MODULE 05

Insights into the relationships between yield and water in wine grapes

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The aim of this module is to consolidate current thinking around the relationships between yield and water across the key growing regions within the Murray Darling Basin. There are many other variables, including varieties, climate, soils, mangement practices and their complex interactions that could be discussed, however this module has been designed to provide guiding information to the winegrape growing community about the management of irrigation water, particularly deficit irrigation, and the possible impact on production (yield and quality).

1 Background

Lack of water, in conjunction with variable and unreliable water supply, is emerging as the single biggest threat to the viability and sustainability of Australian horticulture. Water supply for irrigation of vineyards continues to be at drastically low levels. Historically, irrigated horticultural production has not been limited by access to water. However, the combination of changing environmental conditions (more drought events), increased competition from new crops and new plantings, loss of some producers from irrigation districts, as well as rapid urbanisation has dramatically reduced the availability of water.

Across the Murray-Darling Basin, wine grape production relies on irrigation for consistent, viable production. Historically, irrigated grapevines have a tendency to be vigorous, producing large canopies, which tend to shade fruit and lead to potential problems such as pest and disease outbreaks, delayed fruit ripening and variability in fruit quality. Careful control of irrigation inputs is widely regarded as the Australian wine industry's best management tool for manipulating vegetative vigour and grape quality, while conserving irrigation water. When crops are exposed to water stress, photosynthesis, cell division and cell expansion are reduced. Water stress occurs when potential water loss from the leaf canopy exceeds the plants' ability to draw water from the soil. Efficient irrigation systems that are managed properly involve applying the right amount of water at the right time to maintain root-zone soil moisture at adequate levels to prevent both water stress and water-logging. During times of water shortages, determining the minimum irrigation requirement and scheduling for vines to survive and its impact on fruit and wine quality is becoming critical.

2 Components of grapevine yield development

In order to understand how to manage wine grapes under minimal water inputs, it is important to have an understanding of the annual growth cycle of a grapevine. A grapevine's annual growth cycle includes a vegetative and a fruiting or reproductive cycle (Figure 1.). These cycles comprise five stages of the grapevine's development. That is budburst to flowering, flowering to fruit-set, fruit-set to veraison, veraison to harvest and post-harvest.

In the Murray-Darling region vines are dormant from May through early August. Bud burst is in late August to early September and continues through to mid-September for most wine grape varieties. Flowering and berry set occur in early to mid-November. During the same time span the floral structures of the subsequent season are initiated in developing buds located in leaf axils. Between bud burst and flowering vines undergo a period of strong vegetative growth during which the leaf canopy is established. After fruit set berries expand rapidly until around veraison in mid-January where sugars accumulate in the berries. Berries begin to reach maturity in mid to late February and leaf fall occurs towards mid-May when the vine goes back into dormancy.

The cycle of berry/yield development for grapevines extends over two growing seasons with bud initiation occurring in Year 1 to harvest in Year 2 (Krstic et al., 2005). During this cycle there are a number of stages that are critical to yield development. The most important stage to determining yield potential is inflorescence initiation and differentiation which begins about 18 months prior to harvest. Floral bud development and budburst are key events that influence yield followed by flowering and fruit-set where a proportion of flowers will successfully set and become berries.

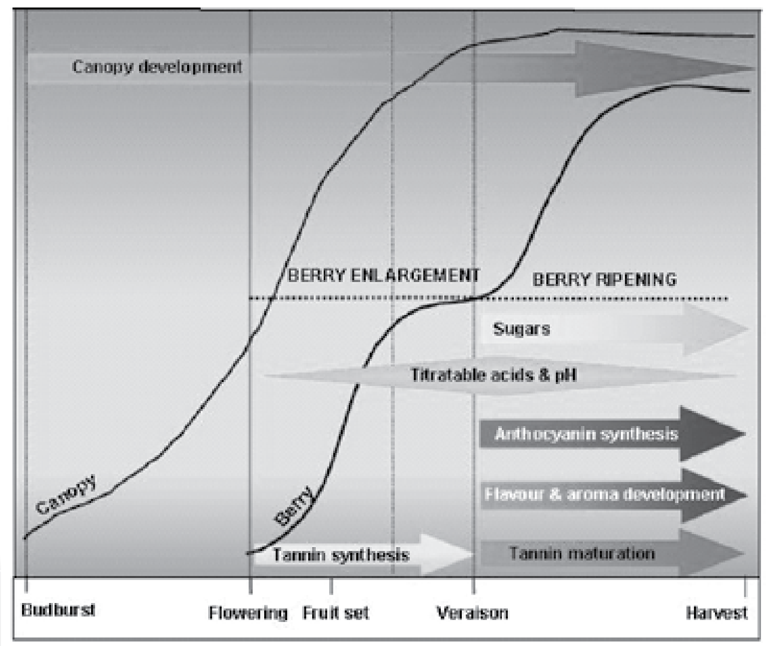


Figure 1. Schemmatic representation of canopy growth and grape berry development during a grapevine's growing season (adapted from Coombe, 1992; Coombe & McCarthy, 2000).

The variation in grapevine phenology (budburst, flowering, veraison and harvest) between regions is influenced by a complex interaction between the variety, climate, soil type, season-to-season fluctuations and viticultural practices (irrigation management, nutrition levels, pruning). Temperature is considered the major factor influencing grapevine phenology, however water stress due to low soil moisture levels and/or drought conditions can also inhibit vegetative growth and yield development (Pearce & Coombe, 2005).

3 Water relations in grapevines

Studying grapevine physiology is an important tool in helping to understand how deficit irrigation may influence grape yield and berry composition. Overall, grapevine water relations are complex and dynamic systems that have evolved a high degree of adaptability to different environmental conditions. Grapevines control water loss by varying the aperture (opening) of the leaf stomata, which in turn regulate transpiration and prevents leaf water potentials decreasing to levels that harm the hydraulic (plumbing) system. Stomata also have to remain sufficiently open to allow carbon dioxide to diffuse into leaves from the atmosphere for photosynthesis. Consequently, stomata have a dual role of balancing transpiration and carbon dioxide exchange to prevent excessive water loss, whilst maintaining adequate carbon dioxide levels to support photosynthetic activity to maintain healthy vine function and reproduction.

The amount of water required at different stages of grapevine growth will depend on the variety, rootstock-to-scion interaction, climate (rainfall and evaporation), soil type/depth and crop load. Figure 2 illustrates the approximate annual percentage of water required by vines at each stage of the growth cycles described earlier.

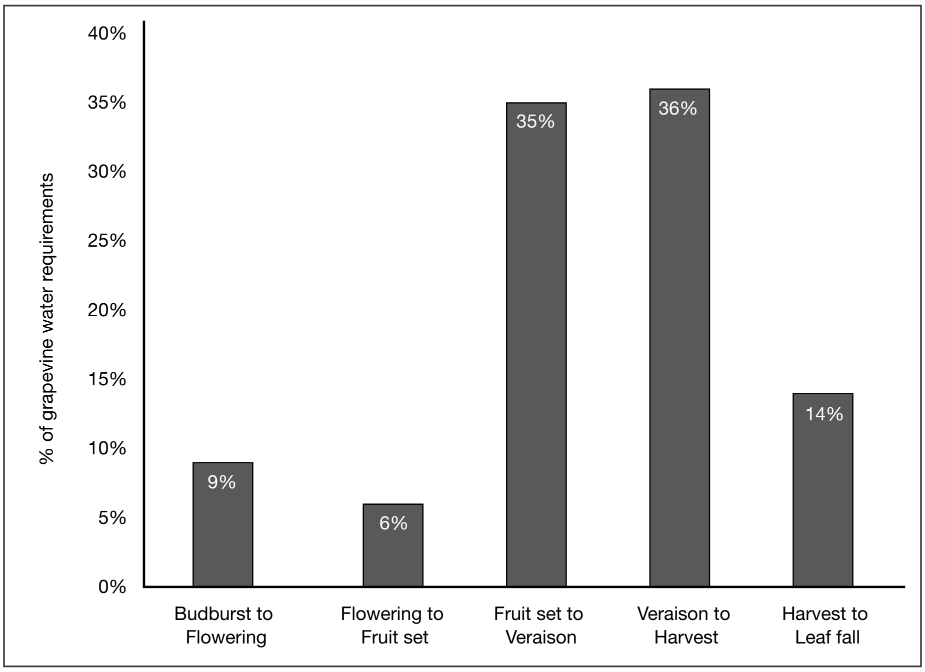


Figure 2. Grapevine growth stages and the approximate water requirement at each stage as a proportion of the annual requirement (Adapted from NSW Agriculture (2004).

3.1 Budburst to fruit set

Stages 1 & 2 include budburst, flowering and fruit-set. When combined, these stages utilize approximately 14% of the annual water requirement. They are critical stages for establishing canopy size and yield. Irrigations that are applied too soon will be wasted and not utilized by the vines. During this period, rapid vegetative growth ensures the development of an adequate leaf canopy to sustain production. Once the leaf canopy is fully developed, towards early to mid-November, vines flower. Water use at this time is still moderate and water stress should be avoided to ensure optimum flower retention and fruit set. Bud initiation and differentiation for the subsequent season also takes place at around the same time. High water stress at flowering can result in poor fruit set (hen and chicken) or aborted fruit (shot berries) – both of which lead to yield reductions. It should also be noted that heat stress around flowering and fruit set can lead to flower abortion leading to a potential yield reduction.

3.2 Fruit set to veraison

Stage 3 extends from fruit-set to veraison and uses approximately 35% of the annual water requirements. This is the time that deficit irrigation strategies, such as regulated deficit irrigation (RDI), can be used to control berry size. Severe water stress can affect bud fruitfulness that may impact yields in the following season. Berry expansion occurs between fruit-set and veraison and water deficits at this time tend to reduce berry size, often resulting in a higher sugar concentration per berry. In this period of berry growth the vine tends to be tolerable to moderate water deficits. Several studies on winegrapes have shown that water deficits during this period do not have a negative impact on the accumulation of soluble solids even though berry size may be reduced.

3.3 Veraison to harvest

Stage 4 is from veraison to harvest with vines requiring about 36% of the annual water requirements. Deficit irrigation strategies can reduce yield but more importantly it will affect the rate of ripening and ultimately fruit quality (sugar levels, acid balance, colour, flavour and aroma). Ripening may be delayed if soil water deficits are too severe because sugar assimilation is impaired by water deficits. It is also important to maintain healthy leaf function to maximize berry sugar accumulation. Hence, severe deficits should be avoided to prevent plant defoliation.

3.4 Post-harvest

Stage 5 is harvest to leaf-fall and uses at least 14% of annual water allocated at this growth stage. It is still important to maintain some leaf function during this period, especially from April-June, to ensure that the vine is able to build up sufficient reserves for the subsequent season before going into dormancy. Water stress during this stage may lead to restricted growth symptoms in the spring, particularly in young vines. In contrast, irrigation to match crop water requirement can lead to re-growth of shoots that can then compete with storage. Insufficient irrigation during the winter months may not be enough to leach salts, accumulated during the season, from the root zone. If they remain in the root zone they may be taken up by the plant and accumulate in the leaf tissue in the subsequent season resulting in salt stress and tissue damage. To avoid this risk, a leaching irrigation during winter is recommended.

4 Quantifying Water Use Capability

Production of high quality wine grapes is dependent on sufficient irrigation and will not be achieved from water stressed vines. To improve irrigation efficiency it is important to make sure the irrigation system is regularly maintained and that a water-efficient management strategy is implemented. This would include the creation of a water budget and monitoring soil moisture levels. Familiarisation with soil moisture monitoring equipment and key visual signs of water stress are simple and effective ways of monitoring soil and vine water status. Scheduling of irrigations will be influenced by soil type, weather and growth stage of the vine.

Crop factors and crop coefficients are helpful guides to determining the likely water requirements of the vine relative to the evapotranspiration of a reference crop. In vineyards where bare soil or a cover crop is likely to influence the total evapotranspiration from that site, crop coefficients are scaled to accommodate variation from canopy size as a result of these influencing factors. It should also be noted that when using a deficit irrigation strategy the physiological response of a grapevine decreases due to stomatal closure which inturn will lower crop coefficients. Furthermore, as total canopy cover has an influence on vineyard evapotranspiration it is expected that smaller values of crop coefficients would occur at the beginning of the irrigation season (October-November).

4.1 Crop coefficients

The product of crop coefficient (), by reference crop evaporation (), as shown in equation 1, estimates a seasonal water requirement for the Sunraysia and Riverland regions of between 7.4 – 8.9 Ml/ha with a mean of 8.4 Ml/ha. Equation 1 integrates the relationships between evapotranspiration of the crop and the reference crop evaporation into a single coefficient .

$$ET_c = K_c \text{ ‘ } ET_o \qquad (1)$$

In an alternative approach, as outlined in equation 2, is split into two factors that separately describe the evaporation () and transpiration () components.

$$ET_c = K_{cb} \text{ ‘ } ET_o + K_e \text{ ‘ } ET_o \qquad (2)$$

4.2 Alternatives to crop coefficients

A recent variation of the above concept (see equation 3) has suggested substituting with an estimate of the Effective Area of Shade (EAS) (O'Connell & Goodwin, 2007). The latter is measured in the vineyard of interest and is closely correlated with the size of the leaf canopy. On the other hand, or rely on published values and may not account for differences due to cultivar or management choice. Currently, the concept has been validated for peaches and apples but should be equally applicable to grapevines.

$$ET_c = 1.1 \text{ ‘ } EAS \text{ ‘ } ET_o + K_e \text{ ‘ } ET_o \qquad (3)$$

A further variation substitutes EAS with the Effective Canopy Cover (ECC, see equation 4). Similar to EAS, ECC is directly estimated in the vineyard of interest. ECC is derived using one measurement around solar noon, while EAS is derived from 3 consecutive measurements, one in the morning approximately 3 h prior to solar noon, one at solar noon and the third in the afternoon approximately 3 h after solar noon. Both ECC and EAS have been shown to correlate closely.

$$ET_c = 1.5 \text{ ‘ } ECC \text{ ‘ } ET_o + K_e \text{ ‘ } ET_o \qquad (4)$$

4.3 Crop factors

A further approach for estimating potential crop water use is based on daily records from standard class A evaporation pans (Epan) in combination with monthly crop factors () as outlined in equation 5.

$$ET_c = C_f \text{ ‘ } ET_{pan} \qquad (5)$$

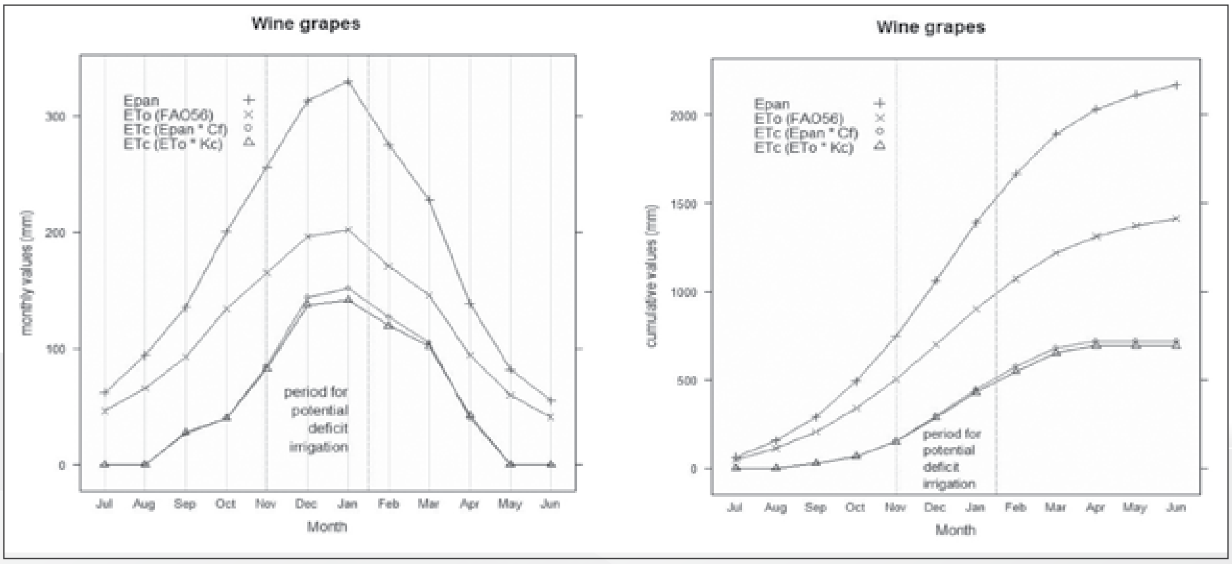
In applying this method irrigators mostly rely on published readings from Bureau of Meteorology stations (Bureau of Meteorology, 2008). Crop factors are provided by the industry or are obtained from government sources. It is important to note that in order to avoid erroneous results, crop factors () should only be applied to readings whereas crop coefficients () should only be applied to values of reference crop evapotranspiration ().

Trying to determine precise figures on vine water requirements is difficult due to large variations in planting characteristics (variety, soil type, climate) and management systems. For the purpose of this module potential crop water use (ETc) presented in Table 1 and Figure 1 was calculated according to equations (1) and (5) respectively. Kc and Cf used are in accordance with those published in Irrigated Crop Management Services (2001) and are based on those published in FAO56 (Allen et al 1998). Weather records came from Mildura Airport (Lat: -34.23, Long: 142.08) and were sourced from the Bureau of Meteorology (2008). All average weather records were calculated for the period between July 1970 and June 2007.

Table 1. Suggested winegrape crop factors and coefficients for mature vines in the Sunraysia region. Winegrape average water use based on Mildura BoM weather records (Jul 1970 - Jun 2007).

Month	FAO56		Epan		ETo (FAO56)		ETc (Epan * Cf)		ETc (ETo * Kc)	
	crop factor (Cf)	crop coefficient (Kc)	*monthly*	*cumulative*	*monthly*	*cumulative*	*monthly*	*cumulative*	*monthly*	*cumulative*
Jul	0	0	62	62	46	46	0	0	0	0
Aug	0	0	94	156	66	112	0	0	0	0
Sep	0.2	0.3	135	291	93	205	27	27	28	28
Oct	0.2	0.3	200	491	134	339	40	67	40	68
Nov	0.33	0.5	256	747	165	504	84	151	83	151
Dec	0.46	0.7	313	1060	196	700	144	295	137	288
Jan	0.46	0.7	330	1390	202	902	152	447	141	429
Feb	0.46	0.7	275	1665	171	1073	127	574	119	548
Mar	0.46	0.7	228	1893	146	1219	105	679	102	650
Apr	0.29	0.45	139	2032	94	1313	40	719	42	692
May	0	0	82	2114	60	1373	0	719	0	692
Jun	0	0	55	2169	41	1414	0	719	0	692
Total			**2169**		**1414**		719		692	

Figure 2. Monthly (left) and cumulative (right) pan evaporation (Epan), reference crop evaporation (ETo) calculated according to Allen et al. (1998) and estimated crop water use ETc. ETc was estimated either as the product of Epan times monthly crop factors (Cf) or as the product of ETo times monthly crop coefficients (Kc). Cf and Kc values are in accordance with those published in Irrigated Crop Management Services (2001).



5 Water deficit effects on grapevine physiology

Soil water deficits can reduce photosynthesis thereby affecting vegetative growth, yield development and berry composition. During a soil water deficit, stomatal closure in grapevines is a dominant factor in minimising transpiration and preventing subsequent damage to a grapevine's hydraulic system. Prolonged stomatal closure also limits photosynthesis, sugar assimiliation and carbohydrtae prodcution. When carbohydrtae production is limited vines prioritise its use according to certain partioning rules.

Generally, as a soil dries out a decrease in stomatal conductance is associated with a reduction in leaf water potential. Differences in stomatal control of grapevines to water deficit are thought to be due to a combination of hydraulic signals and/or root-sourced chemical signals (Dry & Loveys 1999; Davies et al., 2002; Schultz, 2003; Soar et al., 2006b). In various partial root zone drying (PRD) studies, reductions in leaf stomatal conductance were found to be regulated by chemical signals (hormonal), predominantly abscisic acid (ABA), that were triggered by root responses to drying soil before being transported to the leaves via the transpiration stream (Dry & Loveys, 1999; Stoll et al., 2000).

Since grapevine varieties are grown in diverse environments, vine cultivars have evolved a high degree of adaptability to different soils, climates and water availability. These variations in grapevine origin and genotype have ultimately influenced their physiological responses to water stress to the point of potentially categorising grape cultivars based on their stomatal response to soil water deficits (Schultz & Matthews, 1993; Schultz, 1996; Schultz, 2003; Soar et al., 2006b). In brief, isohydric plants tend to maintain a more constant water status by controlling stomatal conductance from an interaction between hydraulic and chemical signals, whereas anisohydric species tend to have less rigid stomatal control which allows a greater fluctuation in leaf water potential with decreasing soil water potential (Lambers et al., 1998; Tardieu & Simonneau, 1998) or increased evaporative demand (Soar et al., 2006b).

Apart from a soil water deficit manipulating the root-derived hormonal (ABA) levels, it has also been noted that rootstock genotypes may vary in sensitivity to soil mositure levels and subsequent hormonal production. Rootstock studies by Soar et al., (2006a) suggested that rootstock effects on the grapevine scion response to water deficit was due to the capacity of the rootstock's ability (root architecture and ABA production) to supply water to the scion. Consequently, the rootstock/scion combination could possibly influence the scion sensitivity to a soil water deficit, particularly when less-vigorous rootstocks are grafted to scions that have a more optimistic (anisohydric) growth response.

6 Water deficit effects on grapevine yield

It is widely known that water deficit can influence grapevine canopy structure, yield components and berry composition. The effect of water deficit on grapevine production differs depending on the stage of canopy growth and berry development when the water deficit is applied. Various studies have used different irrigation regimes to manipulate canopy vigour and have noted that yield and quality at harvest are dependent on when the irrigation is applied in relation to the stage of berry growth. For instance, regulated deficit irrigation (RDI) applied to Shiraz during early canopy development (between budburst and flowering) and early berry formation (flowering to setting) can reduce shoot growth and affect berry cell division leading to smaller berries and potentially reduced yield (McCarthy, 1997; McCarthy, 2000). By contrast, winegrapes exposed to PRD generally maintain berry size and yields despite receiving a reduction in irrigation water (Kriedemann & Goodwin, 2003).

When a water deficit is applied between fruit set and veraison there is potential to reduce yield by affecting berry size (Hardie & Considine, 1976; Matthews et al., 1987; McCarthy, 2000). Hardie & Considine (1976) noted that the most sensitive stage for affecting berry development was during the flowering to fruit set stage, whereas a water deficit applied post-veraison tended to cause a reduction in berry weight. Early and late season water deficits can affect the development of the current season's berries as well as the primordia for the subsequent season's berries (Matthews & Anderson, 1989).

7 Relationships between yield and water

The effect of irrigation on yield is not a linear relationship (Figure 3). Theoretically, there is an irrigation threshold which maximizes yield and productivity. Irrigation above this level results in wasted water to deep drainage and evaporation that can also lead to excessive vegetative growth, nutrient leaching, pest and disease problems and poorer fruit quality (Figure 4).

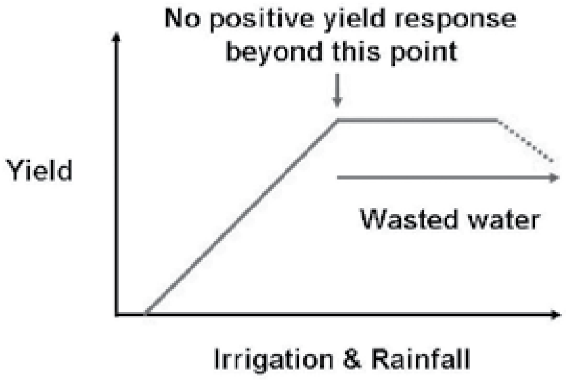


Figure 3. Theoretical interpretation of the effect of irrigation on yield.

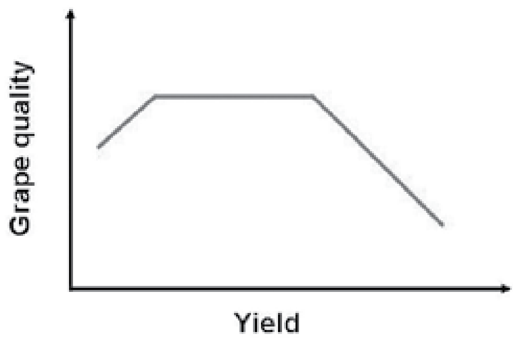


Figure 4. Theoretical interpretation of the effect of yield on quality.

With the realisation that some form of deficit irrigation management will be necessary to produce sustainable wine grape production into the future, there needs to be greater understanding as to how a managed soil water deficit will affect yield, quality and long-term vineyard sustainability. Currently, the Australian wine industry has widely adopted various irrigation management strategies such as regulated deficit irrigation (RDI), partial rootzone drying (PRD) and sustained deficit irrigation (SDI) to improve and sustain water use effciciency (WUE) which is calculated as tonnes of fruit per megalitre of water (Kreidemann & Goodwin, 2003). A common feature of these irrigation techniques is the reduction in available soil water but how the water is applied is fundamentally different. In the case of RDI, a controlled application of irrigation water at less than the crop water use is applied at a specific vine growth stage (temporal deficit) (Kriedemann & Goodwin, 2003). By contrast with PRD, the irrigation water is manipulated over the soil area (spatial deficit) by applying alternate irrigations to each side of the grapevine, thus creating discrete wet and dry zones around the root system (Dry et al., 1996; McCarthy, 1998). Conversely, for a sustained deficit irrigation (SDI) the water deficit is not created by withholding water but by applying less water than the optimum required at each irrigation event for the entire irrigation season.

While much is known on how conventional drip, RDI, PRD and to a lesser extent SDI have improved WUE, there is less knowledge on how low we can irrigate vines before having a negative impact on growth and yield. In order for growers to make a decision whether to focus on irrigating select patches (high value varieties) or applying reduced water across all patches there needs to be information on the immediate impact of water deficit on yield and quality not only in the current season but also preceding years. Trying to generalize this is challenging as the differences between varieties, soil type, irrigation water quality and climatic conditions for each winegrape growing region are unique. However there are some general concepts that can be considered when trying to budget and prioritise water when water restrictions are imposed.

This section describes a number of scenarios ranging from no irrigation at all to those aiming to achieve maximum yield.

- **Scenario 1:** No irrigation and likely abandoning of the vineyard. Vines may have to be removed because of the potential of pest and disease carryover. After one season without irrigation it may be possible to revive the vineyard in the subsequent season. Survival will depend on rootstock and variety. Ramsey grafted vines are more likely to survive than vines on their own roots.
- **Scenario 2:** Irrigation for survival. This scenario suggests keeping the vines alive to protect the future production capacity under very limited water supplies. To maximise the potential for a crop in the next season, it is important to maintain bud fruitfulness and retain as much of the vine's carbohydrate reserves as possible. This could be achieved by winter pruning to reduce the number of buds retained so as a small canopy is maintained. Furthermore, the removal of bunches shortly after berry set will reduce the tranpsirational demand required to ripen a crop. Irrigation should only be applied once shoot growth ceases, which tends to be near flowering. Where possible, limit shoots to approximately 30-40cm in length (6-8 healthy leaves per shoot) either by withholding irrigations or summer hedging. Large amounts of leaf loss should be avoided during veraison to harvest, as it will lead to reduced carbohydrate reserves and poor fruitfulness of the basal buds. Careful observation of the vines for signs of early water stress in conjunction with soil moisture monitoring will help in avoiding the vines shutting down.

- **Scenario 3:** Irrigate to minimise the loss in yield. Most appropriate is the application of either a RDI or SDI irrigation strategy. Severe stress prior to flowering and set should be avoided because of its negative impact on fruiting potential in the current and subsequent season. Post-set RDI has less impact on fruiting potential but may reduce berry size and yield. The least sensitive period to apply RDI is after fruit set to veraison (around mid to late November to mid to late January). Applying a sustained deficit below the estimated plant water requirement has been shown as a successful strategy for conserving water. However it should probably not be less than 70% of crop water requirement and some reduction in yield will be inevitable.

Conclusion

Horticulture is highly vulnerable to the potential impact of climate change, including the risk of exacerbating other natural resource degradation problems such as salinity, water tables and drought induced soil erosion. As water supply is the driving factor that limits yield the sustained drought conditions prevailing in recent years have heightened awareness of the need to adapt to predicted changes in the climate. Government and the wine grape industry have accepted that severe shortages of water for irrigation will continue. Irrigation is now a substantial cost and in some regions will limit wine production.

This module and a complementary powerpoint presentation have been prepared to provide growers and industry with immediate information that can be used to aid irrigation management decisions. The powerpoint presentation has been tailored to suit specific winegrape growing regions by providing regional data on yield and irrigation water for Shiraz, Cabernet Sauvignon, Merlot and Chardonnay. Both tools should be used to aid irrigation management decisions.

References

Allen, R. G., Pereira, L. S., Reas, D., & Smith, M. (1998). 'Cropevapotranspiration'. FAO Irrigation and Drainage Paper No. 56, Crop evapotranspiration. FAO. 290 pp.

Coombe, B.G. (1992) Research on development and ripening of the grape berry. American Journal of Enology and Viticulture 43, 101-110.

Coombe, B.G. and McCarthy, M.G. (2000) Dynamics of grape berry growth and physiology of ripening. Australian Journal of Grape and Wine Research 6, 131-135.

Davies, W.J., Wilkinson, S. and Loveys, B. (2002) Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. New Phytologist 153, 449-460.

Dry, P., Loveys, B.R., Botting, D.D. and Düring, H. (1996) Effects of partial root-zone drying on grapevine vigour, yield, composition of fruit and use of water. In 'Proceedings of the Ninth Australian Wine Industry Technical Conference held 16-19 July, 1996, Adelaide, SA.' pp. 128-131. Winetitles, Adelaide, Australia.

Dry P.R. and Loveys B.R. (1999) Grapevine shoot growth and stomatal conductance are reduced when part of the root system is dried. Vitis 38, 151-146.

Hardie, W.J. and Considine, J.A. (1976) Response of grapes to water-deficit stress in particular stages of development. American Journal of Enology and Viticulture 27, 55-61.

Irrigated Crop Management Services (2001). 'Annual Irrigation Requirement for Horticultural Crops.' Primary Industries and Resources SA, Adelaide. ISSN 1039-8791. ISBN 0 7308 4349 1.

Kriedemann, P.E. and Goodwin, I. (2003) 'Regulated deficit irrigation and partial rootzone drying: an overview of principles and applications.' Land & Water Australia, Canberra, ACT, Australia.

Krstic, M., Clingeleffer, P., Dunn, G., Martin, S. and Petrie, P. (2005) Grapevine growth and reproduction: an overview. In 'Transforming Flowers to Fruit.' ASVO Proceedings held 29 July, 2005, Mildura, Vic., Australia. pp. 7-10.

Lambers, H., Chapin III, F.S. and Pons, T.L. (1998) 'Plant physiological ecology.' Springer-Verlag, New York, USA.

Matthews, M.A. and Anderson, M.M. (1989) Reproductive development in grape (Vitis vinifera L.): reponses to seasonal water deficits. American Journal of Enology and Viticulture 40, 52-60.

Matthews M.A., Anderson M.M. and Schultz H.R. (1987) Phenologic and growth responses to early and late season water deficits in Cabernet franc. Vitis 26, 147-160.

McCarthy, M.G. (1997) 'Effect of timing of water deficit on fruit development and composition of Vitis vinifera cv. Shiraz.' PhD Thesis. University of Adelaide, Adelaide, Australia.

McCarthy, M.G. (1998) Irrigation management to improve winegrape quality – nearly 10 years on. The Australian Grapegrower & Winemaker Annual Technical Issue 414a, 65-71.

McCarthy, M.G. (2000) Developmental variation in sensitivity of Vitis vinifera L. (Shiraz) berries to soil water deficit. Australian Journal of Grape and Wine Research 6, 136-140.

NSW Agriculture (2004). 'Irrigating grapevines with limited water supplies.' Agricultural Note. ISBN 0 7347 1574 9.

O'Connell, M.G. and Goodwin, I. (2007) Water stress and reduced fruit size in micro-irrigated pear trees under deficit partical rootzone drying. Australian Journal of Agricultural Research 58, 670-679.

Pearce, I and Coombe, B.G. (2005) Grapevine phenology. In 'Viticulture Volume 1 – Resources. 2nd Edition.' (Eds. Dry, P.R. and Coombe, B.G.) pp. 150-166. Winetitles, Adelaide, Australia.

Schultz, H.R. (1996) Water relations and photosynthetic responses of two grapevine cultivars of different geographic origin during water stress. Acta Horticulturae 427, 251-266.

Schultz, H.R. (2003) Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown Vitis vinifera L. cultivars during drought. Plant, Cell and Environment 26, 1393-1405.

Schultz, H.R. and Matthews M.A. (1993) Growth, osmotic adjustment, and cell-wall mechanics of expanding grape leaves during water deficits. Crop Science 33, 287-294.

Soar, C.J., Dry, P.R. and Loveys, B.R. (2006a) Scion photosynthesis and leaf gas exchange in Vitis vinifera L. cv. Shiraz: Mediation of rootstock effects via xylem sap ABA. Australian Journal of Grape and Wine Research 12, 82-96.

Soar, C.J., Spiers, J., Maffei, S.M., Penrose, A.B., McCarthy, M.G. and Loveys, B.R. (2006b) Grape vine varieties Shiraz and Grenache differ in their stomatal response to VPD: apparent links with ABA physiology and gene expression in leaf tissue. Australian Journal of Grape and Wine Research 12, 2-12.

Stoll, M., Loveys, B. and Dry, P. (2000) Hormonal changes induced by partial rootzone drying of irrigated grapevine. Journal of Experimental Botany 51, 1627-1634.

Tardieu, F. and Simonneau, T. (1998) Variability among species of stomatal control under fluctuating soil water status and evaporative demand: modelling isohydric and anisohydric behaviours. Journal of Experimental Botany 49, 419-432.

Useful Websites

www.pir.sa.gov.au wine-viticulture-irrigation-developing a water budget

www.riverlink.gov.au/waterlink/w_factsheets.html

www.vic.dpi.gov.au/Agriculture & food-horticulture-wine & grapes-information