD treatments, pear trees showed a compensatory response to partial rootzone drying whereby the water uptake from wet roots relative to average water uptake by an entire root system was greater than 1.0, implying that "a compensatory effect occurred in the wet part of the root system for both FPRD and APRD". Presumably, "pear trees are able to modify their spatial patterns of water uptake in response to different levels of available water in their rootzone" and thus lend themselves to deficit irrigation.

CHAPTER 4

SITE AND SYSTEM REQUIREMENTS

This chapter is based on a combination of published information, outcomes from trial sites covered in chapters 2 and 3 and information contributed by research scientists and extension personnel. Some of the information about site effects on outcomes of both regulated deficit and partial rootzone drying field trials have been interpreted as a way of encouraging discussion, and are not meant to be definitive. Similarly, irrigation network options for implementing partial rootzone drying on fine textured soils must not be taken literally as they still need to be validated.

Features of regulated deficit irrigation and partial rootzone drying

Regulated deficit irrigation	**Partial rootzone drying**
Developed initially with fruit trees and subsequently extended to grapevines.	Developed initially with grapevines and being extended to fruit trees and other crops.
Deficit irrigation applied to entire planting but over a discrete time period (subsequent to fruitset and only until onset of rapid fruit growth).	Deficit applied in a spatially discrete way and potentially over an entire season (but commonly during cropping phase).
Fruit size not affected in peach and pear crops. Grape berries smaller and with increased risk of millerandage (hens and chickens) or coulture (straggley bunches) if it is applied too soon after flowering.	Berry size unaffected (grape berries and bunches remain same size with no risk of millerandage or coulture).
Vegetative vigour reduced as a result of shorter shoots in fruit trees and grapevines. Grapevines produce fewer laterals, canes thinner and with shorter internodes.	Vegetative vigour reduced. Grapevines produce fewer laterals, canes of similar thickness but with fewer nodes. Internode length remains unaffected.
Plants under deficit irrigation commonly wilt on hot days, grapevines shed tendrils, pre-dawn leaf water potential lower in trees and grapevines, stomatal conductance reduced.	Stomatal conductance is reduced but plants remain turgid if partial rootzone drying is implemented effectively, no loss of old leaves or tendrils and pre-dawn leaf water potential unaffected.
Crop only at risk if deficit too severe.	Crop not vulnerable during effective partial rootzone drying because shoots should stay turgid.
Increased water use efficiency assured in fruit crops. In grapevines, net gains in water use for crop production over entire season can be offset as a result of shatter (fruit abscission).	Increased water use efficiency for crop production is virtually assured when partial rootzone drying is correctly implemented on suitable sites because of a shift in growth phenology and stomatal physiology.
Meagre irrigation during regulated deficit irrigation phase re-wets top few centimetres (little and often) to sustain plants until deficit irrigation is relieved.	During alternation between wet and dry sides, rewetting to depth is essential. Irrigation must penetrate to bottom of root zone on wetted side, while some water is still being extracted from the drying side.

Regulated deficit irrigation	Partial rootzone drying
Soil type is not critical, but there is little margin for error with shallow sandy soils. Regulated deficit irrigation was originally developed on fine-textured clay soils that provided a substantial reserve of plant-available moisture. Irrigation scheduling criteria were later modified for lighter loam soils.	Deep porous light sandy loam soils offer best prospects for successful partial rootzone drying. Shallow sandy soils predispose crops to chronic stress, while rootzones in deep clay soils wet only slowly, and allow too much lateral spread of wetted zones. A clear separation between wet and dry roots is not maintained easily on such soils.
Irrigation scheduling can be broadly based on measurement of E_{pan} or calculation of ET_{crop} and adjusting water application rates according to values for crop factor or crop coefficient respectively that match regulated deficit irrigation requirements. Soil moisture sensors are used as a trigger in timing irrigation, and for assessing outcomes following irrigation, but indications from soil water sensors need to be validated with an auger or dig stick.	Less emphasis on evaporative indicators of irrigation requirement and more emphasis on direct measurement of rootzone soil water content to drive both duration of irrigation, and timing of switch from drying to re-wetting. Soil profiles need comprehensive instrumentation to ensure alternating wet/dry sides are re-wetted to full depth.
No new equipment required in addition to existing standard soil moisture instrumentation for irrigation scheduling. Note that rootzone soil water sensors, such as gypsum blocks, that provide a meaningful picture of plant available reserves of soil water are necessary.	Alternating wet/dry zones must be separated, usually by having two sets of independent drippers so that both submains and dripper lines need to be duplicated. Install wetting front detectors to ensure alternating portions of the rootzone are totally but discretely rewetted by successive irrigations.

Implementing regulated deficit irrigation

For regulated deficit irrigation to be effective, a number of prerequisites must be met for either fruit trees or grapevines. These are as follows:

- For fruit trees measure shoot and fruit growth because understanding the changes in fruit and shoot growth for different varieties is critical for timing regulated deficit irrigation. Water stress should be applied only during the vegetative growth period when fruit is growing slowly. Water stress must be avoided or minimised (if water is limited) during rapid fruit growth. The stages of fruit growth for a given variety can be easily determined by tagging several fruit and shoots and weekly measuring their circumference and length with a tape measure. Fruit circumference is converted to volume [volume = 0.02 x $(\text{circumference})^3$] to give a true indication of fruit weight. This technique is very simple and the measurements can be quite useful to adjust irrigations, especially if shoot growth continues despite high soil water deficits.
- Assess root distribution so you can calculate the potential store of available moisture in the soil. The best method to determine root distribution is to dig a pit next to an orchard tree and estimate the amount of roots in 20 cm depth increments until the bottom of the rootzone (80% of roots). Root depth is important to determine the volume of water in the rootzone when the profile is wet from rainfall, and where to site soil moisture sensors.
- Estimate soil waterholding capacity in the rootzone. In particular, determine a representative value of readily-available water (RAW) for each sector in the irrigated orchard or vineyard, i.e. shallow *versus* deep profiles and coarse sand *versus* finer textured soils. As a general rule, RAW (as a percentage of soil volume) for major types of horticultural soils are as follows: coarse 3%; fine sandy loam, 6%; loam, 8% clay-loam, 6 to 8%; and finer textured (heavy) clay soils, 6%.

- Identify wetting patterns to determine the volume of the wetted rootzone. This can be estimated from the root distribution and the wetted volume of soil. To determine the wetting volume it is necessary to observe the wetted surface area and depth following an irrigation event.
- Dig a hole so you can see wetting at depth. The wetted rootzone is then estimated from the volume of roots that are wet following irrigation. The calculation in the following irrigation plan assumes that the wetting pattern is a continuous strip of soil with a wetting depth of 30 cm. This wetted strip pattern will occur with closely spaced micro-jets or drippers where the wetting pattern overlaps. For other irrigation systems where the wetting patterns are separate, the wetted rootzone is calculated assuming the shape of a cylinder.

Irrigation systems

No specialised irrigation equipment or system modification is needed for regulated deficit irrigation beyond what would normally be installed for closely managed irrigation. This includes irrigation supply network, rootzone soil moisture sensing and environmental monitoring (weather station or evaporative pan).

Successful regulated deficit irrigation requires the following:

- that the entire irrigation system permits frequent and measured applications of water at critical times during the regulated deficit irrigation phase
- that the system has enough capacity to restore rootzone moisture quickly over the entire orchard or vineyard following release from deficit.

A secure water supply is crucial and must be available on demand to meet the widely varying irrigation requirements of orchards and vineyards on a deficit regime. Frequent deficit irrigations will be needed during regulated deficit irrigation, while substantial and sustained irrigation is needed during subsequent restoration to full irrigation. Application rates after regulated deficit irrigation are likely be 100 to 150% of potential crop evapotranspiration to fully restore rootzone moisture in time for rapid fruit growth.

Soil attributes

Successfully implementing regulated deficit irrigation hinges on certain soil attributes, including a limited store of rootzone soil water, readily permeable surface layers that make irrigation water easier to absorb, and a well defined soil type and depth that allows an irrigation schedule to be calculated.

At budburst in most temperate-climate orchards and vineyards, soil profiles are usually fully charged after rain in winter or spring. To impose some water stress (as required by regulated deficit irrigation), the rootzone must first be de-watered. Canopy transpiration and surface evaporation contribute to that process and, even though soil water content decreases to a point where canopy transpiration cannot match atmospheric demand, irrigation is withheld until the soil is dry enough to induce water stress in the fruit trees or grapevines.

The time required for de-watering will depend on evaporative conditions, rootzone depth, the extent of lateral root distribution, soil waterholding capacity, and further rainfall. For successful regulated deficit irrigation, rootzone depth needs to be less than about 1 metre, and rainfall during the regulated deficit irrigation period at an absolute minimum (ideally nil).

Soil type is important in determining what irrigation system should be installed for efficient regulated deficit irrigation. For deep sandy soils, such as those referred to in figures 8 and 11 (pages 17 and 26 respectively), and the sandy loam referred to in Figure 6 (page 11), regulated deficit irrigation would most likely use a pressurised system of closely spaced (75 cm) drippers (vineyards) or microjets (tree crops). For successful regulated deficit irrigation, enough soil must be wet up to enable rapid relief of water stress for maximum fruit growth or sugar accumulation, or both, once full irrigation is restored. In drip-irrigated tree crops a second dripline is often installed. Low-level sprinklers would also be suitable, as would overhead sprinklers on properties where these systems are installed.

Where citrus orchards on deep sandy soils were originally established under overhead sprinklers, and irrigation has been scheduled for some years on the basis of replacing potential crop evapotranspiration, tree roots will be extensive (both within rows and across inter rows) and will make a total contribution to tree transpiration. In such cases, full cover irrigation must be retained when converting to a regulated deficit irrigation regime to ensure the entire root system benefits from scheduled irrigations. A comprehensive network of either microjets or low-level sprinklers will do the job.

Fine-textured soils call for a different regulated deficit irrigation management strategy, compared with sandy loams, because of their permeability, water release curves, and root distribution.

An example is the light clay soil in Figure 6, and referred to in connection with pear and peach production in the Goulburn Valley (figures 3 and 4, pages 8 and 9 respectively).

Such clay soils offer a greater range of plant-available water between field capacity and wilting point compared with sandy soils (compare light clay with sandy loam in Figure 6). One consequence of this greater volume of plant-available water is that rootzones dry down more slowly under regulated deficit irrigation. However, rootzones also tend to be shallower under clay soils compared with sandy soils, so that any increased margin for error in scheduling regulated deficit irrigation because of the range of plant-available water can be offset by a lower total volume of rootzones and lower root-length density within that rootzone.

A lower hydraulic conductivity in fine-textured clay soils slows the downward permeation of irrigation water, so that rootzones re-wet more slowly compared with sandy loam soils. Increasing delivery rate from a point source is not a solution to this slower re-wetting because low permeability quickly results in wasteful runoff. Consequently, a point source such as a dripper (or a set of drippers close together) that works so effectively on sandy soils, might have to be replaced by a diffuse source such as a series of low output microjets or low-level sprinklers. Overhead sprinklers or flooding could also be options if orchard or vineyard topography allows.

On balance, sandy loam soils offer more options than fine-textured soils (light clays) in terms of irrigation supply and management of regulated deficit irrigation, but similar principles apply for successful crop management.

Estimates of when and how much to irrigate will depend on soil type and depth. Estimates of RAW and deficit-available water (DAW), together with values for rootzone depth and wetting pattern based on soil type and depth, are all used in calculating an irrigation schedule both during and after regulated deficit irrigation. These calculations are illustrated in a later section.

Light shallow soils are very difficult to manage during regulated deficit irrigation and provide little margin for error. Often, levels of stress are excessive because light shallow soils dry out rapidly, and reserves of DAW are limited. In such situations, meagre irrigation that is consistent with regulated deficit irrigation must also be frequent, and close attention must be paid to scheduling by observing (and measuring) plant water stress.

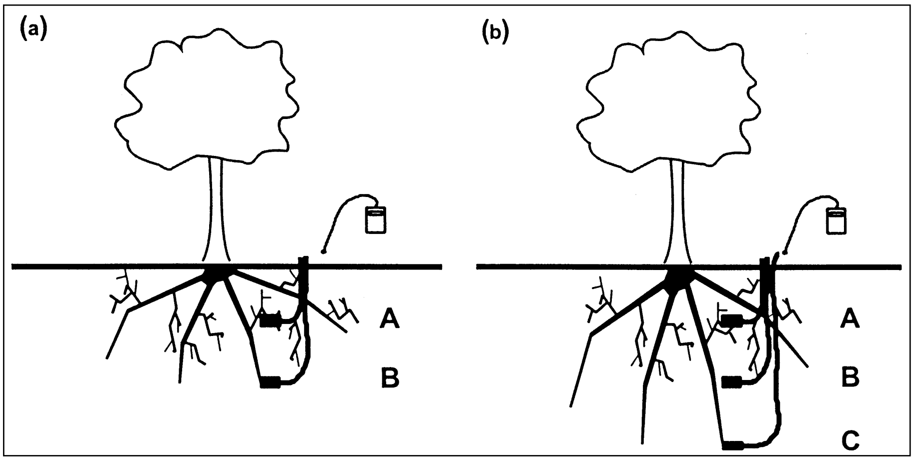
Soil water sensing

Soil water must be measured to schedule regulated deficit irrigation using either point measurement of soil water tension, such as gypsum blocks, or total rootzone soil water content using devices such as a capacitance probe or a neutron moisture meter. Using gypsum blocks in a shallow rootzone, soil water is measured at two depths (Figure 17a). In deep rootzones (>60 cm) soil water is measured at three depths (Figure 17b). The aim is to dry out the soil throughout the rootzone to a minimum tension of 200 kPa by withholding irrigation (positions A, B and C). If there is no rain, the soil in the upper rootzone (positions A and B) will become much drier than the soil towards the bottom of the rootzone (position C). If the entire rootzone becomes drier than 200 kPa, stress levels on the tree will cause loss in productivity. Irrigation must be applied.

Once irrigation starts, the aim is to maintain a moderate level of stress on the trees. This is best achieved by irrigating with less water than the usual full recommendation. Irrigations should aim to wet to 30 cm depth (position A).

Soil water must be measured 6 to 12 hours after irrigation to adjust the amount of water applied in following irrigations. If the soil in the top rootzone (position A) stays dry then the irrigation amount must be increased. If the soil in the mid rootzone (position B) becomes wet immediately after irrigation then the irrigation amount must be cut.

Figure 17. Position of soil water sensors in (a) shallow and (b) deep rootzone soils.



Alternatively, soil samples may be collected with an auger and the moisture content assessed. This is much less accurate than the gypsum block method, but may be useful to assess wetted depth and moisture below the top 5 cm depth.

Interpreting data collected from instruments that measure total rootzone water content is more complex. Initially, to impose regulated deficit irrigation, the entire rootzone is de-watered. As this is done total soil water content will gradually decline. Under regulated deficit irrigation, water is not reapplied until the total soil water content has dropped below the refill point for irrigation.

At soil water contents less than the refill point for full irrigation, grapevines and fruit trees will extract water more slowly because canopy transpiration is responding to partial stomatal closure under those moderately stressful conditions. In light soil, the stress point for regulated deficit irrigation should be about 3% below the full irrigation refill point. For heavier soils, the stress point should be about 5% below the full irrigation refill point.

To ensure fruit trees and grapevines are sustained adequately during regulated deficit irrigation, soil water content within only the top few centimetres needs to increase quickly after irrigation. Recognising that the aim of regulated deficit irrigation is to maintain a moderate level of stress by rewetting only a fraction of the rootzone, irrigation water need only penetrate to about 30 cm. Soil water below this depth will stay dry (or at least depleted of plant-available water).

After each small irrigation, soil water content in the rewetted zone will again decline, however, the rate will be slightly faster than the rate of initial de-watering because the volume of wetted roots is now much less than the wetted volume following winter or spring rain or both.

Characteristics of different types of soil water sensors, including ease of operation, cost, installation, measurement principle, data collection/interpretation and operating range, are outlined comprehensively in Charlesworth (2000). A summary of comparative measurement range for several soil-water tension monitoring instruments is given in Figure 5, Appendix 1.

Irrigation scheduling for regulated deficit irrigation - practical examples

Pear orchard

To illustrate irrigation scheduling we will use a hypothetical mature pear orchard. The orchard is on a fine-textured clay loam in the Goulburn Valley in Victoria on a traditional planting pattern of 6 x 6 m (= 280 trees/ha) and pan evaporation is 40 mm/week.

In this scenario, pan evaporation will set the amount of irrigation needed because irrigation frequency is fixed by the availability of irrigation water. In an alternative arrangement where irrigation water is available on demand, pan evaporation will be used to set irrigation frequency because the amount needed each time will be fixed. That second scenario is considered later in this section (a vineyard in Sunraysia).

Returning to our hypothetical pear orchard, assume a rooting depth of 70 cm so that rootzone volume per tree will be

0.7 m x 10,000 m^2* ÷ 280 trees/ha = 25 cubic metres (= 25,000 L)

* 10,000 m^2 = one hectare

If readily available water corresponds to 8% of rootzone volume, total volume of water available to each tree will be

25,000 L x 8% = 2000 L

Recognising that regulated deficit irrigation calls for both readily-available water (8%) and some deficit-available water (5%) to be extracted, these two components can be taken to approximate 2000 and 1260 L respectively, i.e. a total water resource of 3260 L/tree.

Taking pan evaporation of 40 mm a week, and an initial crop factor of 0.6 (leading up to regulated deficit irrigation implementation), crop evapotranspiration will be

40 mm/week x 0.6 = 24 mm/week

which translates to 10,000 m^2 x 24 mm/week = 240,000 L/week over each hectare of orchard. Given a planting density of 280 trees/ha, crop evapotranspiration is then equivalent to 240,000 L/week/ha ÷ 280 trees/ha ≈ 860 L/tree/week.

As the total volume of soil water resources initially available per tree was estimated to be 3260 L, there would be enough rootzone soil water to sustain orchard evapotranspiration during this initial phase (before implementing regulated deficit irrigation) for 3260 ÷ 860 = 3 to 4 weeks. Note, however, that the value taken for our crop factor will have to be adjusted downwards to about 0.3 as water stress intensifies and canopy transpiration is constrained (partial stomatal closure). Given such adjustments, rootzone soil water reserves would extend from an initial estimate of 3 to 4 weeks to perhaps 5 to 6 weeks.

Having now de-watered the whole rootzone, trees are sustained during regulated deficit irrigation by frequent, light irrigations that are designed to re-wet only the top few centimetres of the rootzone. Those regulated deficit irrigation events can be scheduled either on a fixed interval that matches availability of irrigation water, say, every 7 days, or if water is available on demand, such regulated deficit irrigation events can be based on an estimate of crop evapotranspiration.

Taking a fixed interval of 7 days and recalling that pan evaporation = 40 mm/week, and that crop factor is now 0.3, the irrigation requirement = 40 mm/week x 0.3 = 12 mm/week. Translated to a volume basis this is 430 L/tree/week. Assuming a pressurised irrigation system, with a minisprinkler discharge rate of 80 L/hr, irrigation runtime will then be

430 L/tree/week ÷ 80 L/hr = 5.4 hours/week

Recognising that under regulated deficit irrigation only a top few centimetres of a rootzone will be re-wetted, and assuming the wetted volume is shaped like a cylinder, the wetted volume and thus the depth of penetration, can now be estimated from irrigation volume and soil water-holding capacity.

If each mini-sprinkler wets to a diameter of 5 m, each wetted area will be about 20 square metres (m^2). If the combination of RAW + DAW is equivalent to 13% by volume, 430 L of irrigation water would produce 430 L/tree/week ÷ 0.13 = 3300 L = 3.3 cubic metres (m^3) of wet soil. With a surface area of 20 m^2, the depth of penetration will be

$$3.3\ m^3 \div 20\ m^2 = 0.17\ m = 17\ cm$$

Recurring cycles of light irrigation thus sustain this hypothetical pear orchard during regulated deficit irrigation by re-wetting only the top 17cm of the soil profile back to field capacity.

Vineyard

The hypothetical vineyard considered in this example is a well-established one in Sunraysia under drip irrigation on a deep sandy loam. Planting density is 2 m in-row x 3 m between rows = 1700 grapevines per hectare.

Assume an effective rooting depth of 80 cm (0.8 m), and with 1700 vines/ha, rootzone volume per vine = 0.8 m x 10,000 m^2 ÷ 1700 vines/ha = 4.7 m^3= 4,700 L. To define the amount of water within that rootzone volume that is available for evapotranspiration, assume that readily-available water (RAW) plus a measure of deficit-available water (DAW) is equivalent to 9% on a volumetric basis. Total rootzone water resource is therefore

4,700 L x 9% = 423 L/grapevine.

How long will the vineyard take to de-water that rootzone once regulated deficit irrigation is implemented? Assume for that time of year (late November – early December) that pan evaporation is 50 mm/week, and take a crop factor of 0.7 to represent a well developed and freely transpiring canopy (before regulated deficit irrigation).

Evapotranspiration on an area basis is thus 0.7 x 50 mm/week = 35 mm/week over a hectare, and given a planting density of 1700 grapevines/ha, evapotranspiration on a volume basis is

$$35 \text{ mm/week} \times 10{,}000 \text{ m}^2\text{/ha} \div 1700 \text{ (vines/ha)} = 206 \text{ L/grapevine/week.}$$

Since each grapevine can access a total of about 423 L of water from initially moist soil, and evapotranspiration is equivalent to about 206 L/grapevine/week, then by simple arithmetic, 423 ÷ 206 = 2.05 weeks. Just over 2 weeks will be required to de-water the rootzone before implementing regulated deficit irrigation. Note, however, that under milder conditions and with low-vigour vines on a clay-loam soil, more like 5 to 6 weeks may be needed to achieve that same effect, so that prospects for effective regulated deficit irrigation diminish under such conditions.

Returning to our hypothetical mature vineyard on a deep loam soil, once regulated deficit irrigation is started, only the uppermost 25 cm of the rootzone has to be re-wetted to sustain the grapevines and subsequently improve crop quality. The amount of water that needs to be applied at successive irrigations during regulated deficit irrigation can thus be set by the depth of that wetted zone, and because we assume for this present exercise that water is available on demand, irrigation frequency can be geared to evaporative conditions.

During regulated deficit irrigation, what volume of irrigation is needed to restore the top 25 cm back to field capacity?

Based on well-documented water-release curves (such as a loam soil in Figure 6, page 11) we can assume that the volumetric water content of a de-watered rootzone will be on average about 9% below field capacity. We can further assume a circular wetting pattern of 45 cm diameter will form under each dripper (typical of a sandy loam soil). Again, assuming that the wetted zone is shaped like a cylinder (as in the pear orchard), but this time with a depth of only 25 cm, total volume will be about 40 L. The total volume of water required to re-wet that cylinder back to field capacity will thus be 9% of 40 L = 3.6 L. Based on 3 L/hour drippers, irrigation run time will be 3.6 L ÷ 3 L/hr = 1.2 hours (or a little longer to allow for minor inefficiencies in the irrigation system).

Next, irrigation frequency must be calculated; or put another way, what is the allowable interval between successive irrigations during regulated deficit irrigation?

Assume that drippers are spaced at 0.75 m along each row, and that the inter-row spacing between dripper lines is 3 m (i.e. a single dripline per row of vines). The total number of drippers on an area basis will then be 10,000 m^2 ÷ (3 m x 0.75 m) = 4444 drippers/ha.

Each dripper delivers 3.6 L per irrigation, so the total volume of irrigation water applied to each hectare = 3.6 L x 4444 drippers/ha = 16,000 L/ha. Spread evenly over a hectare, that volume is equivalent to a depth of 16,000 L ÷ 10,000 m^2 = 1.6 mm.

Now take daily evapotranspiration during regulated deficit irrigation as pan evaporation x 0.35 (a lower crop factor to allow for partial stomatal closure and some measure of leaf loss due to moisture stress). With pan evaporation = 50 mm/week, average daily pan evaporation = 50 mm/week ÷ 7 day ~ 7 mm/day, so that daily evapotranspiration from this hypothetical vineyard will be

$$7 \text{ mm/day} \times 0.35 = 2.5 \text{ mm}$$

Based on these calculations, daily restoration of the topmost 25 cm of the vineyard rootzone to field capacity would **not** provide enough water to meet vineyard evapotranspiration under hot conditions. If frequency is not increased during such periods of high evaporative demand, the balance would have to be met from subsoil moisture.

In this hot-weather scenario a vineyard on a shallow sandy soil, or following a dry winter and spring (subsoil water reserves not recharged), a regulated deficit irrigation vineyard would be at risk of terminal (lethal) drought stress. In such cases, irrigation frequency could remain geared to pan evaporation but site-specific patterns of soil water extraction, especially depth of wetted zones, would need to be assessed using soil water monitoring equipment, and adjusted accordingly.

For example, if wetted depth was increased to 30 cm, wetted diameter was increased to 55 cm, and still assuming that a de-watered rootzone holds a volume of soil water that is 9% below the volume stored at field capacity, the wetted volume under each dripper would then be 71 L. The volume of irrigation water required to re-wet that portion would be

$$71 \text{ L x } 9\% = 6.5 \text{ L}$$

and irrigation run time would have to be increased to 2 to 3 hours. The total amount applied would translate in area terms (per hectare) to a depth of 2.9 mm. Assuming vineyard evapotranspiration stays at 2.5 mm/day, this revised scenario now calls for at least daily irrigation to avoid an intensifying, and potentially lethal, drought stress.

Implementing partial rootzone drying

Irrigation systems

Partial rootzone drying necessitates that every row of trees or grapevines is served by dual dripper lines, each of which can be worked independently. To achieve that full independence, both sub-mains, and the valves regulating water flow to those submains, have to be duplicated.

Where existing dripper systems are being upgraded to partial rootzone drying, a second dripper line is commonly laid along each row, and next to the existing dripper line. Where a new orchard or vineyard is being established, either two independent dripper lines are strung out or, as a preferred alternative, a duplex line with dual fused conduits is laid along each row of trees or grapevines.

As discussed in connection with the vineyard at Langhorne Creek (page 38), a pair of independent dripper lines can shrink differentially following the tension applied during installation. That differential shrinkage then results in misalignment of alternating sets of partial rootzone drying drippers on adjacent driplines so a duplex line where two 13 mm cores are fused together along their entire length has been developed.

Either way, an arrangement is needed whereby two spatially separated portions of each plant's root system can be alternately wetted and dried on a duty cycle that lasts somewhere between 7 and 14 days. While one part of the rootzone is being kept moist by modest but frequent irrigations, the opposite (alternate) portion is being allowed to dry down, and roots on that drying side will start to experience soil depleted in readily-available water before the system is switched. Following switching, the previously dry roots are rapidly re-wetted.

Those two alternating zones of each plant's root system can be either aligned along the length of each row, i.e. 'in-row' as for a sandy soil (Figure 18 and photo, page 58), or arranged on opposite sides of each row and irrigating the inter-row space as for a clay soil (Figure 19 and photo, page 59).

Regardless of soil type and wet/dry rootzone configuration, a critical issue can arise when existing orchards or vineyards are converted from full-cover irrigation to a partial rootzone drying regime. As already discussed, effective partial rootzone drying requires a pair of physically discrete root systems that are wetted alternately, where each alternate side is allowed to dry down between successive cycles of irrigation. Recurring allocations of water (and dissolved nutrients) that wet only a limited volume of soil on each side of a tree or grapevine, encourage lots of roots to grow within those two wetted volumes. Containing roots is therefore the best way to exercise close control over plant access to soil water.

However, when orchards or vineyards are established with some form of full-cover irrigation, roots proliferate underneath the entire wetted area. Therefore, when a partial rootzone drying regime is imposed, only a small portion of the entire root system of any particular tree or grapevine will be subject to its influence. Initially, and at least for the first season, plant access to soil water will not be limited to uptake from alternating wetted zones. This means that partial rootzone drying will fail to 'work' until root system architecture has adjusted to the new pattern of wetted zones, and plant access to soil water is restricted to extraction of water from those alternating wetted zones.

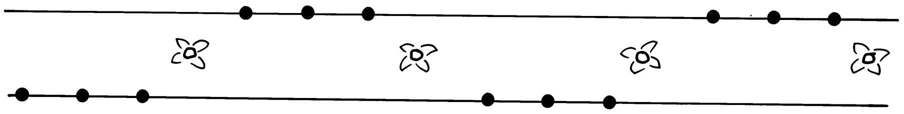
Orchards and vineyards that have been established with a drip irrigation system will most likely already have restricted rootzones, and are thus more immediately suited to a partial rootzone drying irrigation regime.

Soil attributes

Sandy soils

Deep sandy soils lend themselves to an in-row partial rootzone drying configuration (see Figure 18) that is simple, robust and readily installed. Lateral diffusion of irrigation water from a point source is minor compared with downward movement from that same source, and roots grow mainly within a contained volume of soil that corresponds to the re-wetted zone. Such a system has proved highly effective at the Wingara Wine Estate (Karadoc, Victoria), and is shown below in Figure 18 (not to scale).

Figure 18. In-row partial rootzone drying configuration suitable for sandy soils.



✿ = Grapevine stem (1.8 m in-row spacing)

-●- = Dripper (0.75 m spacing 3 outlets on alternating sides)

— = Dripper line (in practice, these two dripper lines are in loose contact and closely aligned along the grapevine stems in each row).

At Karadoc, in-row spacing of grapevines is 1.8 m, and the inter-row space is 3 m. Drippers on each of the two lines serving each row of grapevines are spaced at 0.75 m. Both dripper lines are pressurised enough to ensure even delivery along the entire length of each line, and individual drippers deliver around 4 L/hr. When irrigation is operating, each half of each vine is thus being re-wetted at a rate of equivalent to 1.11 mm/hr [calculated as (4.0 L/hr x 3 drippers) ÷ (3 m x 1.8 m) ÷ 2 to allow for alternating operations = 1.11 L/hr/m^2, or 1.11 mm/hr because 1 L of water covers a square metre to a depth of 1 mm].

As discussed earlier the partial rootzone drying duty cycle in this vineyard was reduced to 7 days in response to high values for summertime evapotranspiration, where rootzone water content on the drying side was approaching wilting point within about 7 days of withholding water.

After switching sides, re-wetting of the previously dry side is routinely done in about a day (see change in volumetric soil moisture from 8 January to 9 January on the south side root system in photo). A combination of deep porous soil and a compact root system thus ensures that partial rootzone drying at Karadoc is implemented to best effect through definitive wetting/drying cycles on alternating sides of each grapevine.

Dual dripper lines for Shiraz grapevines (grafted to Schwartzman rootstock) on a deep sandy loam (overlaying a clay-loam subsoil) at Wingara Wine Estate (Karadoc, northern Victoria). These grapevines were originally established in 1994 and converted to an irrigation regime of partial rootzone drying in 1998 (photographed in August 2002). In-row spacing between grapevines is 1.8 m, with 75 cm between drippers that are located as groups of three on alternate sides (see diagram in Figure 18).

The situation is similar at Oxford Landing, near Waikerie in the South Australian Riverland, with Riesling grapes on Ramsey rootstock. The vineyard was established on a deep sandy loam with a highly saline watertable, but careful management of deficit irrigation through partial rootzone drying has consistently returned much improved irrigation water use efficiency with no significant loss of yield.

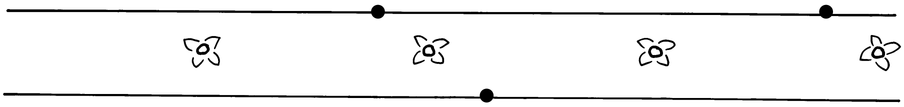
Contrast those two cases with the Nuriootpa trial (Table 9, page 43), where partial rootzone drying failed to improve apparent efficiency of irrigation water use compared with continuous deficit irrigation.

Regardless of water use outcomes, the Nuriootpa trial has already provided valuable experience regarding application of irrigation water to a poorly structured soil. The trial site had been previously irrigated with bore water for 17 years before the trial was established and this had rendered this site less suitable for partial rootzone drying. Soil structure was poor and it had lost porosity. It is possible that partial rootzone drying failed to work because reduced permeability slowed re-wetting after switching from dry to wet; a problem exacerbated by having only a single dripper on each side of each vine (photo on next page and shown in Figure 19). A wider separation between drippers in combination with more diffuse source of irrigation water may have been more successful producing a positive partial rootzone drying effect on irrigation water use efficiency.

Clay soils

Fine textured (clay) soils of inland Australia support large areas of irrigated cropping, mainly because of topography. Flat alluvial plains lend themselves to flood irrigation, and were preferred regions for early developments such as the Murrumbidgee Irrigation Area (MIA) that were initially based on gravity-fed systems. Nutrient-rich deep clay soils with a substantial water-holding capacity are a feature of these regions. Under irrigation, such clay soils are less tractable than light soils, and especially deep sandy loams.

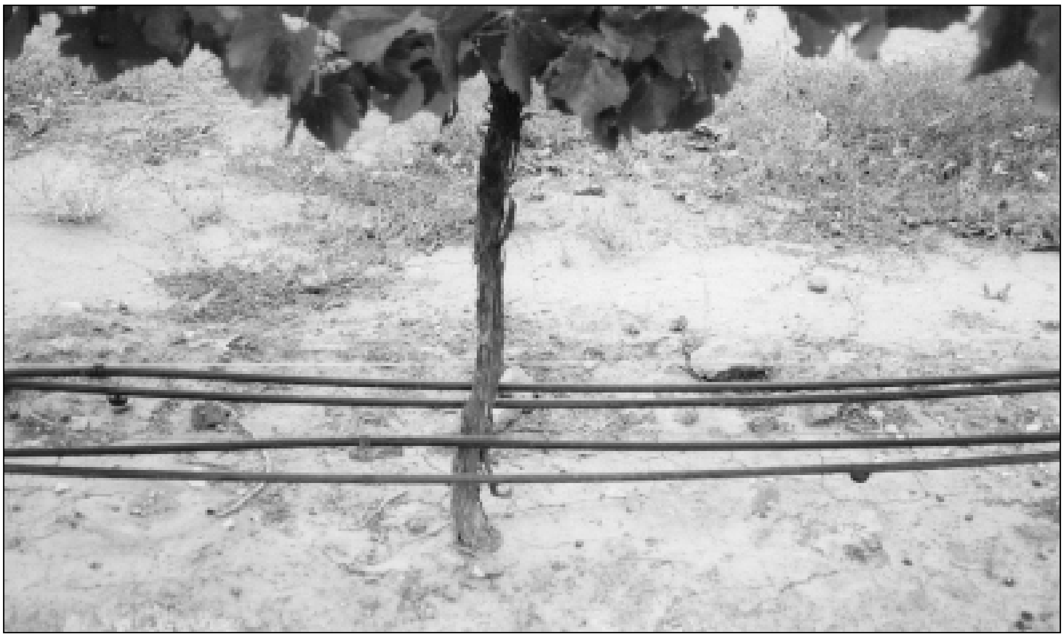
Figure 19. SARDI Nuriootpa trial



✿ = Grapevine stem (2.25 m in-row spacing)

-●- = Dripper (0.5 m from grapevine stem on each side)

— = Dripper line (irrigation layout is not to scale)



Combined deficit irrigation and partial rootzone drying trial site at SARDI Nurioopta using Chardonnay (own roots) and showing 2 L/hr PRD dripper locations (1 metre apart and 50 cm on either side of each vine stem). Photograph courtesy Shannon Pudney, SARDI/CRCV, Plant Science Centre, University of Adelaide.

Nevertheless, decades of investment in general infrastructure within regions such as the MIA, and more recent establishment of large capital-intensive enterprises on floodplains and ancient lake beds, represent a long-term commitment to irrigated cropping on clay soils despite their mixed attributes.

The small or even nil responses to partial rootzone drying in terms of improved irrigation water use efficiency or of excessive yield losses from Shiraz grapes under regulated deficit irrigation, which have been described in this publication, were associated with either poorly structured clay soils or with shallow light soils that overlay heavy clay subsoils. Trial outcomes from

Padthaway, Nuriootpa and Griffith (summarised in Chapter 3) point to a mix of soil features that work against successful implementation of partial rootzone drying on clay soils compared with deep loam soils. Those features include the following:

- a greater increase in soil strength as rootzones dry down so that root growth is inhibited
- slower re-wetting of the rootzone so that relief from drought stress is not immediate
- poorer aeration after re-wetting so that root function is impaired
- a bigger reserve of plant-available water, but lower hydraulic conductivity over part of the available range
- a generally lower root-length density so that a smaller fraction of plant-available water within the overall profile is actually extracted
- shallower rootzones, so that the vertical extent of water extraction down the soil profile is also diminished
- a tendency towards a greater lateral spread of irrigation water that consequently strays from the nominally wet, into the nominally dry side.

A likely scenario, and one with adverse implications for partial rootzone drying on clay soils, might be as follows.

Not enough roots on the drying side actually dry down fast enough to generate a distinctive surge in root signals, while roots on the re-wetting side are not wetting fast enough to totally satisfy canopy transpiration. Transpiring shoots are thus drawing some xylem sap more or less continuously, but to a varying extent, from both sides. Indeed, measurements of daily patterns of variation in xylem sap ABA concentration in such situations imply an overnight cross traffic in xylem sap from the ‘wet’ side to the ‘dry’ side that results in an early morning surge in ABA movement to transpiring shoots.

By contrast, in a sandy soil, the dry side generates signals (especially ABA) that stay in that same half of the root’s vascular system until irrigation water returns to flush them out. During most of each partial rootzone drying cycle, roots on the dry side exist at too low a water potential to act as a significant source of water for shoot transpiration. During that time, roots on the dry side are accumulating inhibitory substances. Meanwhile, roots on the wet side are more or less totally responsible for meeting day-to-day canopy transpiration. These two distinctive sets of processes then reverse upon switching from dry to wet.

Given such contrasting scenarios between clay versus sandy soils, how can partial rootzone drying be applied to clay soils? Possible options are discussed below.

Options for partial rootzone drying in clay soils. With orchards or vineyards established on deep sandy loams, irrigation from point sources is known to be highly effective for partial rootzone drying. However, on less permeable light clay soils, irrigation water has to be applied from a diffuse source if a similar root volume is to be re-wetted during the limited time frame that successive partial rootzone drying cycles require. Pairs of irrigation sources also have to be further apart on clay soils than on deep sandy soils to offset lateral permeation and thus a loss of distinctively wet and dry regions within the rootzone of each tree or grapevine. Widely spaced outlets also help avoid poor aeration while increasing wetted volume.

Irrigation from diffuse sources such as microjets or low-level sprinklers aims to take account of the lower permeability of fine-textured soils, and calls for a different configuration, called an ‘inter-row’ or ‘between row’ partial rootzone drying system (Figure 20). Compared to the ‘in-row’ system discussed above (figures 18 and 19) an inter-row partial rootzone drying system is more complex to install, more demanding in terms of maintenance and, because of its multiple components, more vulnerable to damage during routine orchard or vineyard operations.

Different versions of an inter-row partial rootzone drying system are possible, as follows:

- Irrigation water could be applied to the inter-row space via a moveable line or with a subsurface supply line that runs centrally along the length of each inter-row and is equipped with pop-up outlets that distribute water in discrete circular patterns and spaced in relation to each tree or grapevine (Figure 20).
- Microjets with a semi-circular pattern that throw into the inter-row space next to each stem (and alternating between adjacent inter-rows) from two supply lines that are closely aligned with each row (Figure 21).
- Where topography allows and furrow irrigation is still practised, successive irrigations can be applied to alternate rows. This tactic has been applied experimentally to cotton in north Africa and to pears in the Goulburn Valley (see Chapter 3, page 45).

Figure 20

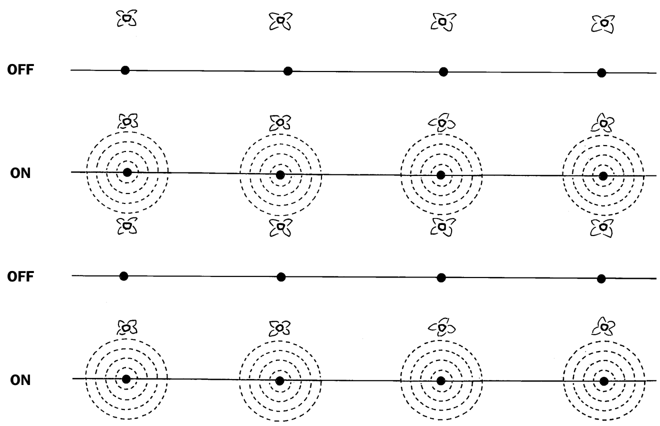
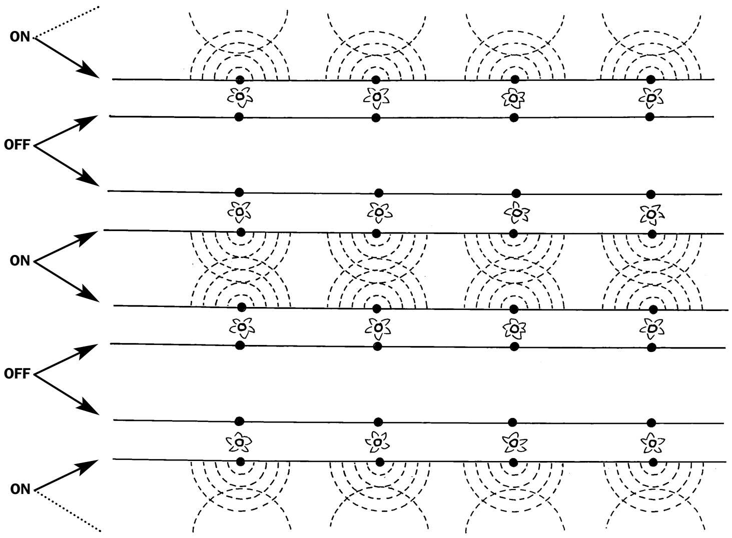


Figure 21



Notional features of irrigation layouts that would enable partial rootzone drying in orchards or vineyards on fine-textured (clay) soils. In Figure 20, alternate inter-row spaces are irrigated from either a moveable line of mini-sprinklers, or from a fixed (and buried) line of 'pop-up' sprinklers. In Figure 21, alternate inter-row spaces are irrigated via two opposing lines of micro-jets or mini-sprinklers with semicircular wetting patterns that meet across the inter-row space.

In both figures, general layout, as well as plant stem and emitter spacings, are purely hypothetical. In practice, such spacings would vary with site requirements. Previously-established high-density orchards for example, would call for pattern overlay along the entire length of each row to ensure partial root systems were adequately wetted. By contrast, newly-established low-density orchards (hot arid environments) might be better served by a wider spacing between emitters that would produce more discrete wetting patterns consistent with more widely spaced plantings.

Soil water sensing

Effective partial rootzone drying requires that just enough water is applied to alternate sides of a root system to re-wet (repeatedly) the same population of roots after their drying cycle. Once that alternating cycle of drying and re-wetting is established for respective sides of a root system, and there are enough roots in the wetted zone to ensure a comprehensive extraction of soil water, then a similar volume of irrigation water will be needed each time afterwards. The major issues that emerge in managing the wetted zone compared to the drying zone are: when and how much water should be applied to the wetted zone, and when should the drying zone be switched back to a wetting cycle?

Frequency of wetting will vary with seasonal conditions, but irrigation volume will stay about the same. Re-wetting frequency will obviously need to be adjusted according to variation in crop evapotranspiration as each season progresses. Reference has already been made to 'duty cycles' of drying and re-wetting that range from 10 to 14 days under mild conditions down to 3 to 5 days under hot conditions, and especially on light sandy soils such as the trial vineyard of the Wingara Wine Group at Karadoc.

Soil water changes within these wet/dry portions of a tree or grapevine root system will thus be highly dynamic. There will be a fast sequence of both drying and re-wetting, as well as big changes in soil water content during each alternating cycle. To track such variation, the soil-water sensor in a partial rootzone drying environment must offer both a short response time as well as a broad operating range and, preferably, an immediate readout of volumetric soil water content. Soil water sensing in such an environment must enable instant detection of wet/dry contrasts in both space (across the wet/dry zones) and in time (subsequent to onset of irrigation). As well, a sensor that helps quantify the total volume of plant-available water within a rootzone will be a further guide to irrigation scheduling.

Neutron moisture sensors meet such exacting requirements. They are well suited to partial rootzone drying irrigation, and are used successfully on the light sandy soils at Karadoc. During periods of high crop evapotranspiration (typically around mid season in January and February), soil water content is often monitored daily, especially in drought-prone parts of this vineyard, using an array of access tubes installed along selected portions of vine rows. Measurements are taken at 10 to 20 cm intervals down the soil profile (less often with increasing depth below the rootzone) down to about 120 cm (see Figure 15, page 36).

On the sandy-loam topsoils of this particular site, and given the sphere of influence of a neutron probe sensor (10 to 15 cm radius), a single access hole 15 to 20 cm from the vine stem (one on each side) is enough to give a representative picture of soil water changes within the wet/dry zones in a grapevine's root system.

On the sandy loam soil at Karadoc, wet/dry zones of the grapevine's root system will typically range between about 40% by volume immediately following an irrigation, drying down to around 25% once readily-available soil water is exhausted and a substantial fraction of deficit-available water has also been extracted. By comparison, soil water content under partial rootzone drying grapevines in a research vineyard in Adelaide range between 35% after irrigation, down to around 22.5% before the next re-wetting (mm of water between 15 and 55 cm depth in Figure 13, page 30, converted to percent). This much change in soil water content can be used to schedule partial rootzone drying with confidence. The contrast in absolute values between Karadoc and Adelaide is presumed to be due to differences in soil type and in calibration settings for soil water sensors.

A lower-cost alternative to measuring changes in soil water under partial rootzone drying with a neutron probe is to install either a specifically designed wetting-front detector (described in

Appendix 2), or an array of gypsum blocks that serve a similar purpose. Some types of wetting-front detectors are robust, reliable and virtually maintenance free. Moreover, when located strategically at depth within the rootzone of an orchard or vineyard, they enable an irrigation system to be automated by triggering irrigation as soil water is extracted, and then stopping supply once the wetting front has passed a certain depth.

An array of gypsum blocks that transects the wetted volume within a plant's rootzone is a semi-permanent arrangement, and has the advantage that it can be readily installed and automated. With data collection facilitated, changes in soil water can be monitored more or less continuously. The operating range of gypsum blocks easily covers the variation in soil water associated with drying/re-wetting cycles, but they lack sensitivity at the 'wet' end of that range, namely from field capacity to around 40 to 60 kPa soil water tension. They also 'sense' soil water tension rather than volumetric water content (as is the case with neutron probes). When gypsum blocks are used, changes in the volume of plant-available water within a partial rootzone drying-rootzone must then be inferred from water-release curves for particular soils (see Figure 6, page 11). Nevertheless, a suitable array of gypsum blocks will serve as a reliable wetting-front detector, and will be especially helpful in deciding when a specific volume of root system is to be rewetted, and thus in determining irrigation run time.

To do this on a sandy loam soil, such an array would be aligned within a representative section of the row of orchard trees or grapevines, and extend on each side of a test plant. Soil water data would be gathered from just beneath the surface, and from successively lower layers (say 10, 25, 75 and 150 cm), with a further set of 10 cm subsurface blocks spaced at increasing intervals from a stem starting at, say, 15 cm, and going out to 35 to 45 cm depending on planting density. Wider spacings would be needed for lower density.

Such an array would be placed strategically within a partial rootzone drying orchard or vineyard to yield information on soil water dynamics for the major soil types within that property, i.e., shallow soils compared to deep soils, and fine textured soils compared to coarse textured soils. As a rule, shallow sites with coarse textured soils would be least flexible for scheduling partial rootzone drying. Deep sites carrying finer textured loam soils would be better buffered with respect to soil water reserves, and would be more flexible in terms of scheduling partial rootzone drying.

Irrigation scheduling for partial rootzone drying

Two central issues emerge when scheduling partial rootzone drying irrigation against a background of evaporative demand. These issues are as follows:

- How many days will rootzone water on the wet side be able to sustain evapotranspiration before re-wetting of that part of the profile is required?
- Will the length of successive cycles of de-watering and subsequent re-wetting on alternating sides of each plant fall within the preferred 'duty cycle' for partial rootzone drying? If cycles are too short (perhaps less than 3 days), definitive surges of root signals seem not to reach the shoot, whereas if cycles are too long (perhaps more than about 15 days), root signals become dissipated, and shoot physiology remains unrestricted.

In addressing these issues, three scenarios are outlined to show possible outcomes for fruit trees or grapevines in three different situations, as follows:

- one that is conducive to effective partial rootzone drying (a warm climate planting in a deep sandy loam)
- where chronic water stress precludes expression of partial rootzone drying (a hot environment on a shallow sandy soil)
- in a mild environment on a clay loam soil where successive cycles of de-watering and re-wetting would be too long for effective partial rootzone drying.

Warm climate and a deep sandy loam

This example is based on a hypothetical, well-established vineyard on a deep sandy loam during a week in summer and representative for Sunraysia or the South Australian Riverland.

Assume that:

pan evaporation for 1 week during summer = 33.3 mm
crop factor = 0.7 (large, vigorous grapevines)

Crop evapotranspiration thus = 33.3 x 0.7 = 23.3 mm

First convert mm of evapotranspiration to volume of water evapotranspired per hectare (noting 1 ha = 10,000 m^2). In this case 23.3 mm over one hectare in one week is equivalent to

$$10{,}000 \text{ m}^2 \text{ x } 0.023 \text{ m} = 233 \text{ m}^3 = 233{,}000 \text{ L}$$

Assume a planting density of 1850 plants/ha so that evapotranspiration per plant =

$$233{,}000 \text{ L} \div 1850 \text{ plants/ha} \approx 126 \text{ L/plant/week} = 18 \text{ L/plant/day}$$

Now estimate how long rootzone water reserves will sustain evapotranspiration equivalent to 18 L/plant/day.

To do this, assume the following:

- Planting configuration equivalent to Figure 18, page 57, with three drippers on each side of each plant.
- A wetted depth of 600 mm (0.6 m)
- The wetted volume beneath each dripper is represented as a cylinder with a diameter of 500 mm (0.5 m). In reality, the wetted rootzone will be shaped more like a giant onion or turnip, but a cylinder is easier to model, and will suit this purpose.

The volume of any cylinder = πr^2 x d, where $\pi \approx 3.142$. In this example r (radius[†]) = 0.5 m ÷ 2 and d (depth) = 0.6 m. The volume of this cylinder is therefore 3.142 x $(0.5 \div 2)^2$ x 0.6 ≈ 120 L.

Since readily available water is about 8% of that volume (40% at field capacity and 32% at the onset of water stress), total volume of water available from three wetted cylinders will be = 3 x 120 L x 8% = 29 L/plant.

With crop evapotranspiration equivalent to 18 L/plant/day under these warm conditions, soil water reserves of 29 L within the wetted rootzone of each plant, would sustain evapotranspiration for one and a half days.

In reality, a number of factors stretch that interval, and enable soil water reserves within the wetted portion to last longer. Those factors include the following:

- Stomatal responses to strong evaporative conditions that lead to partial stomatal closure, and thus a lower crop coefficient. This feed-forward response to evaporative conditions that diminishes transpiration relative to unconstrained rates, is a common feature of vascular plants, but is especially evident in grapevines on a partial rootzone drying irrigation regime as discussed earlier (page 28 and in Figure 3, Appendix1).
- Soil water from the 'drying' portion of the rootzone being absorbed at the same time as the wet side is being irrigated.

[†] a radius is half the diameter of a circle.

- Supplementary soil water from the inter-row space and from beneath the wetted zone being absorbed. Such reserves get replenished during wet winters and perhaps early spring, and are not normally monitored as part of an orchard or vineyard water budget. Nevertheless, water from this source can buffer perennial plants against shortfalls in irrigation and commonly enable cropping, or at least survival, in dryland situations. For example, deep soil reserves of water sustained dryland viticulture in regions such as the Barossa Valley before the widespread adoption of trickle irrigation.

Returning to the hypothetical example of 120 L wetted zones, what irrigation run time would be required to replenish plant-extractable soil water within those zones?

To calculate this, assume that volumetric soil water = 32% at the onset of water stress, referred to here as 'dryness', and 40% at field capacity (see Figure 6, page 11). The volume required for total replacement of evapotranspired water is thus:

(40% - 32%) i.e. 8% of 120 L = 9.6 L

Assuming the pressurised irrigation system is equipped with drippers that deliver 4 L/hr (as fitted at Karadoc), the irrigation run time required to replace this amount of evapotranspiration is therefore

9.6 L ÷ 4 L/hr = 2.4 hours
(or perhaps longer depending on irrigation system efficiency).

Such rapid wetting ensures definitive wet/dry cycles, and supports full expression of shoot response to partial rootzone drying.

Hot conditions and a shallow sand
As a comparison, now consider a hot climate vineyard on a shallow coarse sand.

Assume that: pan evaporation for 1 week during summer = 65 mm, crop factor = 0.6 (to allow for smaller canopies compared with the previous viticultural example).

Crop evapotranspiration is thus = 65 x 0.6 = 39 mm. Converting from depth to volume, 39 mm over one hectare in one week is equivalent to

$10{,}000\ m^2 \times 0.039\ m = 390\ m^3 = 390{,}000\ L$

Assuming a planting density of 1500 plants per hectare (lower density in a hotter climate), evapotranspiration per plant =

390,000 L ÷ 1500 plants/ha ≈ 260 L/plant/week ≈ 37 L/plant/day

How long will rootzone water reserves sustain evapotranspiration equivalent to 37 L/plant/day? Assume once again a planting configuration equivalent to Figure 18 with three drippers on each side of each plant, but assume a wetted depth of only 400 mm (0.4 m), and represent the wetted volume beneath each dripper as a cylinder with a smaller diameter of 250 mm (0.250 m) to allow for reduced lateral spread on a coarse sand. The volume of each wetted cylinder is therefore

$3.142 \times (0.25 \div 2)^2 \times 0.4 \approx 20\ L$

Since plant-extractable water corresponds to about 6% of that volume (38% at field capacity and 32% at 'dryness'), total volume of water extractable from three wetted cylinders will be

$$3 \times 20\ \text{L} \times 6\% = 3.6\ \text{L/plant}$$

Irrigation run time for replacing plant-extractable soil water within each of these 'cylinders' would be short (less than 20 minutes for a 4 L/hr dripper), and soil water reserves would be an inadequate buffer against peaks in transpirational demand. With crop evapotranspiration equivalent to 37 L/plant/day under these hot conditions, soil water reserves of 3.6 L within the wetted rootzone of each plant would not sustain evapotranspiration on a daily basis.

Even allowing for some extraction of soil water from the drying side (but little from deeper layers due to the shallow soil), plus a further reduction in crop factor as foliage sheds, plants will most likely be under chronic stress during hot periods unless drippers run more or less continuously. This scenario of an estimated crop evapotranspiration that is much more than static reserves within the wetted rootzone, is reminiscent of the field trial on a shallow sandy soil at Padthaway (Table 5, page 31), and where partial rootzone drying was ineffective as an irrigation technology.

Cool climate and a deep clay loam

This final scenario is for an apple orchard in a cool climate such as the Adelaide Hills or north-eastern Victoria, on a fine-textured soil where irrigation is applied more diffusely (from semi-circular micro-jets) rather than from a point source (see Figure 21, page 61 for partial rootzone drying on clay soils).

Assume that: pan evaporation for 1 week during summer = 25 mm
crop factor = 0.8 (vigorous growth).

Crop evapotranspiration is thus = 25 mm x 0.8 = 20 mm. Converting from depth to volume, 20 mm over one hectare in one week is equivalent to

$$10{,}000\ \text{m}^2 \times 0.020\ \text{m} = 200\ \text{m}^3 = 200{,}000\ \text{L}$$

Assume a planting configuration of 2 m in-row x 5 m between rows (density of 1000 trees per hectare). Evapotranspiration per plant can then be calculated as:

$$200{,}000\ \text{L} \div 1000\ \text{plants/ha} \approx 200\ \text{L/plant/week} \approx 30\ \text{L/plant/day}$$

How long will rootzone water reserves sustain evapotranspiration equivalent to 30 L/plant/day?

To calculate this assume the following:

- Planting configuration equivalent to Figure 21 with a single semi-circular emitter on each side of each plant
- A wetted depth of 500 mm (0.50 m).

Represent the wetted volume beneath each emitter as a cylinder with a larger diameter of 4000 mm (4 m) to allow for operation of an emitter plus greater lateral spread on a clay loam soil. The volume of each wetted cylinder is therefore

$$3.142 \times (4/2)^2 \div 2 \times 0.50 \approx 3.1\ \text{m}^3 = 3{,}100\ \text{L}$$

Since plant-extractable water corresponds to about 8% of that volume (42% at field capacity and 34% at the onset of water stress or soil 'dryness'), total volume of water extractable from a single large wetted cylinder will be

3100 L x 8% ≈ 250 L/plant

There would be enough soil water reserves to sustain this planting for at least a week. Allowing for the possibility of plants extracting extra soil water from depth as upper-profile supplies diminish (a feature of clay loam soils in Table 8, page 40), there may be 2 or 3 weeks between irrigations. As well, small amounts of soil water extracted from the drying zone would make that interval even longer.

As to re-wetting, an emitter might deliver 30 L/hr and theoretically would need to run for 5 to 6 hours to recharge soil water. However, given a low permeability clay loam compared to a sandy loam or, more especially, a coarse sandy soil, that irrigation run time would have to be spread over 3 to 5 days to avoid excess runoff. Total time for a wet/dry cycle could thus stretch to 3 to 4 weeks.

In partial rootzone drying irrigation, an alternating wet/dry cycle of 10 to 14 days on each side of a plant seems about optimal (at least for grapevines) for managing vigour and water use efficiency. Even shorter cycles of 3 to 5 days have been effective at Karadoc. Consequently, orchards and vineyards on clay loam soils in cool climates (as described above) might not 'cycle' rootzone water fast enough to generate successive and definitive pulses of the root signals that appear necessary for plants to benefit from this novel irrigation technology.

At first sight, one solution to this slow 'cycling' on clay soils might be to reduce the depth of the wetted zone. This would certainly diminish water supply through irrigation, and could shorten cycling time, but would also have extra effects that are at present hard to gauge. For example, plant roots are likely to extend even further in their quest for water from greater depth within the profile, and in so doing, the fraction of the root volume managed according to partial rootzone drying becomes a smaller fraction of total root volume. A threshold fraction below which partial rootzone drying becomes ineffective is yet to be defined and, without this data, we can only speculate that such an issue might arise with partial rootzone drying on clay soils.

The three scenarios outlined above for cool, warm and hot conditions are of course contrived, but they are meant to be indicative of orchard or vineyard behaviour in those situations. They must not be taken as definitive of particular outcomes or of scheduling criteria. Nevertheless, the situations described are plausible and highlight issues that will confront irrigation managers. As such they should be considered by horticultural developers.

Clearly, partial rootzone drying irrigation is an exacting technology and calls for astute judgement that covers both the broad issues of estimating crop evapotranspiration in relation to rootzone water reserves, and the more specific issues of monitoring changes in rootzone water reserves. Soil water reserves or, more precisely, the amount of plant-extractable water that remains on the 'dry' side of a root system, normally serves as the trigger for restoring irrigation to that side. The time course of such extraction is best illustrated in Figure 13, page 30, which shows recurring cycles of rapid de-watering, followed by slower withdrawal to a minimum volumetric soil water around 80 mm (summed for 15 to 55 cm depth). That pattern of drawdown implies an initial extraction of readily-available soil water, followed by some deficit-available water as well.

Some form of soil-water sensing is needed to follow such changes and thus schedule irrigation under a partial rootzone drying regime (discussed further in Appendix 2). Plant indicators of rootzone water reserves such as pre-dawn water potentials that are helpful guides in regulated deficit irrigation or standard irrigation, are less appropriate under partial rootzone drying because the wetted portion of the plant's roots will tend to keep shoots turgid even when plant-extractable soil water on the 'drying' side is virtually exhausted. A combination of soil probes plus advanced versions of sap-flow sensors that could track water extraction from both wet and 'drying' sides at the same time may eventually provide that information for practical irrigators but at present such methodology exists only as a research tool.

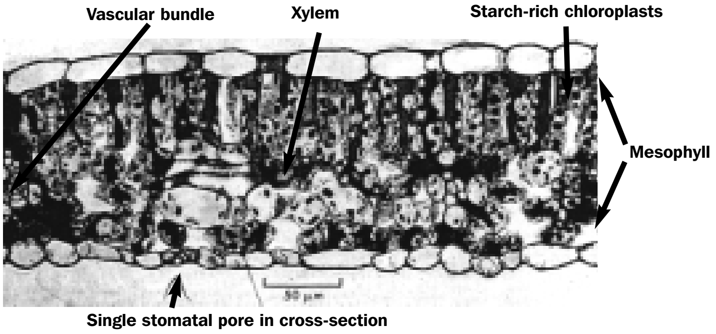
APPENDIX 1

PRINCIPLES UNDERLYING PLANT WATER USE FOR GROWTH AND CROPPING

Leaf gas exchange

Plants must transpire to photosynthesise, so that water loss is an inevitable accompaniment to carbon gain. Well-nourished crop plants will commonly lose at least 100 g of water for every gram of carbon fixed (in the form of sugars, starch and other carbohydrates), and during hot, dry summers in vineyards and orchards of semi-arid regions such as inland Australia, even more water is lost. To see why this happens, see Figure 1 for the functional anatomy of a typical leaf such as grapevine.

Figure 1. A transverse section from a mature grapevine leaf *(Vitis vinifera L.)* showing a vascular bundle, single stomatal pore, also leaf xylem element and (photosynthetic) mesophyll tissue. Mesophyll cells are packed with starch-rich chloroplasts. Scale bar = 50 µm (photomicrograph courtesy P E Kriedemann).



In strong light, photosynthetic tissues (mesophyll cells) in a turgid leaf (mesophyll in Figure 1) fix enough internal carbon dioxide to lower the intercellular partial pressure of carbon dioxide and thus help to trigger stomatal opening (Figure 2, A and B). Fresh supplies of carbon dioxide from the atmosphere then spread inwards and are assimilated into sugars within the mesophyll tissue. Because mesophyll cells are wet, this inward diffusion of carbon dioxide is accompanied by water molecules spreading outwards from wet cells to the air (transpiration). The carbon dioxide molecules then move in slowly, while the water molecules move out more quickly. This results in the transpiration rate being much higher than the photosynthetic rate.

On an average day the inward gradient for carbon dioxide is from around 35 Pa in ambient air, down to around 25 Pa for intercellular carbon dioxide, a difference of only 10 Pa. By contrast, the water vapour pressure difference between mesophyll cells and ambient air on a hot dry day is more like 3500 Pa. This represents a potentially huge outward flow of water compared to a rather meagre inward flow of carbon dioxide. In this situation, some stomatal regulation occurs (see Figure 2, A and B), but even with stomatal modulation in place, an actively photosynthesising leaf canopy still needs a steady supply of soil water to replace unavoidable transpirational loss.

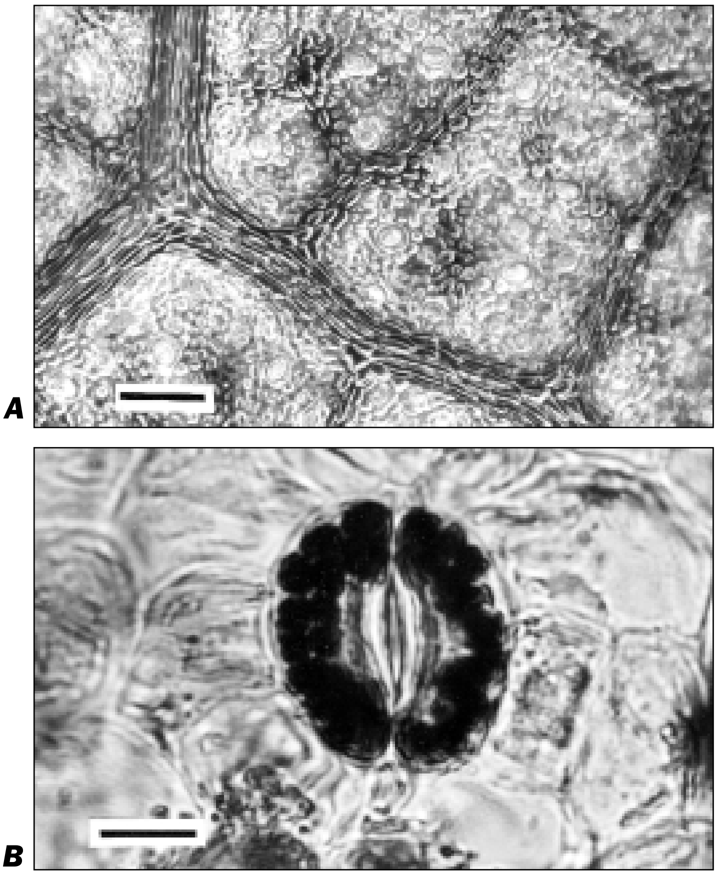


Figure 2. Surface view of the underside of a mature grapevine leaf showing stomata clumped within islets of minor veins.
A = low magnification view of stomatal field (scale bar = 100 μm)
B = higher magnification view of a single (partially open) stomatal pore where both guard cells are packed with starch-rich chloroplasts (scale bar = 20 μm) (photomicrograph courtesy P E Kriedemann).

Transpiring foliage is thus vulnerable to moisture stress, and whenever the rate of water loss through leaf transpiration is higher than the rate of replenishment through uptake and distribution of soil water, leaves lose turgor. A combination of that loss in turgor, accumulation of leaf tissue ABA (the stress related plant hormone, abscisic acid) and increased carbon dioxide levels in sub-stomatal cavities (see Figure 1, page 69) then trigger stomata to close (onset takes only a few minutes). Significantly, stomata cannot function as self-regulating resistances to water loss without ABA, and mutant plants that are incapable of synthesising ABA fail to survive under natural conditions. ABA physiology thus features in modulating stomatal resistance under well-watered conditions, as well as in initiating stomatal closure in response to water stress.

When stomata start to close, leaf moisture is conserved, but because water and carbon dioxide molecules share a common pathway through stomatal pores, photosynthesis is also decreased. The photosynthetic rate (A) declines in proportion to the degree of closure, shown from right to left in Figure 3 (over page) as a decrease in stomatal conductance (g_s). Significantly, the relationship between photosynthetic rate and stomatal conductance is curvilinear, so that partial closure of fully open stomata lowers transpiration more than photosynthesis under well ventilated conditions. Conversely, when tightly closed stomata begin to open (from left to right in Figure 3) photosynthesis increases in step with stomatal conductance. This curvilinear relationship is used to good effect in both regulated deficit irrigation and partial rootzone drying where imposing mild water stress leads to partial stomatal closure, and puts leaves into a more water efficient mode of gas exchange.

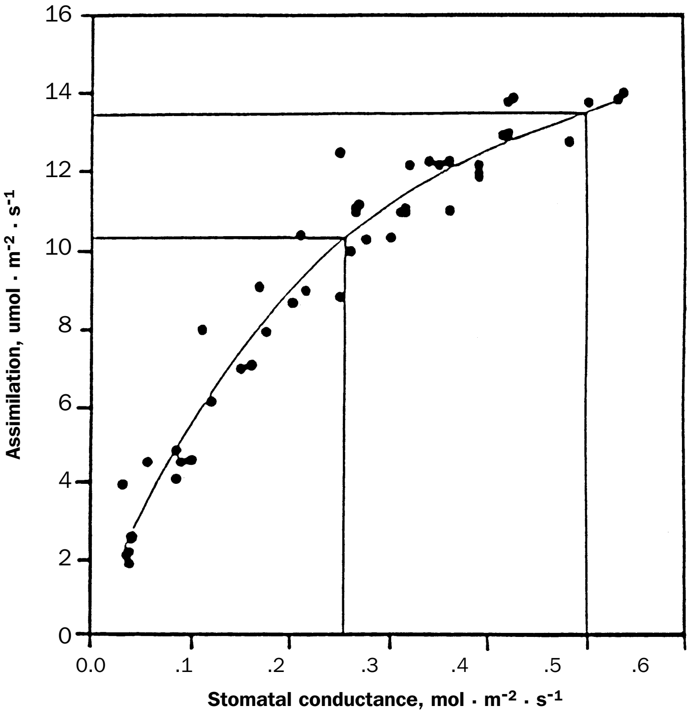


Figure 3. Photosynthesis (single leaf) increases curvilinearly with stomatal conductance. Concurrent measurement of CO_2 and H_2O vapour exchange by this grapevine leaf in an illuminated chamber enables calculation of net photosynthesis (A) and stomatal conductance (g_s). Starting with a plant showing maximum exchange rate (right hand end of curve) factors such as a reduction in plant moisture status, increased leaf to air vapour pressure difference or application of a stress-related hormone, will induce stomata to start closing, and the exchange will reduce. Initial stages of closure cause a greater reduction in transpiration than in photosynthesis. That increase in water use efficiency is exploited to good effect in plants managed via partial rootzone drying (based on Düring *et al*. 1996).

Turgor loss in transpiring leaves also induces them to make ABA, a hormone that can trigger stomatal closure even in turgid leaves. In plants that are moisture stressed, ABA amplifies the largely hydraulic effects on stomatal conductance referred to above. If moisture stress is not relieved, that synthesis of ABA spreads to other plant tissues and contributes to a general shutdown in canopy gas exchange. ABA generation is thus an important aspect of regulated deficit irrigation, and as discussed later, is a key element of plant response to partial rootzone drying.

Evapotranspiration

Soil evaporation and canopy transpiration

Cumulative annual evapotranspiration from both natural and cultivated ecosystems is usually much higher than annual rainfall (rare exceptions include temperate and tropical fog forests). As a result, soil-moisture stress is a chronic issue for most perennial plants, especially in arid and semiarid regions. In nature, species in arid environments have evolved so that they are drought tolerant, but their priority is species survival rather than plant productivity. Because productivity is the aim with horticultural and some agricultural crops, irrigation is necessary. Irrigation requirements will increase with aridity, while margins for error in meeting those requirements will decrease accordingly, especially on light shallow soils. It is for this reason that gauging evaporative losses from orchards and vineyards is a central issue in irrigation scheduling, and some underlying principles are outlined below.

Evaporation from a free water surface is driven by sunlight and atmospheric turbulence where factors including air temperature, atmospheric humidity and wind are especially relevant. Sunlight provides energy, while temperature and humidity dictate the drying power of ambient air (combined into a value for atmospheric vapour pressure deficit or 'vpd' and expressed in units of kPa). Wind encourages evaporation by enhancing conductance at the evaporating surface. The actual rate of evaporation plus evapotranspiration in orchards and vineyards will depend on the interaction of all these physical factors as well as the particular characteristics of the orchard or vineyard, such as age and density of the plants.

In 1948, Penman, from the Physics department of Rothamsted Experimental Station in England, devised a generalised equation that would predict evaporation rate from wet soil, a free water surface or wet grass. It was hard to validate the original equation because of the variation in boundary layer conductance between different sized water bodies or other structures, and their dissimilar response to variation in wind conditions. Maximum potential evaporation from a well watered crop (ET_o) soon followed (Monteith 1965).

Further refinement by an FAO panel of experts (see Preface in Allen *et al.* 1998) led to the FAO Penman-Monteith method where 'reference crop' is defined as a hypothetical crop with an assumed height of 0.12 m, with a surface resistance of 70 seconds per metre (s/m), and an albedo of 0.23 (i.e. 23% of incident light is reflected). Such a hypothetical crop closely resembles evapotranspiration from an extensive surface of green grass of uniform height, actively growing, and adequately watered.

When estimating ET_o (as defined by FAO; see Allen *et al,* 1998), all driving variables and parameters are specified. Values for ET_o are then consistent with actual crop water-use data that have been derived from sources worldwide. Furthermore, 'recommendations have been developed using the FAO Penman-Monteith method with only limited climatic data, thereby largely eliminating the need for any other reference evapotranspiration methods and creating a consistent and transparent basis for a globally valid standard for crop water requirement calculations'. In effect, an automated weather station will generate values for daily ET_o expressed as mm evaporation, and that value for evapotranspiration is what a well watered reference crop would be expected to evapotranspire in the orchard or vineyard where that particular weather station is located.

A first approximation of evapotranspiration from the orchard or vineyard surrounding that weather station (referred to here as ET_{crop}) is then calculated as:

$$ET_{crop} = ET_o * K_c \qquad \text{Equation 1}$$

In Equation 1, K_c is a crop coefficient that takes into account key differences between the hypothetical reference crop, and the canopy characteristics of the orchard or vineyard in question. Those canopy characteristics are influenced by orchard or vineyard layout as well as by canopy architecture and hence interception of sunlight, and boundary layer conductance. The parameter K_c thus characterises an orchard or vineyard for purposes of calculating ET_{crop}, and varies in a systematic way with crop growth and development.

Stomatal effects on K_c are of particular relevance to regulated deficit irrigation and partial rootzone drying because the stomata of plants managed under deficit irrigation can partially close in strong evaporative conditions (hot dry windy days) and thus lower their value for K_c. Partial stomatal closure then reduces tree or grapevine transpiration well below what a well-watered reference crop would be assumed to do under equivalent conditions, so that ET_{crop} will be over estimated under those conditions unless K_c is revised downwards (discussed later in connection with irrigation scheduling criteria).

Values estimated by McCarthy (1997a,b) are listed in Table 1. (over page) as an example of how K_c diminishes (e.g. January to February 1995) because of partial stomatal closure as the soil profile dries between successive irrigations. An increasing resistance to water flow within the soil-vine-atmosphere continuum with a partially dry profile would have also contributed to this reduced K_c. Numerically smaller values for vineyard K_c in October and November derive from incomplete canopy cover, and serve as a reminder that total canopy surface area is a major driver of vineyard evapotranspiration.

K_c is only rarely derived from first principles, rather it is generally estimated by comparing a test crop evapotranspiration (ET_{crop}) with a reference crop evapotranspiration (ET_o) using either weighing lysimeters containing a few individual trees or grapevines from a larger orchard or vineyard, or by following changes in rootzone soil moisture to measure rates of water extraction by the transpiring test crop as well as by a reference crop under similar conditions. Aerodynamic methods (based on micrometeorological measurements of heat and mass transfer above extensive plant communities) have also been used to estimate evapotranspiration in agronomy and some natural ecosystems, but fetch requirements and canopy roughness in orchards and vineyards make these methods difficult to apply to irrigation scheduling in horticulture.

Table 1. Daily water use and crop coefficient (average per month) at 'Sunlands' near Waikerie SA for irrigated Shiraz vines (based on Table 2.4 in McCarthy 1997a,b). Daily average water use was inferred from neutron probe measurements of soil water between October 1994 and March 1995. Grapevines were spaced at 2 m within rows that were 4 m apart running east-west and trained to a horizontally divided canopy 1 m wide.

MONTH	DAILY WATER USE (mm)	MONTHLY CROP COEFFICIENT
October	2.3	0.38
November	2.6	0.42
December	4.9	0.57
January	5.7	0.72
February	3.8	0.53
March	3.2	0.50

In orchards or vineyards where bare soil or a covercrop is likely to contribute greatly to total evapotranspiration from that site, crop coefficients (K_c) are scaled to accommodate variation in the relative contributions from canopy *vs* covercrop or bare soil for computing orchard or vineyard evapotranspiration.

An alternative and low-cost approach to scheduling irrigation is to estimate ET_{crop} from direct measurement of pan evaporation (E_{pan}) in combination with an empirically-determined crop factor (CF) where:

$$ET_{crop} = E_{pan} * CF \qquad \text{Equation 2}$$

Implicit in this approach (Equation 2) is an assumption that the orchard or vineyard evapotranspiration will react to sunlight and atmospheric factors in the same way as pan evaporation.

While the underlying physical principles of heat and mass transfer from a Class A Pan and from an orchard or vineyard will be the same, the sensitivity of those responses to driving variables differs significantly. Pan evaporation is occurring from an isolated entity, and on a much smaller scale compared with evapotranspiration from an extensive orchard or vineyard so that boundary layer conductance and sensitivity to wind are very different between the two systems. Moreover, the relative importance of sunlight as opposed to atmospheric turbulence in driving evaporation from those two systems will also vary so that precision estimate would need virtually minute-by-minute adjustment.

Canopy conductance is another issue. As discussed in Chapter 2, stomatal physiology of tree crops and grapevines is influenced directly by both regulated deficit irrigation and partial rootzone drying probably because of the upward movement of chemical (hormonal) signals from roots to transpiring shoots. Estimates of ET_{crop} based on either meteorological data or inferred from pan evaporation should take this factor into account. Deficit irrigation (certainly partial rootzone drying, and perhaps regulated deficit irrigation as well) actually heightens the sensitivity of stomatal conductance to potentially high rates of transpiration on days of high evaporative demand.

Because pan evaporation is devoid of stomatal control and responds directly to vapour pressure deficit (vpd), whereas stomata tend to close so stomatal conductance becomes progressively lower with increased vpd, any discrepancy between E_{pan} and actual ET_{crop} will be even more accentuated under extreme conditions (high values for vpd on hot dry windy days).

Recognising that ET_{crop} includes soil evaporation, and knowing that this component of orchard or vineyard evapotranspiration will also vary with microclimate and effective canopy cover, conversion factors such as CF and K_c will have to be adjusted accordingly (see Yunusa *et al.* 2000 for an analysis of vineyard evapotranspiration components, and the section, 'Effective Canopy Cover', page 76).

Despite these limitations on translating pan evaporation to crop evapotranspiration, irrigation scheduling criteria are often referenced to Class A pan evaporation with a crop factor (CF). Unfortunately, CF is at times also referred to as a 'crop coefficient'. Clearly, the crop factor 'CF' is not the same as the crop coefficient 'K_c' so that any assumptions underlying estimates of ET_{crop} must be viewed circumspectly.

An issue to clarify before adopting such estimates of evapotranspiration is to determine whether the published or advised estimate of ET_{crop} has been derived from meteorological data from a crop coefficient (K_c) and ET_o (as in Equation 1) or derived from an empirical measurement of E_{pan} that has been adjusted with a crop factor (CF) (as in Equation 2).

This distinction is made in providing crop factors for irrigation scheduling in vineyards for either minimally-stressed full irrigation or regulated deficit irrigation management. Some values developed for these different purposes are summarised in Table 2 below. These values apply to spur pruned vines on a single wire with a sprawling canopy to about 2 m height covering about 80% of the vineyard floor and with a mown undervine sward. Pan evaporation during the growing season averaged around 6 to 8 mm a day.

Two features of the data in Table 2 warrant comment. First, the fivefold increase in CF from budburst to veraison tracks canopy development and corresponds to a similar, but more muted, pattern of increased K_c for an irrigated vineyard in Table 1. Second, regulated deficit irrigation is most assuredly a regime of deficit irrigation. Vines receive the equivalent of only 25% E_{pan}.

Table 2. Crop factors for irrigated grapevines referenced to E_{pan} (based on Goodwin 1995).

SEASON	**CROP FACTOR (CF)**	
	FULL IRRIGATION	**RDI**
Budburst	0.10	0.10
Flowering	0.25	0.25
Veraison	0.50	0.25
Harvest	0.50	0.25
Post harvest	0.25	0.15

Irrigation scheduling for peach orchards can be similarly referenced to E_{pan} and canopy development is a major factor for ET_{crop}. Data from an intensive peach orchard (Figure 4, below) show how CF tracks peach growth, ranging from around 0.7 at the start of fruit growth (50 days after bloom in Figure 4) and peaking around 1.4 when peach fruit were showing maximum rates of increase. Increased stomatal conductance during rapid fruit growth (120 to 160 days following bloom) may well have contributed to higher values for peach orchard CF over that period.

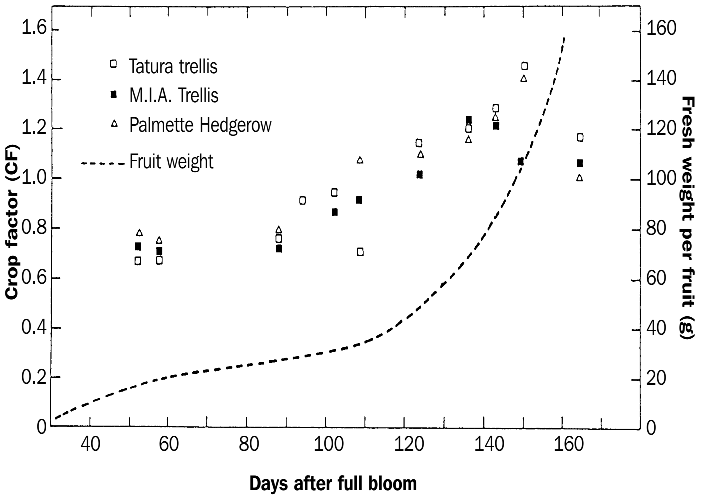


Figure 4. Potential evapotranspiration from a high input peach orchard with different training systems (symbols) increases substantially with crop development during the rapid fruit expansion phase (dotted line). Crop factor (CF) is a dimensionless ratio and is a convenient way of summarising that response in a way that is independent of variation in weather (evaporative conditions). CF is estimated from direct measurement of orchard evapotranspiration (ET_{crop}) and pan evaporation (E_{pan}), where CF = $ET_{crop} \div E_{pan}$ (based on Hutton *et al.* 1987).

In general, differences in both canopy architecture and leaf physiology (especially stomatal conductance) would have contributed to the significant difference in absolute values for CF between grapevines and intensively managed peach trees referred to above. Systematic differences between horticultural species with respect to their maximum stomatal conductance (bright sun and well watered conditions) are recognised, and an approximate ranking is: almond > pear > peach > grape > citrus.

Irrigation scheduling in orchards and vineyards that is based on either meteorological data plus crop coefficients (e.g. Table 2) or pan evaporation plus crop factors (e.g. Table 3) provides only a small fraction of potential evapotranspiration that would be incurred by a reference crop over that same area. While irrigation scheduled this way tracks fluctuations in evapotranspiration, the amount of water actually applied is only a fraction of potential evapotranspiration as implied by either E_{pan} or ET_o. Traditional row crop irrigation aimed to replace evapotranspiration every few days, and productivity from agronomic and pasture plants justified that practice. By contrast, decades of practical experience have now established that deficit irrigation will sustain cropping from perennial plants.

An explanation of this apparent paradox has two elements. One element relates to the growth and cropping behaviour of woody perennial crop plants as opposed to cereals and herbs that serve as reference crops in establishing values for ET_o. The second element relates to the buffering capacity of plant-extractable soil moisture, and the modulating effect that soil-moisture resources have on canopy conductance. In effect, a diminishing stock of water held in the rootzone of an orchard or vineyard will trigger stomata to close partly, and maximum daily values for canopy conductance will decrease. That partial stomatal closure intensifies as daily cycles of transpiration extract more and more of the remaining plant-available soil moisture. ET_{crop} is thus sustained at a progressively smaller fraction of potential evapotranspiration. Soil moisture reserves thus bridge a substantial shortfall between potential evapotranspiration and water input from rain plus supplementary irrigation.

Acquiring those soil moisture reserves then becomes a critical issue for both crop production and, in extreme cases, plant survival.

Effective canopy cover

Ian Goodwin and Mark O'Connell, Institute for Sustainable Irrigated Agriculture, Department of Natural Resources and Environment, Tatura, Victoria

Accurate estimates of crop water requirements enable irrigation industries to expand, to maximise productivity from existing areas, and to minimise adverse environmental impacts (including surface run off and watertable accession via deep drainage).

Being able to reliably estimate potential crop water use would enable irrigation managers to improve on-farm irrigation management by minimising deep drainage and surface runoff. This would contribute to more effective water resource budgeting at a regional level, and lessen adverse environmental impacts such as secondary salinisation.

In this context, strategies such as regulated deficit irrigation and partial rootzone drying can be very useful by sustaining orchards and vineyards on irrigation application rates that are only a fraction of potential crop water use. Water applied is then used to better effect, and throughput to groundwater is greatly diminished.

In any orchard or vineyard, irrigation is needed mainly to replace losses due to evapotranspiration. Some water is retained in fruit, shoots, leaves, woody tissue and roots, but those components represent a tiny fraction of evapotranspiration.

Total orchard or vineyard evapotranspiration (ET_{crop}) is the sum of fruit tree or vine transpiration plus understorey evapotranspiration. Understorey evapotranspiration can be further broken down into bare soil evaporation and covercrop evapotranspiration.

Under micro-irrigation, understorey evapotranspiration is kept to a minimum, and the notional target for an efficient irrigator is to match water lost as a result of tree or grapevine transpiration. Extra irrigation amounts may be needed for leaching in saline environments, to replace soil evaporation and, to a lesser degree, to replace covercrop water use from the wetted zone.

Inevitably, some water will be lost unproductively, but most orchard or vineyard losses from sources such as soil evaporation, assuming ponding and no interception of direct sunlight by the canopy, will equal the fractional area of wetted soil. Under micro-irrigation this is usually no larger than 0.25, while under drip irrigation it is more likely to be around 0.1. In addition, once an orchard or vineyard canopy limits penetration of direct sunlight onto the wetted soil area, the amount of soil evaporation will be much reduced. In that circumstance, plant transpiration predominates in determining ET_{crop} for a micro-irrigated orchard or vineyard.

Transpiration will vary according to stage of growth within an orchard or vineyard. However, transpiration will also vary depending on canopy volume (or extent of leaf cover), leaf area density, row orientation and the zenith angle of incident sunlight. In effect, K_c in a micro-irrigated orchard or vineyard will vary with sunlit leaf area.

Practical methods to adjust K_c according to effective canopy cover are currently being developed for fruit crops and vineyards. One such method is to measure the amount of direct sunlight intercepted by the canopy, to yield a value for effective canopy cover (ECC).

The Food and Agriculture Organisation (FAO) define effective canopy cover as:

> "the proportion of the soil surface shaded by a tree at solar noon"

and provide a detailed formula to calculate it. As an alternative to complex formulas, there are simple tools to measure effective canopy cover in the field. Recently, Larry Williams from University of California, Davis, compared measures of vineyard ET_{crop} in a weighing lysimeter and effective canopy cover and derived the linear relationship:

$K_c = 1.7$ ECC for $0.05 < ECC < 0.75$ ($R^2 = 0.96$).

In this study effective canopy cover was measured by taking digital photographs of the fraction of shaded ground area at solar noon.

In a separate study by Scott Johnson, Univesity of California, Kearney, measures of peach orchard ET_{crop} in a weighing lysimeter and effective canopy cover were compared and the linear relationship derived:

$K_c = 1.6$ ECC for $0.15 < ECC < 0.71$ ($R^2 = 0.86$).

Effective canopy cover was estimated from the fraction of photosynthetically-active radiation interception at solar noon.

Both these studies show that the crop water requirements can be inferred from an evapotranspiration parameter such as K_c which in turn is derived from a measure of effective canopy cover at any time during the season. Under either regulated deficit irrigation or partial rootzone drying, partial stomatal closure will impose more constraints on canopy transpiration resulting in a further reduction in K_c.

More research is needed to test this concept for a range of canopy management systems and row orientations. For example, in hedgerow canopies effective canopy cover might need to be measured three times during a day (at solar noon, and 3 hours before and after solar noon).

Such data gathering need not be tedious. Modern instruments help measure sunlight interception by a canopy, and produce a value for effective canopy cover expressed in terms of the fraction of total incident photosynthetically-active radiation that has been intercepted. One such instrument consists of an array of light sensors on an 80 cm long rod fixed to a meter. This is held perpendicular to a row and several passes are made under each canopy. Measurements are automatically integrated at 0.25 second intervals and an average value stored in a microprocessor.

Preliminary studies for pear, peach and apple orchards, as well as vineyards, suggest that effective canopy cover can be used to estimate ET_{crop} and thus calculate irrigation requirements. Measures of effective canopy cover remained constant for much of the season, thereby reducing any need for repetitive measures of effective canopy cover. These studies were extended to orchards and vineyards under partial rootzone drying as well as deficit irrigation treatments (irrigation set at 50% of potential ET_{crop}). Taking one pear orchard as an example, effective canopy cover peaked at 33% during the 2001-02 season, irrigation supply matched derived ET_{crop}, and tree water stress was observed only under the 50% potential ET_{crop} partial rootzone drying treatment.

In conclusion, orchard and vineyard water requirements will vary with climatic and biophysical conditions. To account for these differences reference crop evapotranspiration (ET_o) can be calculated from weather data and adjusted by a crop coefficient to yield an estimate of likely evapotranspiration from a particular orchard or vineyard (i.e. ET_{crop}). Research summarised here suggests that suitable crop coefficients for vines and peaches are also directly proportional to effective canopy cover, which in turn can be measured according to the fraction of either photosynthetically-active interception, or even more simply, according to shaded ground area.

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Root extraction of soil water

If water is applied to a vertical column of soil and allowed to drain freely, the amount of water left in that column and held against the downwards pull of gravity represents field capacity (Figure 5). The tension with which liquid water is held at field capacity by soil particles is generally about between 2 and 5 kPa for a clay soil and 8 and 10 kPa for a sandy soil[†].

At field capacity, volumetric soil moisture will range from around 25 to 30% in a sandy loam up to 35 to 40% in a light clay (Figure 6). A volumetric moisture content of 25% is equivalent to 250 mm of water within a 1m column of soil; a volumetric moisture content of 40% would be equivalent to 400 mm of water.

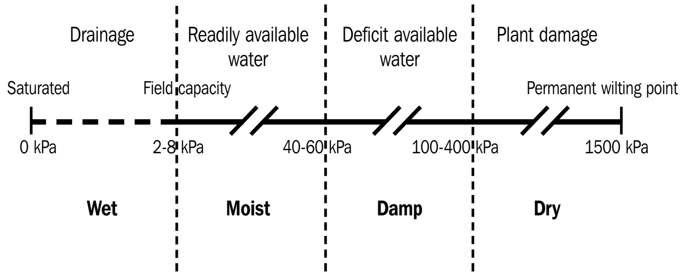

Figure 5. A schematic representation of plant-available soil moisture and the physical tension with which that moisture is held within soil pores. Recently irrigated soils that had drained to field capacity will hold moisture at a tension equivalent to 2 to 8 kPa. As transpiring plants extract moisture, depletion of readily available water occurs around 40 to 60 kPa, with deficit available water exhausted between about 100 and 400 kPa (depending on soil type). Under an regulated deficit irrigation regime, irrigation is warranted once soil moisture tension falls to around 100 kPa in light soils, 200 kPa in medium textured soils, and 400 kPa in soils of heavy texture (based on Goodwin 1995).

Having wetted an orchard or vineyard soil to field capacity, soil water is soon lost to canopy transpiration. As soil water extraction continues, the tension with which remaining water is held around individual particles increases (moving from right to left in Figure 6). Once soil

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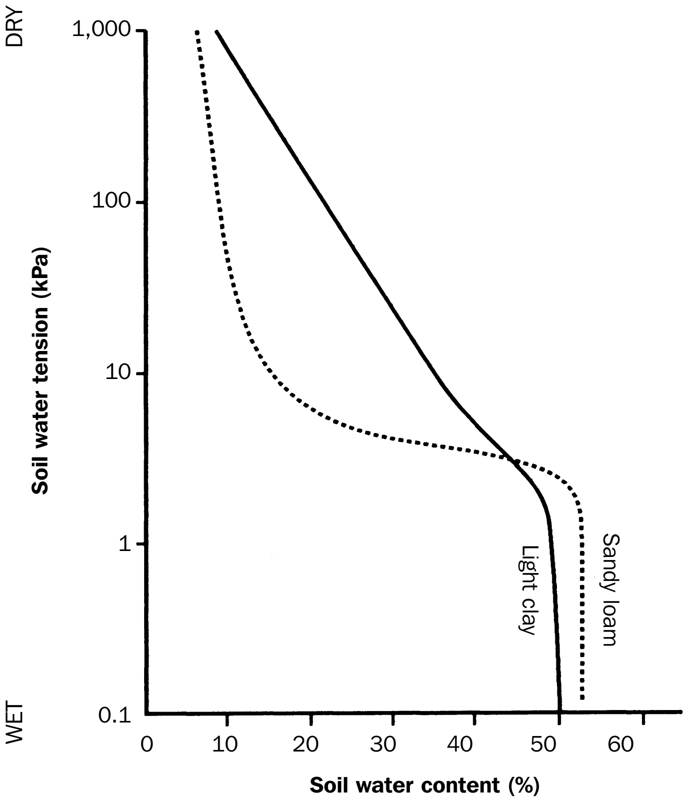
[†] **Note.** Plant-available soil water can be viewed as either an amount (expressed as a percentage of soil volume), or as a tension (expressed in kPa). This duality provides a convenient way of discussing soil moisture trigger points for irrigation in terms of kPa, and then calculating irrigation budgets in terms of litres. Inter-conversion between amount and tension depends upon the water-release characteristics of a particular soil, and some comparative curves for soil moisture tension as a function of changes in volumetric moisture content are shown in Figure 6.

water tension reaches somewhere between 1000 and 1500 kPa, a rapidly transpiring plant can no longer generate enough tension within its vascular system (xylem network) for roots to extract enough soil water to meet canopy transpiration, and stomata close. With daytime stomatal transpiration minimised, shoot turgor might be maintained, but some degree of water loss from cuticles will continue despite stomatal closure and, if soil water is not restored, the plant will eventually wilt. If the plant does not regain turgor, even overnight, then rootzone soil water content can be regarded as having fallen to permanent wilting point. That point will correspond in the examples provided in Figure 6 to a volumetric moisture content of around 10% (or 100 mm of water per one metre depth of soil).

The total plant-available soil water reserves that are nominally available from the sandy loam in Figure 6 with a rootzone depth of 1 m, can be represented by the arithmetic difference between the volumetric water content at field capacity (say 300 mm) compared with permanent wilting point (say 100 mm) = 200 mm. By comparison, the light clay in Figure 6 has a nominally available soil water reserve of 400 – 100 = 300 mm.

Figure 6. Generalised water release curves for contrasting soils (sandy loam compared with a light clay). Starting with a wet soil at field capacity (around 50% volumetric soil water content and soil water tension 0 to 2 kPa) and allowing water extraction by transpiring plants to proceed, both soils fall to wilting point at about 10% volumetric soil water and 1000 kPa soil water tension. The light clay shows a steady (near linear) increase in tension with decrease in volumetric water content over that range. Soil water tension in the sandy soil initially changes little with loss of volumetric soil water, but then increased dramatically with further extraction of water below a volumetric content of around 20%. Onset of plant water tension is thus more abrupt on a sandy loam than on a light clay (based on Mitchell and Goodwin 1996).



Moreover, the decrease in soil-water hydraulic conductivity as soil dries (Figure 7, over page) is less acute in the light clay than in the sandy loam, so that liquid water should move more readily from bulk soil to root surfaces in a partially dry clay loam than in the sandy loam. Although water does move more freely in a wet sandy loam than in a wet light clay (compare hydraulic conductivities in Figure 7), taken overall, the light clay appears to offer a better-buffered source of plant-available soil water than does the sandy loam. As outlined below, this apparently superior water holding capacity in a clay soil does not translate directly to plant-extractable water for horticultural purposes.

Whether or not that wider range of plant-available water in the light clay is as readily **extractable** as an equivalent depth of water from a 1 metre sandy loam is not obvious. The outcome hinges on depth of rootzone as well as the total length of actively absorbing roots per unit volume of soil within that rootzone (see species variation in Table 3). Both rooting depth and root-length density vary with soil type in a way that favours deep sandy loam soils as a preferred medium for irrigated horticulture. Rootzones tend to be deeper and root-length density tends to be higher in loam soils. Consequently, more nominally plant-available soil moisture is actually extractable from light (loam) soils than from clay soils.

A case for deficit irrigation

Without rain or supplementary irrigation, rootzone soil moisture is soon depleted from high availability at field capacity (held at a tension around 2 to 10 kPa), to non availability around permanent wilting point (1200 to 1500 kPa). At that point, soil water is held tenaciously, and rapidly transpiring plants cannot generate enough tension at root surfaces to match transpiration, and wilting follows.

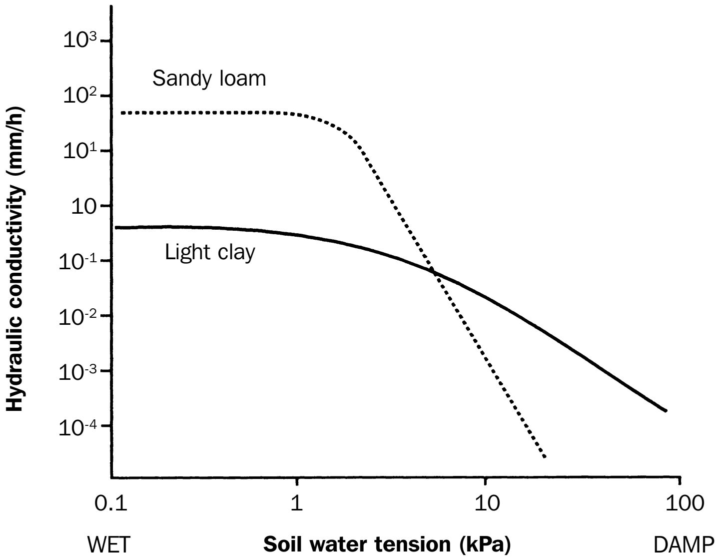


Figure 7. Generalised hydraulic conductivities for two contrasting soils (a sandy loam and a light clay). Water moves more freely in a sandy loam than in a light clay when both are wet, but as these soils dry (moving left to right) the sandy loam advantage is soon lost. Readily available soil water migrating from bulk soil towards absorbing roots in response to the moisture-tension gradient generated by a transpiring plant, will thus move more freely in the light clay. This difference becomes even more pronounced with further increase in soil water tension (based on Mitchell and Goodwin 1996).

With unlimited irrigation, rootzone soil water tension would never be allowed to even approach permanent wilting point, and would more likely be kept close to field capacity (with tensions only rarely exceeding 80 kPa). Biomass of grasses, herbs and annual crop plants would be maximised. Moreover yield from annual crop plants such as cereals will also be maximised because the proportion of total biomass that is partitioned into grain (or 'harvest index') is genetically-driven and represents a fairly constant proportion of total biomass in healthy plants. In irrigated wheat for example, as much as 55% of final (above ground) biomass can be partitioned into grain by a suitably spaced crop, while potatoes commonly return over 80%. In crops grown for herbage (hay or silage) or in cereals and coarse grains where harvest index is a strongly conserved feature of their growth and reproductive development, yield is more or less a direct function of total seasonal evapotranspiration, so that more irrigation generally means higher yield. This assumption that:

more irrigation ➔ more transpiration ➔ more yield

has been implicit in Australian horticulture, and has contributed to high levels of water use and problems of rising watertables and salinisation.

A new culture of irrigation management has now emerged with a strong emphasis on water use efficiency in crop production. Against this background, some of the qualitative differences between annuals and perennials in their growth and cropping behaviour, and thus water use efficiency, are worth considering.

Annual versus *perennial crops*

Perennial crop plants differ from annual crop plants in two important respects. First, perennial plants, including fruit trees and grapevines, have a generally lower and more variable harvest index compared with annual species such as cereals. Second, perennial plants generally develop a much lower root-length density during each growing season (length of active roots per unit volume of rootzone, Table 3).

Mature agronomic crop plants sustain about ten times more roots per unit volume of rootzone than do woody perennial crop plants in the middle of their cropping cycle (see Table 3). That contrast puts cereals and other such annuals at an advantage in terms of acquiring water and nutrients, and is an adaptive feature that favours successive annual growth cycles to be successfully completed. As an example, plants such as wheat are able to extract over 95% of plant-available moisture held in soil between field capacity and wilting point. By comparison, citrus and grapevines could be expected to absorb less than half that amount, although the hydraulic properties of the soil in question will have a large bearing on percentage extraction by virtue of how easily soil water migrates to root surfaces. Even with, excess irrigation water is more likely to add to drainage in orchards and vineyards than in irrigated agronomy (apart from rice and other flooded crops), and rising watertables, once common in horticultural regions, bear testimony to this fact.

Table 3. Root-length densities for different crop species (expressed on both a soil surface area and soil volume basis).

CROP PLANT	DEPTH SAMPLED (cm)	ROOT LENGTH PER UNIT SURFACE AREA (cm/cm^2)	ROOT LENGTH PER UNIT VOLUME OF ROOTZONE (cm/cm^3)
Apple[1]	120	0.8 - 4.3	0.01 – 0.04
	120	3.6 – 23.8	0.03 – 0.20
Pear[2]	110	26 – 69	0.29 – 0.56
Peach[2]	110	17 – 68	0.29 – 0.56
Grapevine[3]	40	24.6	0.40
Citrus[4]	60	—	1.50
	100	—	1.24
Lupin[5]	20	9	0.05
Clover[5]	20	92	1.10
Peas[5]	20	13	0.21
Medics[5]	20	57	0.60
Wheat[6]	20	300	7.5 – 10.0
Wheat[5,7]	20	120 – 400	—

Depth sampled (cm) refers to the total depth within the rootzone (measured downwards from the soil surface) from which root material was recovered.
Root length per unit surface area (cm/cm^2) refers to total root length under a unit area of soil surface.
Wheat[6] refers to winter wheat in the UK, wheat[5,7] refers to spring wheat in Australia.
Sources: [1]Atkinson 1980,[2]Cockroft and Wallbrink 1966, [3]Freeman and Barrs 1984, [4]Bevington and Castle 1982, [5]Hamblin and Hamblin 1985, [6]Barraclough and Leigh 1984, [7]Walter and Barley 1971.

Harvest index. Irrigated annuals such as wheat or rice commonly partition as much as 45 to 55% of aboveground biomass into harvestable yield, i.e. a harvest index of between 0.45 and 0.55. Unlike most perennial crop plants, harvest index in wheat or rice is not greatly diminished in favour of vegetative biomass under high-yielding conditions. While tree crops on dwarfing rootstocks or vineyards under regulated deficit irrigation can match that value, harvest index will drop to between 0.35 and 0.45 for peach, and to 0.25 in vigorous vineyards under high input conditions.

When woody perennial crop plants such as grapevines and fruit trees are provided with abundant water and nutrients under the warm conditions that are typical of high-input irrigation horticulture of inland Australia, they undergo massive canopy growth that is counterproductive in terms of cropping. Skilful manipulation of vegetative-reproductive balance is crucial for maintaining productivity as well as for improving water use efficiency in crop production. Dwarfing rootstocks have been used to good effect on apples to contain vigour, but such rootstocks are not generally available for other horticultural crops. Indeed, grapevine rootstocks that protect scions against adverse soil conditions (such as salt or nematodes) are actually invigorating, so that the inherent tendency of vines to excess vigour is exacerbated in grafted grapevines.

Drought stress

In irrigated vineyards and other forms of high input horticulture, constraining vegetative vigour by biological means is not yet practicable. However, deficit irrigation is an option for controlling canopy growth. Timing and duration of that water deficit must then be managed carefully or plants will suffer a terminal drought stress. Some notional scenarios showing plant response to cumulative water stress are given in Figure 8, and the nature of stress acclimation, as well as the time course of recovery from progressively intense episodes, is discussed below.

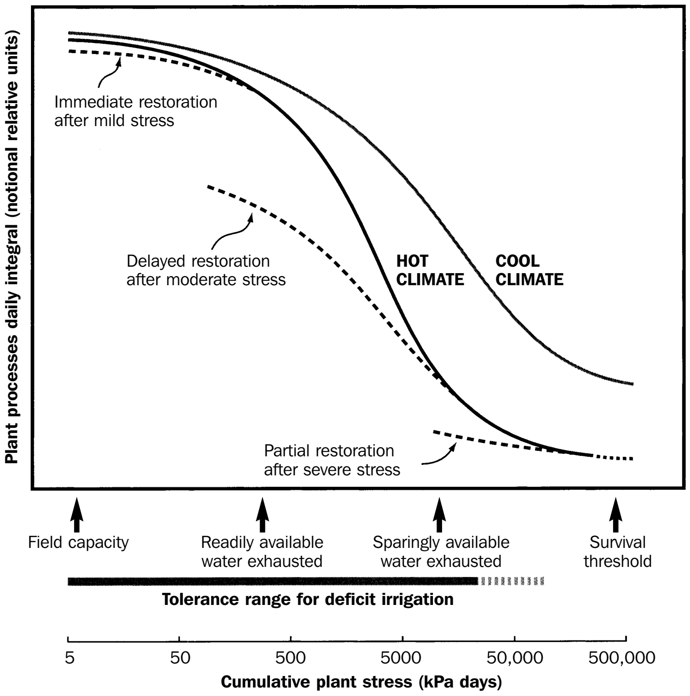


Figure 8. A notional and conceptual model of how cumulative plant stress might be expected to affect physiological processes in perennial plants during a stress-recovery cycle occurring between successive irrigations. Physiological processes underpinning yield include assimilation of water, nutrients, and atmospheric carbon, as well as formation and transport of photoassimilates for sustaining plant growth and crop productivity. The nature and form of these relationships are hypothetical, are intended as an aid to discussion (see text) and must not be taken literally.

In this figure solid lines represent a progressive loss in physiological activity as stress intensifies, and that loss will be more accentuated in a hot climate compared to a cool climate. Broken lines represent restoration in physiological activity following irrigation after either mild stress (readily-available soil moisture exhausted), or a moderate stress (sparingly-available soil water exhausted). Under severe stress, plants shift into a survival mode, and production physiology is not regained till next season. 'Cumulative plant stress' (kPa days) represents the daily integral of plant moisture tension (in kPa) summed over the number of days between successive irrigation cycles. Unlimited irrigation might result in cumulative plant stress of only 100 to 250 kPa days between successive irrigations, whereas regulated deficit irrigation might involve a cumulative plant stress of around 10,000 kPa days before stress relief through full irrigation.

Cumulative plant stress of ≥ 150,000 kPa days is suggested as an approximate survival threshold for perennial crop plants.

With unlimited irrigation, where measured or inferred ET_{crop} is replaced on a frequent (even daily) basis, crop plants will operate at the top end of the plant process curve (left side in Figure 8) and thus within the dynamic range of readily reversible variation in physiology. Soil water tension will vary between field capacity and the lower limit of readily available soil water (RAW) around 50 to 80 kPa. Such crops will usually regain full function within a day of rewatering, and without hystersis in that recovery. Vegetable crops such as carrots on light soils in Western Australia are managed this way. In the case of those carrots, ET_{crop} is replaced at least daily, and even more often under highly evaporative conditions.

As cumulative stress intensifies (from mild to severe in Figure 8), readily-available rootzone water content is almost exhausted with soil water tensions now around 250 to 300 kPa and increasing quickly as volumetric water content decreases in response to plant extraction, especially on sandy soils. Recovery of plant function following re-wetting takes longer, and a strong hysteresis is evident.

Imposing that level of stress as part of regulated deficit irrigation for about 5 to 7 weeks without losing plants to drought stress needs skillful management, but a variety of soil water sensing devices plus some key biological indicators on the plants make regulated deficit irrigation possible. In terms of visible indicators, active processes such as tendril extension and leaf expansion are affected first. Indeed, shoot growth on de-fruited grapevines even shows a quantitative relationship with soil water tension (discussed in *Plant indicators of soil water* in Chapter 4). As cumulative stress intensifies with grapevines, wilting by entire canopies, tendril shedding and loss of terminal growing points signal that vines in that state are at their survival threshold, and have to be rescued from a terminal drought stress. Rootzone soil water sensors will be registering values well below RAW, and partial re-wetting of rootzones is warranted.

Fruit trees and grapevines under regulated deficit irrigation are maintained in this state for days on end and kept alive for five to seven weeks by judicious application of only enough irrigation to replace around 25 to 50% of ET_{crop} for the period in question (a fraction that will of course have to be varied according to regional conditions, and will need to be higher in arid environments). During regulated deficit irrigation, only the top few centimetres of the rootzone are being re-wetted; just enough to hold plants in a latent state and forestall a premature onset of dormancy, or at worst a lethal drought stress.

Ultimately, and if cumulative plant stress is not relieved, our hypothetical perennial crop plant (Figure 8) shifts into survival mode where only structural elements and axillary growing points are retained (grapevines will have already lost terminal buds). Re-wetting the rootzone at that stage does not have an obvious visible effect, and the tree or grapevine will remain dormant until a natural seasonal cycle is completed and growth returns (perhaps only in part) the following spring.

Drought acclimation

Fruit trees and grapevines that experience recurring and wide amplitude cycles of rootzone drying and re-wetting are able to adjust their physiology and become acclimated to cumulative stress. Those adjustments are part structural and part functional. Structurally, acclimation to cumulative water stress involves smaller leaves, shorter inter-nodes, reduced canopy volume and a shift in biomass partitioning towards root growth. In functional terms, stress-related hormones are generated (especially ABA plus sugars and sugar alcohols) that constrain stomatal physiology, while particular amino acids such as proline accumulate. Together with other

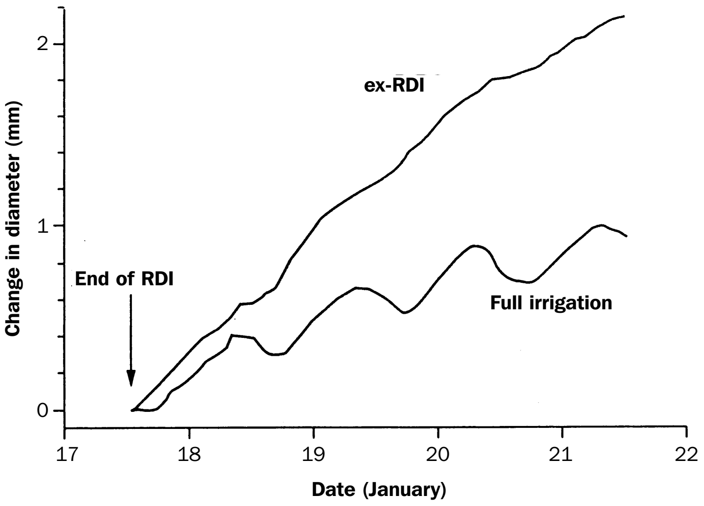
N-containing solutes that are also compatible with cell biochemistry, these substances appear to have a protective effect on membrane integrity and cell function.

Of particular significance for plant-tissue water relations during drought stress, an accumulation of such compatible solutes increases tissue osmotic pressure, and enables stress-acclimated plants to generate a positive turgor, despite a reduction in bulk tissue water potential. Such turgor enables acclimated plants to maintain processes such as shoot extension, fruit enlargement and stomatal opening to a greater extent than would occur in a non-acclimated plant.

Most plants show some degree of acclimation to drought stress, and the burst of pear fruit enlargement following release from regulated deficit irrigation is a case in point (Figure 9, below). This burst of growth bears some analogy to other turgor-driven processes mentioned above.

In pears the rate of volume increase in fruit on previously stressed trees greatly exceeds the rate of enlargement on control trees. In that example, fruit osmotic pressure following regulated deficit irrigation was 2400 kPa (2.4 MPa) compared with 1700 kPa (1.7 MPa) on trees with full irrigation. Such acclimation (compatible solutes for membrane protection and turgor generation) enables fruit trees and grapevines to alleviate the debilitating impact of cumulative water stress and thus helps to sustain processes critical to plant survival during deficit irrigation.

Figure 9. Growth of pear fruits over four days after changing from regulated deficit irrigation to full irrigation (ex-regulated deficit irrigation) compared with continuous full irrigation. Fluctuations on full irrigation reflect the daily rhythm of variation of water potential within the soil-plant-atmosphere continuum. A surge of fruit growth follows restoration of full irrigation after regulated deficit irrigation due to turgor generated from an accumulation of osmotically-active materials in fruit on trees previously subjected to regulated deficit irrigation (based on Jerie *et al*. 1989).



APPENDIX 2

PRACTICAL ISSUES IN PLANT WATER USE FOR GROWTH AND CROPPING

1 Pan evaporation and ET_{crop}
2 From ET_{crop} (mm) to litres per plant
3 Soil water sensing
4 Irrigation scheduling criteria

Pan evaporation and ET_{crop}

Any wet surface will evaporate at a rate that is driven by a combination of incoming energy (mainly sunlight) and atmospheric conditions (mainly wind, temperature and humidity). That combination of inputs obviously varies during each day, and during the course of each season, so that evaporation rate from a free water surface will also vary.

Measured carefully with a standard evaporimeter (see Figure 10), that rate of evaporation becomes E_{pan}, which is commonly expressed as mm per day (or summed over relevant intervals of days or weeks between successive irrigations) for irrigation purposes. In absolute terms, E_{pan} does not equal potential evapotranspiration from a reference crop (ET_o) because of huge differences in boundary layer resistance, but **variation** in E_{pan} during the course of days or weeks will track **variation** in ET_o. Moreover, values for E_{pan} can be used to calculate an estimate of ET_o, provided measurements of E_{pan} come from a designated type of evaporimeter (such as a US Class A pan described in Figure 10).

As an aside, changes in weather conditions that cause variation in E_{pan}, will have a similar, but not identical, impact on potential evapotranspiration from an orchard or vineyard or reference crop. This discrepancy comes about mainly from the effects of wind on turbulent transfer of water vapour from source to atmosphere. A boundary layer above any evaporating surface restricts turbulent transfer, and because a reference crop has a much greater boundary layer resistance than does an evaporimeter, ET_o will be less affected by variation in wind (above a certain threshold) compared to E_{pan}.

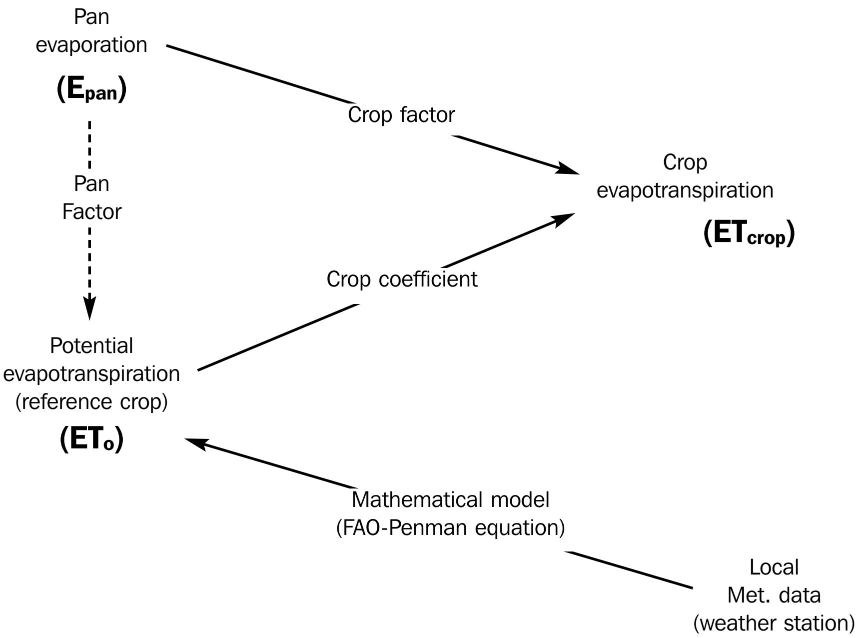
Such measurements of E_{pan} can then be used to estimate both potential evapotranspiration from a reference crop (ET_o) using a 'Pan factor', and actual evapotranspiration (ET_{crop}) using a 'crop factor' (relationships summarised in Figure 11).

Simple evaporative pans (yielding a value for E_{pan}) are useful tools for irrigation scheduling. Historically, values for E_{pan} have been applied successfully in scaling application of irrigation water according to potential evaporative demand (adjusted with a crop factor), and in estimating likely requirements for both farms and regions for planning purposes. As a more modern alternative, sophisticated meteorological sensors in combination with high-speed data capture and improved computing capacity, now enable prediction of ET_o in real time. These predictions are then used to forecast evapotranspiration from orchards and vineyards (ET_{crop}) by applying crop coefficients discussed earlier.

Estimates of evapotranspiration from various crops based on either meteorological data (both real time and historic records) or inferred from direct measurement of pan evaporation, are available for major cropping regions of Australia.

Weather stations like this one are used to estimate evapotranspiration. Photo courtesy Steve Bailey, Campbell Scientific Australia.

Figure 10. The relationships between potential and actual evapotranspiration.



Such regional estimates of evapotranspiration for various crops, derived either from E_{pan} and a series of crop factors, or from ET_o and a series of crop coefficients, are especially helpful in feasibility studies for new regional developments, or in budgeting water resources for existing developments. However, by their very nature, such estimates of evapotranspiration are indicative of evaporative conditions over broad regions. They collapse variation within a region into a general estimate and are not meant to offer predictions district by district within a region, and will certainly not reflect variation over single properties. Strategically placed evaporation pans or automated meteorological stations meet such on-farm needs but they have to be installed where they will represent orchard or vineyard conditions and data generated have to be interpreted carefully.

Even with reliable and properly calibrated sensors, estimates of ET_o are tied to meteorological station or pan location, and in dealing with practical realities their siting is commonly less than ideal. Placed upwind of a substantial irrigation district there will be a 'clothesline' effect and ET_o for that district will be overestimated, especially under windy conditions typical of hot blustery days that precede low-pressure fronts in summer time.

Placed downwind of a substantial area, there is an 'oasis effect' and ET_o will be underestimated compared with the district at large. Placed in a large collection of orchards or vineyards (hundreds of hectares) estimates of ET_o will be more representative for the community at large, but height above ground is an issue.

For obvious practical reasons, an evaporative pan has to be at ground level, whereas orchard or vineyard evapotranspiration occurs from ground level up to 3 m, depending on canopy architecture. The crop factor chosen to convert E_{pan} to ET_{crop} should take account of this, because such crop factors are generally based on empirical measurement of E_{pan} and accompanying estimates of ET_{crop}. (As discussed in the appendix, ET_{crop} comes from detailed measurements of orchard or vineyard water using either lysimeters or measured variation in volumetric soil water content during irrigation cycles.)

In contrast to evaporative pans, portable meteorological stations (usually an instrumented mast) need not be at ground level, and there are good reasons to locate them well away from the impacts of treelines and outbuildings (height x 10 as a general rule). Variables such as sunlight, atmospheric water-vapour pressure, dry-bulb temperature and wind run should be sensed at least 2 m above ground.

Three other issues need to be addressed before even trying to use credible estimates of ET_o for irrigation scheduling. These are as follows:

- the presumed evenness of evaporative losses over an orchard or vineyard that are implicit in broadscale estimates of evapotranspiration
- sources of variation that have to be accommodated within either crop factors or crop coefficients
- the mosaic of wet/dry patches that characterises drip irrigation.

Regardless of whether ET_o has been estimated from meteorological data, or inferred from an evaporative pan, it will be expressed as 'x' mm of water. Does this mean that evapotranspiration is uniform across the entire farm? Not likely, which means that the estimate of 'x' mm presumes uniformity and cannot represent site variation in evapotranspiration. Such site variation in evapotranspiration, and thus irrigation requirement, has to be recognised using other criteria (soil or plant based) and accommodated by strategic scheduling.

Crop factors (and crop coefficients) are generalised but nevertheless helpful guides to likely crop water requirement relative to ET_o. Inevitably, these terms will vary according to absolute canopy surface area, the relative extent of canopy transpiration compared with soil evaporation, and with changes in stomatal physiology. Partial stomatal closure under hot dry conditions is a feed-forward mechanism that helps restrict transpirational losses and thus preserves plant moisture under extreme conditions. As calculating crop factors and crop coefficients has become more sophisticated, such physical and biological factors are taken into account.

Noting such sophistication, irrigation management strategies are usefully referenced to ET_o with these terms, so that managers can estimate likely irrigation requirements as a function of growth stage. Crop factors for such a regime of either standard drip irrigation or regulated deficit irrigation grapevines in the SA Riverland are given in Table 4.

Table 4. Suggested crop factors (generalised) for drip-irrigated grapevines in the SA Riverland (courtesy Michael McCarthy, 2002 unpublished data) and referenced to pan evaporation.

PHENOLOGICAL STAGE	FULL IRRIGATION	RDI*
Budburst-flowering (and at fruitset)	0.21 – 0.35	0.21 – 0.30
Flowering – veraison	0.35 – 0.50	0.25 – 0.30
Veraison – harvest	0.50	0.50
Post harvest	0.50 – 0.30	0.50 – 0.30

*Generally lower crop factors for regulated deficit irrigation in Table 3 (compared to values listed here) relate to what would now be regarded as full season deficit irrigation for the notional grapevines in that table, compared to the example given above for a strictly-regulated deficit irrigation that is applied in a more strategic fashion according to grapevine phenology. Lighter soils in the SA Riverland, and less extensive reserves of subsoil moisture compared with the finer textured soils and milder environments of northern Victoria, also contribute to that difference (hence higher values here compared with Table 3).

Is irrigation requirement best seen as millimetres of water per hectare, spread evenly over an orchard or vineyard, or as litres per plant applied very unevenly? Clearly, amount per plant holds more relevance for drip irrigation (or other forms of localised distribution such as micro-jets), even though guidelines for irrigation are commonly expressed as a certain fraction of “x” mm of ET_o. Translating scheduling guidelines based on mm of evapotranspiration to allocation of irrigation water in terms of litres per plant, hinges on knowing the volume of wetted roots within an orchard or vineyard, and applying some simple formulas. Principles underlying these calculations follow.

From ET_{crop} in millimetres to litres per plant

Rainfall and evaporation are expressed in millimetres per unit time, and when broad scale irrigation is being scheduled against such criteria, applying crop factors or crop coefficients will then generate values for irrigation requirement in millimetres.

However, some aspects of irrigation management call for data on changes in volumetric soil water, and in the case of operating pressurised irrigation systems, ET_{crop}, and thus irrigation requirement, is most usefully expressed as litres per plant (in both orchards and vineyards).

How to apply the underlying principles in converting from ET_{crop} in mm to evapotranspiration and replacement irrigation, per tree in litres, plus volumetric changes in soil moisture (L/plant) is shown below as a worked example.

Example

Consider a peach orchard established on a planting pattern where trees are spaced 5 m (between rows) x 2 m (in-row). That spacing represents 2000 trees/ha.

Issue 1: converting mm evapotranspiration into L/plant

Take a plausible value for E_{pan} in midseason = 50 mm/week.

Apply a crop factor of 0.7 and that value for E_{pan} translates into an ET_{crop} of 35 mm (or 0.035 m).

Given that 1 ha = 10,000 m^2, and a cubic metre = 1000 L, an ET_{crop} of 0.035 m over each hectare is thus equivalent to a volume of

$$35 \text{ mm } \times 10{,}000 \text{ m}^2 = 350{,}000 \text{ L}$$

There are 2000 trees/ha so that each tree has (on average over that week) evapotranspired a total of

350,000 L ÷ 2000 trees/ha = 175 L/tree

Issue 2: were soil water reserves adequate?

The key question here is whether there was enough readily-available soil water (RAW) in the rootzone of our hypothetical peach orchard to meet an ET_{crop} of 175 L/tree.

Assume an effective rootzone depth of 50 cm

With a planting pattern of 5 m x 2 m, and a rootzone depth of 50 cm (0.5 m), each tree will thus have access (on average) to water within a soil volume equivalent to 5 x 2 x 0.5 m = 5 m^3.

How much RAW is held within 5 m^3 of rootzone soil?

Consider a loam soil where RAW is equivalent to 8% by volume.

In such a soil (RAW = 8%), each cubic metre of soil (1000 L) will hold RAW equivalent to

8% x 1000 L = 80 L

Since each tree has access to water within a rootzone volume of 5 m^3, the total volume of RAW per tree will be

80 x 5 = 400 L/tree

Total soil reserves of RAW were thus more than twice ET_{crop} over the period in question (one week).

Issue 3: how much RAW would have been extractable?

In theory, and starting with a loam soil at field capacity (drained upper limit), there should have been enough RAW to meet orchard evapotranspiration for the week in question (RAW = 400 L/tree, ET_{crop} = 175 L/tree).

In practice, tree roots are not distributed evenly down any soil profile so that RAW will not be extracted either evenly or totally from the entire rootzone volume. Those regions serviced by a greater length of roots per unit volume of soil (root-length density in Table 3, page 81) will be exploited more effectively, and because root-length density tends to diminish logarithmically with depth below the nutrient-rich zone within the topmost 25 cm of most horticultural soil profiles, soil water held beneath that zone will stay under-used.

On balance, and perhaps at best, only three quarters of the RAW within the 5 m^3 of rootzone volume per tree would have been extracted during the week in question (yielding 300 L of water per tree).

Moreover, if incomplete extraction is combined with a shallower rootzone, say 35 cm rather than 50 cm, soil water reserves would have then yielded only 240 L per tree. Even allowing for localised extraction of some deficit-available soil water in addition to RAW, rootzone reserves would have been perilously close to ET_{crop}, and irrigation would then have been warranted by week's end.

Issue 4: irrigation run time

If this hypothetical peach orchard was serviced by some form of pressurised irrigation system such as undertree sprinklers that wet the entire floor of the orchard, and if scheduling criteria called for total replacement of ET_{crop}, irrigation run time could then be estimated from system data on emitter rate per tree and irrigation efficiency.

Assume an emitter rate per tree of 50 L an hour, and an overall system efficiency of 87.5% (indicative of a well-maintained network of pipes and outlets).

Run time (hours) = (175 L ÷ 50 L per tree per hour) x (100/87.5% efficiency) = 4 hours.

[see Goodwin and Boland (2002) for further discussion of practicalities in estimating irrigation run time].

Soil water sensing

As outlined previously, potential evapotranspiration (ET_o) sets an expectation of crop water use, but soil water measurement establishes whether that expectation has been realised, and represents a sort of 'ground truth' for irrigation scheduling. As discussed earlier, soil water can be viewed as either:

- an amount which is expressed as a percentage of wetted soil volume or as millimetres of water per unit depth of soil
- a tension (and expressed in kPa).

Both terms relate to the extent of plant-available soil water within a rootzone and extraction of that water by plant roots.

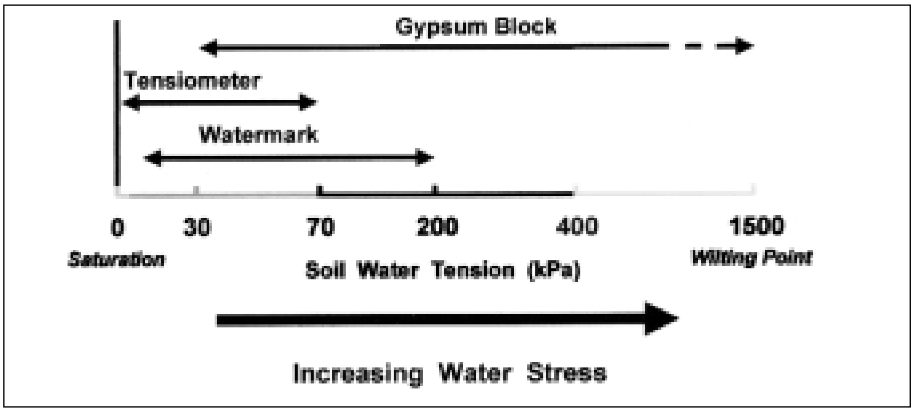
Measurements of tension are useful triggers in deciding to apply water, whereas measurement of amount allows calculation of how much to apply. Both these measurements can be used, combined with a knowledge of the water release properties of the soil in question to schedule irrigation (see Figure 6, page 79 for volumetric-tension relationships in contrasting soil types).

Technologies for measuring soil water status have become more sophisticated in the past decade and devices are now available that return values for either soil water tension (suction) in kPa, or indicate volumetric water content (% of wetted volume when appropriately calibrated).

Those that register suction are most commonly either porous media instruments, and include tensiometers and resistance blocks (gypsum blocks and granular matrix sensors), while those that register volumetric water content include instruments that can rely on changes in soil dielectric properties (capacitance), changes in neutron moderation (neutron moisture meters) or changes in heat dissipation (thermal heat sensors and equitensiometers).

For a comprehensive description of the measuring ranges and general characteristics of 24 different devices for measuring soil water status, see *Irrigation Insights No. 1, Soil Water Monitoring*, published by Land & Water Australia. Comparative attributes of five of those devices are given in Figure 12, and include systems that have been referred to at length in describing reduced deficit irrigation and partial rootzone drying field trials in this present publication.

Figure 11. Comparative attributes of five soil water sensing devices.



Conventional tensiometers detect changes in moist soils (tension limit around 75 kPa) whereas gypsum blocks and granular matrix sensors operate reliably up to 1500 kPa tension, and are thus suitable for managing regulated deficit irrigation.

With many regulated deficit irrigation trial sites, managers often installed a combination of tensiometers and gypsum blocks to enable changes in both readily-available soil water and drought-available soil water to be closely monitored. Thermal heat sensors and equitensiometers span the entire range of plant-available soil moisture, but call for expert operation and are mainly used for research.

Correct placement of soil water tension sensors such as tensiometers and gypsum blocks is critical. Soil moisture measurements must be representative of plant-water availability within a rootzone, and the architecture of that rootzone will vary according to both depth and breadth within an orchard or vineyard. A property survey is the best way to determine soil water-holding capacity and rootzone volume, and will be especially helpful in scheduling irrigation. Plantings on shallower soils will commonly take priority over plantings on deeper soils, especially where water supply is insufficient to meet whole-property needs. Similarly, distribution of sensors down a profile will vary according to rootzone architecture, and recommendations for shallow and deep rootzone soils are summarised in Figure 17, page 52.

Sensor location is less critical with devices that measure volumetric soil water content because such instruments sample a greater volume. Dielectric sensing devices detect changes in soil water within a sphere of about 10 cm radius although 95% of the sphere of influence is within only a 5 cm radius.

Neutron moisture meters sense a larger volume (on average a sphere of radius about 15 cm) but that volume varies inversely with soil water. Despite high initial cost and a perception of a radiation safety threat, neutron moisture meters are still a robust and accurate method for measuring soil water content. They are especially valuable for following changes in rootzone moisture with depth (see Figure 15, page 36), as they are not affected by access-tube air gaps as are devices that rely on dielectric properties of soil, and they are not affected by salinity. However, as well as high initial cost, a licence is required to own, operate and store a neutron moisture meter, and a radiation-exposure tag must be worn and returned periodically to the issuing agency for assessment of exposure. Consequently, neutron moisture meters are used mainly by irrigation consultants and larger farming enterprises.

Another device relevant to management of deficit irrigation (both regulated deficit irrigation and more especially partial rootzone drying) is the wetting-front detector. Any soil water sensor that can distinguish reliably between wet and dry soil can be used as a wetting-front detector.

In practice, there are two basic types of device that fulfil this purpose. One type depends on a change in electrical resistance of a porous material, and is used in the 'wetting-depth probe' and in the 'cut-off sensor'. A wetting-depth probe consists of a long narrow rod comprising eight sensors embedded at 5 cm intervals that can estimate the speed of the advancing wetting front. A cut-off sensor consists of a plastic card with a surface treatment that decreases in electrical resistance upon wetting. Buried at an appropriate depth in the rootzone, a signal from this (20 x 10 cm) card can trigger closure of an irrigation system once the soil wets, and then reset the irrigation system as the soil dries.

The FullStop® is a second alternative to detecting a wetting front, and uses the principle of flow distortion around a buried object (see Figure 6.24 in Charlesworth 2000). The FullStop is buried at an appropriate depth and collects soil water from every wetting front that passes by, raising a float switch that triggers a warning light. This soil water sample is held in a reservoir until either extracted with a syringe, or as the surrounding soil dries, is drawn back via capillary action. It thus resets itself for the next irrigation. This device enables measurement of soil solutes (e.g. salt, nitrate), is inexpensive, easily interpreted and not affected by salinity. The FullStop has immediate relevance to partial rootzone drying irrigation where the same rootzone volume is being constantly dried and re-wetted, or in deep porous soils where nutrient leaching beyond rootzones needs to be forestalled.

In summary, wetting front detectors can help irrigators in three ways, as follows:

- by providing a warning signal that over irrigation is occurring
- automatic shutdown of an irrigation system once a wetting front has reached a proscribed depth (especially helpful if the soil surface is dry, but the rootzone is already moist)
- collection of soil water samples to check on downward migration of salt or nutrients (especially nitrates).

Irrigation scheduling criteria

Gauging soil water reserves, assessing plant responses to water stress, and estimating evapotranspiration from orchards or vineyards (in real time) are difficult issues despite decades of research worldwide. Regardless of geographic location, soil type, irrigation system or crop category, a combination of practical issues and personal philosophies will dictate how individual managers approach the issue of orchard or vineyard water balance, and their preferred criteria for scheduling irrigation.

Three broad approaches prevail, and are focused on either:

- replacing some fraction of crop evapotranspiration (ET_{crop})
- measuring rootzone soil water reserves
- using biological indicators of plant-available soil water.

No single method is totally effective in all situations. Each one has potential application and they are discussed here as complementary technologies and not as mutually exclusive options.

Plant indicators of soil water

Devising plant-based criteria for irrigation scheduling is an ongoing quest in crop science, and a number of approaches have emerged over the past 50 years. All are motivated by a recognition that an irrigated crop plant is in itself an ideal soil-water sensor and should, in principle at least, be able to give an indication of plant-available water within its own rootzone.

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Such indicators include leaf xylem water tension, xylem sap flow, stem circumference, shoot growth, fruit or tendril turgor, stomatal conductance and leaf (canopy) temperature. Despite a huge amount of published literature on the relationship between these variables, and a matching volume of literature on process physiology relevant to soil-plant-atmosphere water relations, only leaf xylem water tension and canopy temperature are recognised as serious possibilities for practical tools in irrigation scheduling.

Underlying physiology is outlined briefly below. Other approaches such as daily variation in stem circumference require highly specialised electronic dendrometers to detect microscopic changes that are correlated with variation in xylem tension; stomatal conductance (g_S) requires expert use of a leaf porometer, a delicate instrument, plus extensive data sets to overcome extreme variability in g_S measurements that usually relate to leaf exposure. Shoot growth rate on de-fruited grapevines is a reliable indicator of soil water tension with a smooth linear reduction in shoot growth as soil water tension increases from 30 kPa up to 70 kPa. However, shoot length measurements are still regarded as tedious, and indicator shoots that have to stay in place for most of a growing season need protection against canopy management mishaps.

Noting those qualifications, instrument-based measurement of leaf xylem water tension is a practical possibility for irrigation scheduling. Moreover, 'water tension' (expressed as kPa) is a meaningful term for soil-plant water relations that is relevant to root extraction of soil moisture (discussed on below).

Leaf water tension

Soil water is drawn into the roots of transpiring plants and moves within the soil-plant-atmosphere continuum in response to water potential gradients generated by evaporative losses from the transpiring canopy. Measuring xylem tension helps track those changes.

Xylem water tension will be greatest close to transpiring leaves and will vary in a systematic way based on the degree to which transpirational loss is being replaced by water drawn upwards from roots. On hot dry days, leaf xylem tension generally increases as the day progresses because canopy transpirational loss is higher than the rate of replacement from soil moisture.

At sunset, stomata close, transpiration virtually stops, and leaf xylem water tensions relax as soil water replaces net loss from the plant. If transpiration at night is near zero, and soil water reserves plus hydraulic properties of the plant allow canopy water to be restored, leaf xylem water soon comes to equilibrium with rootzone soil water (usually by late evening). A late-night, or pre-dawn measurement of leaf xylem water tension will indicate the plant's rootzone soil water status. By covering transpiring leaves with reflective material and cutting transpiration to zero, leaf xylem water tension quickly comes into equilibrium with stem xylem water tension, and that measurement is an even more reliable indicator of soil water availability for individual plants.

Pre-dawn leaf water tension, which is commonly measured on excised leaves with a pressure chamber, can thus help in scheduling irrigation, and the Dareton case study on Okitsu Satsuma mandarin (Chapter 2, page 24) refers to those data. In that case, pre-dawn leaf water tensions around 600 to 800 kPa, or leaf water potentials between –0.6 and –0.8 MPa, corresponded to volumetric water contents of around 75 to 80 mm (summed over a 0 to 80 cm depth of soil) and were used as a trigger for irrigation during a typical regulated deficit irrigation cycle.

Under commercial conditions in Japan, pre-dawn leaf water tension would probably not be higher than 1200 kPa. Permanent wilting point in a sandy loam soil at Dareton would correspond to about 1500 kPa, so that a transpiring canopy must generate an even greater tension if soil water is to reach the foliage. This can happen, and severe moisture stress at Dareton produced some extraordinary pre-dawn values around 2200 to 3200 kPa tension. As explained by Graeme Sanderson, a combination of light sandy soils and trifoliata rootstock contributed to that unusually high tension. Left unrelieved, such tensions would be fatal for Satsuma mandarin trees in a hot, dry climate.

In moist soil, and working within the dynamic range of plant response to daily variation in evaporative conditions, plants in a well-watered orchard or vineyard will regain pre-dawn leaf water tensions around 150 to 250 kPa after tensions at noon the previous day that may have been as high as 1500 to 2500 kPa, especially during a hot dry summer. Stomata may have already closed at that tension, but this need not be a trigger for irrigation even though acquiring rootzone moisture is not keeping up with potential transpiration. That state is temporary, and stomata will reopen under milder conditions.

These closing–opening responses are part of any vascular plant's own self regulation of water status. So finely tuned is that self regulation that a reasonable correlation can exist between midday and predawn tensions and, with the added convenience of daytime operations, midday measurement can thus contribute to decisions on irrigation management. Researchers worldwide use pressure chambers in their studies of soil-plant water relations, but the need for repetitive and painstaking measurement of balance pressures, plus reliance on high pressure cylinders of compressed gas to run the pressure chamber, have stopped this technology being used widely.

Leaf temperature

While pre-dawn leaf water tension reflects soil water availability, variation in canopy leaf temperature reflects soil water use. As well, just as overnight equilibration between canopy and soil can provide a spatial integration of rootzone soil water reserves, canopy temperature is a way of measuring variation in transpiration over a crop. While thermocouples are used to track temperature changes on individual leaves, the logistical problems of combining signals from a large array of sensors, plus the issue of selecting representative leaves, favours use of devices that average over an area, such as infrared thermometers or heat-measuring remote sensors.

Unlike soil-canopy equilibration, which takes hours, atmosphere-canopy exchange of latent and sensible heat is highly dynamic and takes only seconds. Canopy temperature, relative to outside air temperature, is a virtually instantaneous message on change in transpiration. Leaves grow warmer when they stop transpiring, especially large leaves such as grapevine foliage, where transpirational cooling is a large part of their heat budgets. Smaller leaves, such as on pears, apples and peaches, depend on convective heat loss to a greater extent, so that warming due to stomatal closure will be less noticeable.

Whether leaves are small or large, the definitive sign that trees or grapevines do not have enough readily-available moisture to meet transpiration is a steady upward trend in leaf temperature from around early to mid-morning that is either higher than well-watered comparison plants or higher than can be attributed to increasing intensity of sunlight. Temporary wilting, or partial stomatal closure around noon or early afternoon, will also drive up leaf temperature, but those effects are usually temporary and are not reliable criteria for scheduling irrigation.

One more application of canopy temperature is worth commenting on. Strategic surveys of canopy leaf temperature, generally with low altitude remote sensing, help define site variability. The irrigation manager can use these surveys to define areas of an orchard or vineyard that will be especially vulnerable to moisture stress (usually due to shallow soil), and will thus need early attention when scheduling irrigation.

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GLOSSARY

Abscission. Loss of an organ (e.g. leaf, tendril, flower or fruit) from the parent plant via operation of specialized cells an abscission layer or abscission zone. Syn, shatter.

Anthesis. Flowering (or more specifically pollen shed, and commonly associated with flower opening).

Crop coefficient (K_c). Evapotranspiration (ET) from an orchard or vineyard (over a given length of time) expressed as a fraction of ET that would have occurred from a reference crop (ET_o) over that same length of time.

Crop factor (CF). Evapotranspiration (ET) from an orchard or vineyard (over a given length of time) expressed as a fraction of evaporative loss that would have occurred from a Class A evaporation pan (E_{pan}) over that same length of time.

Deficit irrigation. An irrigation practice where the amount of supplementary water applied as irrigation is reduced to only a fraction of potential evapotranspiration from a well-watered reference crop (ET_o). In regulated deficit irrigation, mild to moderate plant moisture stress is allowed to develop at a stage in growth and development that has only minor (or even nil) effects on yield.

Evapotranspiration (ET). Total water loss from an orchard or vineyard via canopy transpiration plus soil evaporation. ET_{crop} refers to an estimate of evapotranspiration from an actual orchard or vineyard. ET_o refers to an estimate of evapotranspiration from a hypothetical reference crop in the same situation as the orchard or vineyard in question. ET_o is commonly inferred from meteorological data using one of a number of mathematical models that estimate ET as a function of incoming energy from sunlight and evaporative conditions including temperature, humidity and wind. Crop coefficient (K_c) as defined above is thus equivalent to $ET_{crop} \div ET_o$ (or put another way, $ET_{crop} = K_c \times ET_o$).

Partial root zone drying (PRD). The practice of using water application (irrigation) to alternately wet and dry (at least) two spatially prescribed parts of the vine root system to simultaneously maintain vine water status at maximum water potential and control vegetative growth for prescribed parts of the seasonal cycle of vine development for the purpose of controlling vegetative growth or improving water use efficiency or both while maintaining reproductive growth and development.

Photoassimilate:. Carbon-based products from photosynthetic assimilation of atmospheric carbon dioxide (largely sugars) in combination with much smaller quantities of nutrient-based substances, especially nitrogen, phosphorus and potassium, that are exported from foliage (sources of photoassimilate) to importing organs such as fruits or other metabolically-active organs and tissues (sinks for photoassimilate).

Plant water tension. The tenacity with which water is held within the freely diffusible spaces and cells of plant tissues, including the vascular system. Plant water tension is commonly measured as the pressure required (in MPa) to express water from the vascular elements of that plant (as with the petiole of an excised leaf protruding from a pressure chamber). Because water potential is referenced to pure water (potential = zero, by definition) plant water potential becomes the negative equivalent of a tension measurement, and for convenience is expressed as –MPa. A leaf moisture tension of 1500 kPa is thus equivalent to a leaf water potential of –1.5 Mpa; or as traditionally cited, –15 bars.

Potential evapotranspiration (ET_o). A estimate devised by Penman (1948, 1956), and in its original form, applied to water loss via evaporation from an open water body or wet soil, of substantial extent. Consistent with that former nomenclature, ET_{ref} then applied to an estimate of evapotranspiration from freely-transpiring grass or from a short reference crop that was well supplied with water. ET_o is now taken (see Allen *et al.* 1998 for FAO definition) to represent potential evapotranspiration from a well-watered reference crop of short stature that is transpiring freely.

Soil water content:. A volumetric measure of soil water expressed either as a percentage of soil volume, or as mm of water per metre depth of soil. For example, a soil water content of 5% is equal to 50 L of water per cubic metre of soil, or alternatively, 50 mm of water per metre depth of soil.

Soil water tension. The tenacity with which water is held within soil pores and on soil particles and commonly expressed as the suction required (in kPa) to draw water from that soil. Tension increases as soils dry down from field capacity (notionally equivalent to a suction of 10 kPa) to permanent wilting point (notionally equivalent to a suction of 1500 kPa, 1.5 Mpa; or as traditionally cited, 15 bars).

Readily available water (RAW). The range of plant-available soil moisture between field capacity and the onset of mild moisture stress (as sometimes indicated by temporary wilting under conditions conducive to fast ET as occurs on hot dry windy days).

Regulated deficit irrigation (RDI). The practice of using water application (irrigation) to maintain vine water status within prescribed limits of deficit with respect to maximum water potential for a prescribed part or parts of the seasonal cycle of vine development for the purpose of controlling reproductive growth and development, vegetative growth or improving water use efficiency or both.

Veraison. The onset of the second phase of fruit growth (in grapevines) and marks a developmental transition from an initial phase of moderate enlargement and acid accumulation by small hard green berries, to a subsequent phase of rapid and substantial berry growth characterized by tissue softening, sugar-accumulation and eventually ripening (including skin colouration in pigmented varieties).

Water use efficiency (WUE). At a single plant or single leaf level, WUE refers to net carbon gain via photosynthesis as a function of water lost via transpiration. In the present context of irrigated horticulture (as discussed by Smith and Maheshwari (2002)), WUE is the effectiveness with which an irrigated enterprise converts water obtained from an irrigation supply plus rainfall, into a saleable product. Irrigation strategies that can improve WUE in that broader sense include:

- on-farm re-use of run-off and drainage water
- laser levelling preparatory to flood irrigation
- optimised distribution networks supporting sprinkler/dripper systems to avoid waterlogging or ponding
- improved scheduling that achieves a closer match between crop water requirement and water application in both time and space.

FURTHER READING

Agnotes. Visit *www.nre.vic.gov.au/notes* and search under Farming and Agriculture. Note in particular AG0293, *Construction of an evaporation pan for irrigation scheduling*; AG0294, *Gypsum blocks for measuring the dryness of soil* and AG0298, *How to use tensiometers*.

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CONVERSIONS

1 hectare (ha) = 10,000 square metres (m^2)

1 hectare = 2.5 acres

1 cubic metre (m^3) = 1000 Litres (L)= 1 kilolitre (kL)

1 Megalitre (ML) = 1,000,000 Litres (L)

1 ML/ha = 100 millimetres (mm) depth of water over one hectare (ha)

Soil water (volumetric measurement)

1% = 10 litres (L) per cubic metre (m^3)

= 10 millimetres (mm) per metre (m) depth of soil

Soil water (tension measurement)

100 kilopascals (kPa) = 1 bar = 100 centibars (cb)

1 pound per square inch (psi) = 6.89 kPa
15 psi = 100 kPa = 1 bar
1 bar = 1 atmosphere (atm)

Evaporation or evapotranspiration

1 inch (in) = 25.4 millimetres (mm)

1 millimetre (mm) = 1 litre (L) per square metre (1 L/m^2)

100 mm = 1 ML/ha

(Based in part on Giddings 2001, Goodwin 1995, Mitchell and Goodwin 1996 and Boland *et al.* 2001).