CUT 1001: AO3 – Recovery of grapevines after severe and long-term water deficits

This is an excerpt from the final report CUT 1001: **Optimising industry returns from existing soil and water research.**

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Adoptable Outcome 3: Recovery of grapevines after severe and long-term water deficits

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1. Background

The last decade (2000-2009) has seen increasing pressure on vineyard irrigation with low rainfall and increasing water restrictions. Subsequent high prices on the water market, combined with decreasing grape prices, have led growers to evaluate their financial situations and adjust management practices accordingly. For some, this has meant decreased irrigation application. While a degree of water deficit is common in winegrape vineyards, the extent to which irrigation can be cutback with minimal impact on subsequent productivity in future seasons is uncertain.

Effects of water deficits on vines, particularly deficits imposed by techniques such as regulated deficit irrigation (RDI) and partial rootzone drying (PRD), have been extensively studied and reviewed (Williams and Matthews 1990, Goodwin 1995, McCarthy et al. 2002, Wample and Smithyman 2002, Kreidemann and Goodwin 2003, Sadras 2009). However, few studies have investigated vine recovery after long-term deficit irrigation or severely reduced irrigation. A number of irrigation trials were initiated in the mid- to late-2000's to examine the impacts of various deficit irrigation strategies that specifically aimed to impose RDI or severely reduce irrigation and, in later seasons, return the irrigation to normal levels. This review describes these projects (Table 1) and summarises initial findings. The literature generated by these projects is summarised in Appendix A.

The projects and literature described in Table 1 and Appendix A refer to three field trials funded by GWRDC and undertaken by SARDI and CSIRO in collaboration with the University of Adelaide. Our purpose in reviewing these projects was to summarise initial findings and highlight the new knowledge that will be gained by industry from supporting these trials.

The new information from these projects that will be of immediate interest to growers will be that pertaining to:

- irrigation strategies and potential water-savings
- prediction of yield losses as a consequence of severe water deficits or long-term (multi-season) application of deficit irrigation,
- vine (particularly yield) recovery, and
- vine management guidelines (during and after water deficits).

Table 1. Site and treatment descriptions for GWRDC funded deficit irrigation and vine recovery projects. Site descriptions for project UA 08/03 provided by M. McCarthy. Site description for project CSP 05/01 summarised from Edwards and Clingeleffer (2011).

Project	**Integrating the carbon and water economies of grapevine for optimal management in challenging environments (UA 08/03)**
Site A **Site description**	Qualco, SA Chardonnay on Ramsey rootstock; drip-irrigated vines; 1.8 x 3.05 m vine and row spacing.
Treatments	Seasonal water application was cutback to 10, 20, 30, and 50 % of the Control volume. The Control represented 'grower practice' (approximately 5 ML/ha/season irrigation). Total water applied (irrigation + effective rainfall) to the Control was less than potential crop evapotranspiration calculated by the Irrigation Recording and Evaluation System (IRES). Deficit irrigation treatments were implemented by decreasing the frequency of irrigation events. Effects of irrigation frequency and volume were examined by a second 30 % treatment in which irrigation frequency was the same as the Control treatment but irrigation volume was decreased. Treatments were imposed for one, two or three seasons (2008/09 – 2010/11) and then returned to the same irrigation as the Control to investigate vine recovery.
Site B **Site description**	Langhorne Creek, SA Cabernet Sauvignon LC14 on own roots; mature, drip-irrigated vines; 1.8 x 2.5 m vine and row spacing; gradational red sandy loam.
Treatments	Seasonal irrigation was cutback to 10 % of the Control volume. The Control represented 'grower practice' (2 – 3 ML/ha/season irrigation). Total water applied (irrigation + effective rainfall) to the Control was less than potential crop evapotranspiration calculated by the Irrigation Recording and Evaluation System (IRES). A 'double irrigation' treatment (= twice the volume applied to the Control) was also imposed. The irrigation treatments were imposed by varying the irrigation volume applied in each irrigation event. The deficit treatment was imposed for one, two or three seasons (2007/08 – 2009/10) and then irrigated as per the Control to investigate vine recovery. Crop removal pre-veraison was applied as a sub-treatment to deficit irrigation; fruit was removed by mechanical harvester in early January each year. Some observations were made of non-irrigated vines in five rows nearby the experimental area.
Project	**Optimising canopy function to increase yield while maintaining wine quality with efficient use of resources (CSP 05/01)**
Site **Site description**	Sunraysia, Vic. Cabernet Sauvignon, own roots; mature, drip-irrigated vines; 2.44 x 3 m spacing; two-wire vertical trellis; mechanically hedged to 40 cm; calcarosol soil.
Treatments	Deficit irrigation and vine recovery was compared to a well-watered treatment and a regulated deficit irrigation Control treatment (post-set RDI, deficit irrigation from fruit set to late-December) over a five year period (2005/06 to 2009/10). The Control represented 'grower practice' (5.3 – 6.4 ML/ha/season irrigation). A 'prolonged deficit' treatment (PD, deficit irrigation from fruit set to late-December and then no irrigation for two to three weeks to the onset of veraison) was applied for three seasons (2005/06 to 2007/08) and then irrigated as per the Control for two seasons (2008/09 to 2009/10) to investigate vine recovery. A 'double irrigation' treatment was applied throughout the season (= twice the volume applied to the Control) for three seasons (2005/06 to 2007/08) and then also irrigated as per the Control for two seasons (2008/09 to 2009/10). Irrigation timing was based on soil moisture monitoring, irrigations were scheduled to refill the soil profile and during the post-set RDI period soil moisture was allowed to decrease to a point lower than during the rest of the season.

Restricting irrigation deficits to moderate levels at particular phenological stages will limit water-savings. To achieve more substantial water-savings, growers need to consider severe irrigation reductions and the immediate impact on yield. Crop water production functions (see Appendix B) describe the relationship between yield and water supply and can therefore be used to predict yield under deficit irrigation. Doorenbos and Kassam (1979) defined a yield response factor (ky) for crops exposed to seasonal water deficits, such that:

$$Y_a = [1 - ky.(1 - ET_a / ET_m)].Y_m \qquad \text{Eqn 1}$$

where Y_a is actual yield, Y_m is maximum yield, ET_a is actual evapotranspiration and ET_m is potential evapotranspiration, and suggested that ky = 0.85 for grapevines. However, this only applied to ET_a / ET_m between 0.5 and 1. Crop water production functions involving more severe deficits remain largely unknown for grapevines.

A recent GWRDC project investigated the effects of substantial reduction in irrigation inputs where irrigation was decreased proportional to the Control (grower practice) for the entire season (Langhorne Creek and Qualco trial sites for project UA 08/03, Table 1). These treatments resulted in a reduction in irrigation inputs ranging from 1.8 to 4.3 ML/ha depending on severity of deficit irrigation (10, 20, 30 or 50 % of water applied to the Control), season and trial site.

Initial results reported by Pech et al. (2010a, see Appendix A) indicate positive relationships between yield and irrigation supply (Figure 1). Furthermore, the reduced irrigation treatments imposed by Pech et al. (2010a) represent water deficits where ET_a/ET_m is less than 0.5 and, therefore, contribute new information to our understanding of crop water production functions. Adjustment of data for differences in maximum yield between seasons would suggest that yield responses to severe deficits were similar in the initial two seasons. Note that, ideally, water supply data would also be normalised and would include effective rainfall.

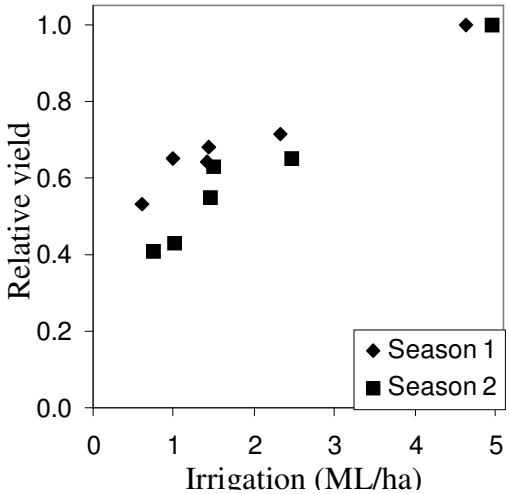


Figure 1. Relative yield (Y_a/Y_m) and irrigation volume applied to Chardonnay grapevines in two seasons at Qualco, South Australia. Data derived from Pech et al. (2010a). Note that yield is plotted against irrigation, not relative water supply.

The alternative to seasonal water deficits described above is to impose a severe deficit either pre-veraison, post-veraison or post-harvest. Most studies have reported the effects of moderate pre- and post-veraison water deficits on yield, vegetative growth and fruit quality (see Williams and Matthews 1990, Goodwin 1995, McCarthy et al. 2002, Wample and Smithyman 2002, Kreidemann

and Goodwin 2003). Here we briefly describe some more recent studies where deficits were more severe.

In a GWRDC project, irrigation was stopped for two to three weeks following the post-set RDI period to the onset of veraison (Edwards and Clingeleffer 2011, Table 1). The reduction in irrigation inputs for this method ranged from 0.8 to 1.5 ML/ha, depending on season, equating to a 15 – 25 % reduction in seasonally applied irrigation compared to grower practice (i.e. post-set RDI). The post-set RDI and the prolonged deficit strategies decreased yield and vegetative growth and improved wine quality compared to a 'double irrigation' treatment. Overall, yield and vegetative growth tended to be affected to a greater extent by the prolonged deficit than the post-set RDI but differences in wine were minor. A basic crop water production function derived from data presented in Edwards and Clingeleffer (2011) shows that effects on relative yield (Y_a/Y_m) were similarly related to the reduction in relative water supply ((irrigation + rainfall)/reference crop evapotranspiration) regardless of the irrigation strategy used (Figure 2). This suggests that, for a given reduction in water supply, deficits during the usual RDI period will have a similar effect on yield as RDI followed by a two or three week cessation of irrigation. Edwards and Clingeleffer (2011) suggested that carry-over (inter-seasonal) effects may be lessened by imposing irrigation reductions over the entire RDI and prolonged deficit periods, rather than stopping irrigation, and returning soil moisture to a non-limiting state prior to veraison. However, this remains to be shown.

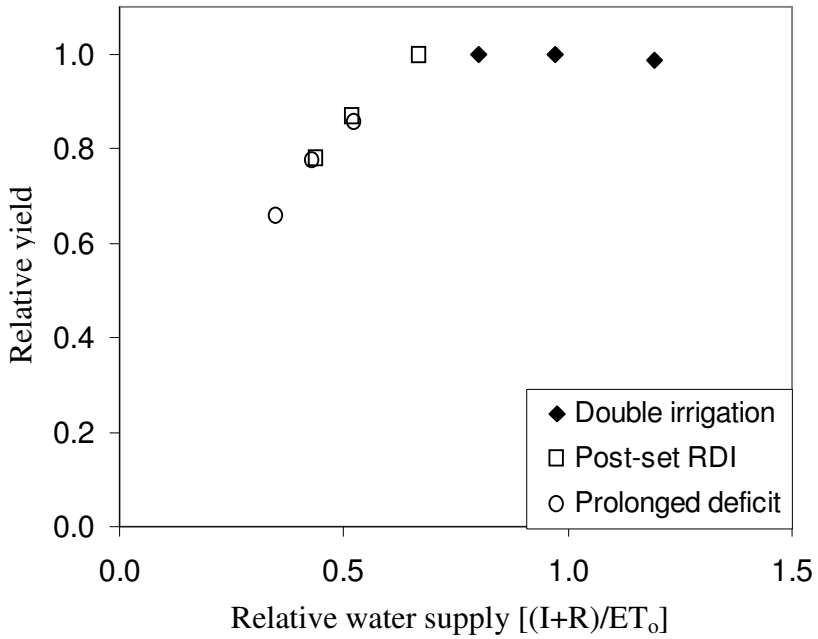


Figure 2. Relative yield (Y_a/Y_m) and relative water supply ((irrigation I + rainfall R)/reference crop evapotranspiration ET_o, from 1 September to harvest) of Cabernet Sauvignon vines at Deakin Estate (data derived from Edwards and Clingeleffer, 2011). Y_{max} was defined as the maximum yield of treatments in the given season. Note that water supply was normalised by ET_o.

In another study, the effects of post-harvest severe water deficits on subsequent yield were investigated. Holzapfel et al. (2009) ceased post-harvest irrigation of Shiraz and Chardonnay vines in the Riverina region for three seasons and observed no significant yield reduction. Irrigation was decreased by 1.1 – 2.3 ML/ha (depending on variety and season), equating to a 35 – 45 % reduction in seasonally applied irrigation (Holzapfel et al. 2009). This may signal a strategy for water-saving, particularly in warm or hot regions (such as the Riverina) where the post-harvest period is long, but requires further examination with regard to site effects (e.g. soil water availability at depth), seasonal conditions (i.e. post-harvest rainfall) and long-term responses.

Implementation of severe irrigation deficits throughout a season raises the practical question of whether to cease irrigation, decrease irrigation volume and maintain the usual irrigation frequency or to decrease irrigation frequency and maintain the volume (run-time) of water applied in each irrigation event. This aspect has been considered at the Qualco site (Pech et al 2010a) with one treatment receiving 30 % irrigation (relative to the Control) at the same frequency as the Control (i.e. decreased volume compared to the Control) and another 30 % treatment receiving irrigation less frequently (i.e. similar volume in each irrigation event compared to the Control). The preferred option will be influenced by soil type and grapevine rooting patterns and, presently, limited information exists to aid growers in deciding which option would best suit their vineyard conditions. Selles et al. (2004) varied irrigation frequency and applied the same total volume of water to vines grown in a deep, well drained, clay loam soil. The different irrigation frequencies resulted in 59, 29 or 20 irrigation events (with approximately 9, 19 or 28 mm applied per irrigation event). Yield, berry weight, soluble solids, vegetative growth, root number and stem water potential were increased by the lowest frequency treatment. This was attributed to a large wetted volume and an improved soil water/air balance when large irrigations were applied with low frequency (Selles et al. 2004). Irrigation was scheduled to match grapevine evapotranspiration (Selles et al. 2004). Responses under deficit irrigation are unknown. A preliminary trial investigating water use efficiency and wine quality effects of irrigating frequently with short run-times compared to less frequent irrigations with long run-times was conducted in the McLaren Vale region (Hyde et al. 2004). Seasonal conditions limited the conclusions that could be drawn from the trial and it was not continued beyond the first season (M. McCarthy, pers. comm.). An earlier trial by the Barossa Valley Viticultural Landcare group had indicated that water use efficiency may be improved by longer, less frequent irrigation events rather than short, more frequent irrigations (M. McCarthy, pers. comm.).

3. Long-term water deficits

A concern for growers is that yield reductions may be amplified by multiple years of water deficits. Following a long-term trial, Edwards and Clingeleffer (2011, Table 1 and Appendix A) concluded that neither post-set RDI nor post-set RDI followed by a two to three week period of no irrigation (prolonged deficit treatment) resulted in continual declines in yields of Cabernet Sauvignon in the Sunraysia region. Rather, it was concluded that yield and vegetative growth responses to water deficits took a number of seasons to be fully expressed and vine balance during this time was disrupted; over a number seasons, vine balance was restored and no further yield reductions occurred (Edwards and Clingeleffer 2011). More severe water deficits may result in progressive yield decline and the irrigation treatments currently under investigation at Langhorne Creek and Qualco by the UA 08/03 project (Pech et al. 2010a,b, Table 1) will enable this to be investigated further.

4. Recovery

The duration of grapevine recovery from severe or long-term irrigation deficits appears to be influenced by both the severity of irrigation deficits and the number of seasons over which the deficits are imposed. The Qualco (Chardonnay) and Langhorne Creek (Cabernet Sauvignon) trials (project UA 08/03, Table 1) subjected grapevines to varying proportions of irrigation deficit over one, two or three seasons and are monitoring vine recovery when irrigation levels are returned to "grower practice". Initial results showed that grapevines subjected to one season of irrigation reduction to 10 % of grower practice experienced decreased yields for at least one season after return to normal irrigation practices (Pech et al. 2010a,b, Appendix A). By contrast, grapevines irrigated for one season at 20 to 50 % of grower practice at Qualco achieved yields similar to the control vines in the first recovery season (i.e. when irrigation returned to grower practice, Pech et al. 2010a). Yield recovery from severe irrigation deficit may be affected by the number of seasons

that deficits are applied. Results from the UA 08/03 project are currently only available for the first two (Qualco site) or three (Langhorne Creek site) seasons. Growers will be better placed to decide the degree and duration of deficit irrigation they wish to impose on completion of this project.

Edwards and Clingeleffer (2011, Table 1 and Appendix A) found that Cabernet Sauvignon vines subjected to two to three weeks of no irrigation following post-set RDI (prolonged deficit treatment, total season irrigation equivalent to 75 to 85 % of grower practice) for several seasons experienced carry-over effects on yield when irrigation was returned to grower practice (post-set RDI). Yield was decreased in the first recovery season but was similar to that of vines irrigated according to grower practice in the second recovery season.

This indicates that long-term (multi-season) deficit irrigation can cause carry-over effects even when deficits are relatively moderate (compared to grower practice).

Carry-over effects on yield are not surprising in perennial crops, especially given the nature of grapevine fruit development with inflorescence initiation occurring in the season prior to fruit growth. However, the mechanisms causing carry-over effects in response to water deficits are less clear. Delayed yield recovery from water deficits in previous seasons may be a result of decreased yield potential due to poor inflorescence initiation as a direct result of water stress. Alternatively. carbohydrate and/or nutrient reserves may be decreased or the vine hydraulic system may be impaired affecting vine growth and reproductive development in recovery seasons. Edwards and Clingeleffer (2011) measured less root biomass in deficit irrigated vines compared to well-watered vines and this may have decreased water and/or nutrient uptake capacity in recovery seasons. In addition to decreased root biomass, trunk growth was decreased by deficit irrigation strategies, compared to well-watered controls, and so, total carbohydrate reserves could have been decreased. An improved understanding of the mechanisms causing carry-over effects of water deficits would aid development of management practices aimed at decreasing vine recovery times.

5. Vine management guidelines

Vine management practices, such as crop thinning (Bravdo et al. 1985, Intrigliolo and Castel 2010b, Mendez et al. 2011), can influence vine response to deficit irrigation. Mendez et al. (2011) observed that crop thinning at veraison decreased potential yield in the season it was undertaken but decreased the degree of negative effects of late-season deficit irrigation on yield and vine water status. Vine management guidelines aimed at improving vine recovery from previous season water deficits are somewhat limited by a lack of understanding of the mechanisms causing carry-over effects. For example, crop thinning has been suggested as a method to improve vine recovery by increasing carbohydrate reserves. Crop thinning at veraison tended to increase carbohydrate reserve concentrations under normal irrigation practices (Holzapfel et al. 2009). Bennett et al. (2005) observed increased inflorescence number per shoot and flower number per inflorescence associated with increased carbohydrate reserve concentrations. By contrast, Holzapfel et al. (2009) reported variable results with regard to yield and carbohydrate reserve concentrations and suggested that seasonal conditions and within-season carbohydrate production would have a greater impact on fruitfulness. Pech et al. (2010b) removed fruit from deficit irrigated vines by mechanical harvest near veraison. Initial results indicated that yield in recovery seasons was not significantly improved by crop removal in previous seasons. It should be noted that early season crop removal could encourage vegetative growth (Bravdo et al. 1985), particularly if soil water content is not limiting at the time, and ultimately exacerbate water deficits later in the season.

Nutrient status of grapevines is associated with soil moisture availability (Falcetti et al. 1995, Sipiora et al 2005). Visual monitoring (or tissue analysis) for symptoms of nutrient deficiencies in

recovery seasons should be undertaken. Applications of amendments such as seaweed fertilisers have been anecdotally linked to increased tolerance of water deficits but fertiliser applications during deficit seasons may exacerbate vine water stress by encouraging early season vegetative growth.

Edwards and Clingeleffer (2011) raised the possibility of multi-season irrigation strategies based on delays they observed in yield response to changes in irrigation strategies. For example, when 'double irrigation' vines were returned to the post-set RDI strategy for the final two seasons of the study, yield remained significantly higher than that of the RDI vines. Multi-season irrigation strategies certainly warrant greater consideration.

While this document has focussed on general grapevine yield responses to severe and long-term water deficits, consideration of varietal (scion and rootstock) differences in response to water deficits, including how well different genetic combinations recover from water deficits, is important. Sommer et al. (2010) showed that rootstock had a strong influence on vine yield under severe water deficits and in the subsequent recovery season.

6. Conclusion

Following a long-term study of regulated deficit irrigation, Edwards and Clingeleffer (2011) concluded that the practice of post-set RDI and prolonged deficit RDI did not result in progressive decline of Cabernet Sauvignon yields in the Sunraysia. Carry-over effects on yield of long-term prolonged deficit RDI were seen in the first recovery year, indicating that more severe water deficits may have a cumulative impact on vine recovery. On-going research regarding severe irrigation deficits will further add to our understanding of within-season vine responses to water deficits and recovery of vines in later seasons.

The results of Pech et al. (2010a,b) showed that extremely severe irrigation deficits (10 % of the Control) will delay vine recovery even when only imposed for one season but that substantial water-savings can be made, without delaying vine recovery, by applying slightly less severe deficits (20 to 50 % of the Control) for one season.

A wet 2010/11 season will shift grower focus from drought management to other vineyard issues. The opportunity to continue to improve our understanding of vine responses to water deficits should not be lost as severe drought conditions will undoubtedly be faced by the viticulture industry again. Continued support of on-going trials examining vine recovery, consideration of trials examining causes of carry-over effects and packaging of new information for the industry should remain a priority.

Reviews by Fereres and Soriano (2007) and Geerts and Raes (2009) demonstrate the importance of understanding crop water production functions to design of effective deficit irrigation strategies. The expression of results from current and future trials in the form of crop water production functions will improve the ability of growers to translate this information to predictions of yield reductions under various deficit irrigation strategies. Indeed, some of the difficulty associated with differing or even conflicting results in terms of vine responses to water deficits may lie in a poor understanding or expression of the degree of water deficit imposed.

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Appendix A. Summary of literature from projects related to grapevine recovery from severe or long-term water deficits

'Results' are summarised from those presented in the relevant reference. 'Conclusions' are summarised or directly quoted from the relevant reference and do not reflect interpretation of the results by the reviewers.

Project	**Integrating the carbon and water economies of grapevine for optimal management in challenging environments (UA 08/03)**
Reference	Pech, J.M., Hall, A.P., Strachan, R.L., Ratcliff, A.M., McCarthy, M.G. and Skewes, M.A. (2010a) *Resuming irrigation after severe reductions - effects on grapevine productivity*. 14th Australian Wine Industry Technical Conference, Adelaide, 3-8 July (poster).
Results	Site A (Qualco SA). After one season of cutback, yield of 50, 30 and 20 % treatment vines recovered to Control levels. Recovery of vines cutback to 10 % of the control was delayed indicating a negative carry-over effect at this level of cutback. Yield in the first two seasons was positively related to irrigation volume. Stomatal conductance and leaf water potential were affected by irrigation volume.
Conclusions	"A single season of reducing irrigation application to as low as 20 % of normal did not reduce yields in the subsequent season when irrigation returned to normal, however a 10 % reduction resulted in a negative yield impact in year 2 when irrigation returned to normal."
Reference	De Bei, R., Feuntes, S., Sullivan, S., Edwards, E., Wilkinson, C., Pech, J., Cozzolino, D., McCarthy, M. and Tyerman, S. (2010) *Carbohydrates reserve dynamics of Chardonnay grapevines as affected by water supply, drought and drought recovering regimes.* 14th Australian Wine Industry Technical Conference, Adelaide, 3-8 July (poster).
Results	Site A (Qualco SA). Data not shown for the 20 % cutback treatment. Trunk carbohydrate concentrations were monitored at harvest 2008/09 and at key phenological stages in 2009/10 up to harvest. Differences in total carbohydrates between irrigation treatments were evident at harvest in both seasons (differences at harvest in 2010 were only significant between the Control and 10% cutback treatments). Starch concentrations in each season at harvest were positively correlated with water applied.
Conclusions	"Returning stressed vines to adequate levels of water supply seemed to have almost recovered the carbohydrates concentration to the control levels within one season. The total storage per vine will be dependent on storage volume (i.e. wood volume) and it is clear that the treatments reduced vine size as reflected by the leaf area index measurements (data not shown)."
Reference	Pech, J.M., McCarthy, M.G., Ayres, M., Crocker, J., Orlando Wines, Skewes, M.A. (2010b) *Recovery of Cabernet Sauvignon Grapevines at Langhorne Creek after 3 years of severe irrigation cutback.* 14th Australian Wine Industry Technical Conference, Adelaide, 3-8 July (poster)
Results	Site B (Langhorne Creek, SA). Severe yield reductions occurred in response to irrigation cutback. Carry-over effects on yield were apparent even when irrigation was only reduced for one season. Recovery was gradual and vines subjected to one year of cutback had not reached Control yield levels in the third season (their second recovery season). Increased yield of the Control treatment in the third season was attributed to higher winter rainfall. Yield reductions were attributed to lower bunch set, smaller berries and bunch weights. Some non-irrigated rows did not produce a crop in seasons two or three. Crop removal "improved yields marginally when vines underwent recovery" and the positive effects of crop removal were greater after two seasons of crop removal than in the first season.
Conclusions	Vine recovery at Langhorne Creek "is retarded after multiple seasons of severe irrigation shortage". Costs of crop removal and possible mechanical damage to vines needs to be weighed against the "small advantages for vine recovery" of this practice.

Project	Optimising canopy function to increase yield while maintaining wine quality with efficient use of resources (CSP 05/01)
Reference	Edwards, E.J., Downie, A.F. and Clingeleffer, P.R. (2010) *Vine response to, and recovery from, multiple years of deficit irrigation.* Proceedings of the 14th Australian Wine Industry Technical Conference, Adelaide, 3-8 July, p. 182-187 (paper).
Results	In seasons **2005/06 to 2007/08**, the prolonged deficit treatment reduced yield by approximately 15 % and the double irrigation treatment increased yield by 20 % relative to the control (post-set RDI) - except in the first season when yield of double irrigation vines did not differ from yield of Control vines. Leaf area (not measured in the 2005/06 season) results mirrored yield with prolonged deficit vines having the smallest leaf area (on average prolonged deficit leaf area was 17 % lower than the Control) and double irrigation vines the largest (30 % higher than the Control). Leaf area effects were evident in the Control and prolonged deficit vines before RDI was imposed in a given season. In the final two seasons (**2008/09 and 2009/10**), when all treatments were irrigated as per the Control, leaf area effects were persistent in the prolonged deficit treatment but yield effects were lost by the second season. Yield of the double irrigation vines remained higher than the Control vines but leaf area was similar by the second season. Berry weight was the only yield component significantly affected by irrigation (and usually only for double irrigation vines). Merbein bunch counts (conducted in 2007/08 and 2009/10) indicated that treatments did not affect fruitfulness (including buds burst per vine, shoots per vine and fraction of shoots with bunches). Non-structural carbohydrates (NSC) in canes, cordons, trunks and roots were measured post-leaf fall in 2008. Cordon and trunk NSC was lower in prolonged deficit vines than double irrigation or Control vines. Sap flux, measured with sap flow sensors in 2007/08, was generally highest in the double irrigation and lowest in the prolonged deficit vines. Wine attributes were affected by irrigation treatments in vintages 2006 to 2009 with colour density, ionised anthocyanins and total phenolics being higher in prolonged deficit and Control treatments than the double irrigation treatment; in two of the vintages these attributes were higher for prolonged deficit than the Control but only anthocyanins were higher in the 2008 vintage. In 2009 there were no significant differences between prolonged deficit and Control wines. **Conclusions** Post-set RDI decreased leaf area and yield compared to well-watered (double irrigation treatment) vines. Prolonged deficit decreased these parameters further. However, there was no evidence of a cumulative negative effect on yield or canopy size over seasons. Effects on leaf area of Control and prolonged deficit treatments, prior to the RDI period in each season, may have been related to treatment effects on photosynthetic carbon gain due to decreased stomatal conductance in previous seasons and, subsequently, decreased carbohydrate reserves. However, results were not conclusive. Water use efficiency was calculated as yield per unit of water applied (WUE) and yield per unit of water transpired (CWUI) in 2007/08. WUE was lower for double irrigation vines (2.9 t/ML) than Control and prolonged deficit vines (5.2 and 5.6 t/ML, respectively). CWUI was similar for double irrigation and Control vines (39 and 38 t/ML respectively) and higher for prolonged deficit vines (54 t/ML), suggesting that the yield reduction of Control vines was in direct proportion to the reduction of transpired water relative to the double irrigation vines whereas the proportional reduction in transpired water was greater than the reduction in yield in prolonged deficit vines. Differences in transpired water between treatments were largely attributed to differences in leaf area. Further reductions in transpiration in the prolonged deficit treatment during the prolonged deficit period were attributed to decreased stomatal conductance. The authors suggest that, since decreased stomatal conductance would decrease carbon gain and there was no difference in soluble solids or foliage area:yield between treatments, the improvement in CWUI for prolonged deficit vines was likely to be linked to decreased carbohydrate reserves. Effects of double irrigation and prolonged deficit treatments on wine attributes were independent of yield and, in the case of the prolonged deficit treatment, berry size effects. “Finally, although [post-set] RDI resulted in improved wine colour compared with that of the [double irrigation treatment], further improvement with [prolonged deficit] was smaller and did not occur in every season.”

Reference	Edwards, E.J., Downie, A.F. and Clingeleffer, P.R. (2010) *Vine response to, and recovery from, multiple years of deficit irrigation.* 14th Australian Wine Industry Technical Conference, Adelaide, 3-8 July, (poster).
Results	Yield: "[Prolonged deficit] consistently reduced yield by 15 %. [Double irrigation] increased yield by 20 % except the first season. Treatment effects maintained in first recovery season. [Prolonged deficit] effect lost and [double irrigation] effect reduced in second recovery season." Growth: "Canopy size, pruning weight, trunk growth and root biomass were all affected by the treatments. There was a clear carry-over effect from one season to the next, with leaf production reduced by [prolonged deficit] despite the [prolonged deficit] treatment not being applied until canopy growth was complete." Water use: "87 % variation accounted for by a combination of [reference crop evapotranspiration (ET_o)], leaf area and soil moisture. Leaf level physiology (photosynthesis, water potential) largely unaffected prior to [prolonged deficit] treatment in a season. Physiology and ET_o response of sap flux affected during and after [prolonged deficit] treatment period within a season."
Conclusions	"The timing of even short periods of deficit irrigation can alter vine growth and production over multiple seasons even after standard watering is re-implemented."
Reference	Edwards, E.J., Lanyon, D.M. and Clingeleffer, P.R. (2008) *Below ground effects of deficit irrigation in Cabernet Sauvignon.* Eighth International Symposium on Grapevine Physiology and Biotechnology: Book of Abstracts*,* Adelaide, 23-28 November 2008, p. 88.
Results	A grid of nine cores taken from two replicates for each treatment prior to budburst in 2007/08 indicated that control vines had 18 % more and prolonged deficit vines had 32 % less biomass than the Control (post-set RDI) vines, mirroring effects on aboveground biomass in the previous season. Approximately 75 % of total root biomass was found in the top 50 cm of soil. Soil conductivity and pH were decreased in the control treatment.
Conclusions	"This work indicates that deficit irrigation can have a major effect on root biomass."
Reference	Edwards, E.J. and Clingeleffer, P.R. (2008) *Intra- and inter-seasonal effects of short-term water deficit on grapevine physiology.* Eighth International Symposium on Grapevine Physiology and Biotechnology: Book of Abstracts*,* Adelaide, 23-28 November 2008, p. 189.
Results	Within seasons 2006/07 and 2007/08, stomatal conductance and assimilation rates of leaves of prolonged deficit and Control (post-set RDI) vines were similar prior to the prolonged deficit period. During the prolonged deficit period conductance and assimilation were decreased in the prolonged deficit vines. Partial recovery occurred when soil moisture was increased to match the Control treatment but differences persisted until the onset of senescence. Leaf area index was lowest in prolonged deficit vines, even early in the growing season.
Conclusions	"A short period of water deficit had both inter- and intra-seasonal effects that lasted beyond the period of water deficit itself. The extent of these effects were seasonally dependent."

Reference	Edwards, E.J. and Clingeleffer, P.R. (2011) *Optimising canopy function to increase yield while maintaining wine quality with efficient use of resources. Final report to Grape and Wine Research and Development Corporation.*
Results	For full details see: www.gwrdc.com.au.
Conclusions	During this project there was no evidence of progressive decline in vegetative growth or yield capacity of Control (post-set RDI) or prolonged deficit treatments. The double irrigation treatment indicated post-set RDI decreased vegetative growth and yield. Yield and vegetative growth were decreased further by the prolonged deficit treatment compared to the Control. Historical data (unpublished) indicated that the decrease in yield and vegetative growth of the prolonged deficit vines occurred over a number of seasons before stabilising. Decreasing double irrigation treatment irrigation to Control levels indicated that post-set RDI effects can also take a number of seasons to be fully realised. Yield responses to increased water application in the double irrigation treatment were not evident in the first season it was imposed. Furthermore, increasing prolonged deficit irrigation to Control levels indicated that recovery from prolonged deficit can take multiple seasons. Persistence of yield and vegetative growth responses differed. The authors concluded that "the link between canopy size and yield ('vine balance') is broken in the period following a change in irrigation" and suggested that there may be value in using rotational, multi-year irrigation strategies. Irrigation strategies in previous seasons did not appear to influence leaf physiology. The authors concluded that "whole vine effects such as alteration of storage reserve pools, vine water use etc. were determined by longer-term effects of irrigation on growth and canopy structure rather than effects at the leaf level." The prolonged deficit period resulted in short-term water stress responses at the leaf level that extended (within the season) beyond the prolonged deficit period. This carry–over of responses led to continued reduction in carbon gain in prolonged deficti vines even when soil and plant water status were similar to other treatments. This response was also observed in trials with grafted Cabernet and Shiraz vines. The authors suggested that "by extending the RDI strategy with a greater than normal water stress over the entire RDI-PD duration, but less severely than imposed during the [prolonged deficit] period the intra-seasonal effect on leaf physiology would be less and the inter-seasonal effect on vine growth and production of the [prolonged deficit] strategy reduced." Fruit and wine attributes were altered by Control and prolonged deficit treatments in comparison to double irrigation, although soluble solids concentrations were not affected. In general, wine quality was more favourable under post-set RDI but prolonged deficit did not result in any further perceivable improvement.

Appendix B. Crop water production functions

Crop water production functions describe the relationship between yield and water supply and can therefore be used to predict yield under deficit irrigation. In order to normalise data for differences in yield potential and evaporative demand between seasons and locations, crop water production functions are often expressed using relative yield (yield/maximum yield, Y_a/Y_m) and relative water supply (actual water supply/potential evapotranspiration, (irrigation+rain)/ET_{max}) (Figure B1). The general form of these functions has been described by several authors (Hexem and Heady 1978, Doorenbos and Kassam 1979, Helweg 1991, Geerts and Raes 2009). Doorenbos and Kassam (1979) defined a yield response factor (ky) for crops exposed to seasonal water deficits, such that:

$$Y_a = [1 - ky.(1 - ET_a/ET_m)].Y_m \qquad \text{Eqn 1}$$

where ET_a is actual evapotranspiration, ET_m is potential evapotranspiration and ky = 0.85 for grapevines. However, this only applied to ET_a/ET_m between 0.5 and 1. Crop water production functions involving more severe deficits remain largely unknown for grapevines, at least in the terms described by Doorenbos and Kassam (1979).

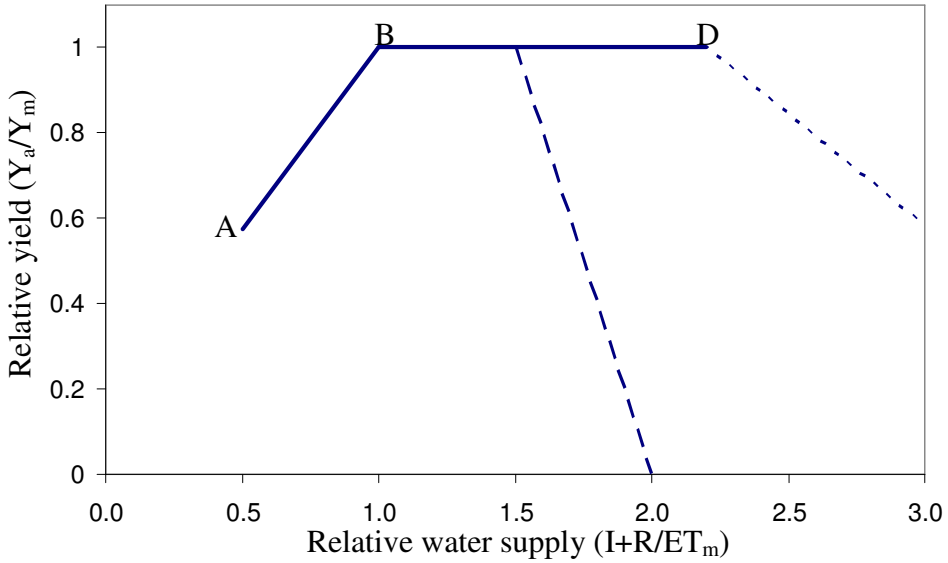


Figure B1. Grapevine crop water production function based on Doorenbos and Kassam (1979) and Clemmens and Molden (2007). Section A-B is based on the yield response factor (ky = 0.85) defined for grapevines by Doorenbos and Kassam (1979), section B-D represents maximum yield attained with water supply either matching or exceeding potential vine water use (ET_m). Clemmens and Molden (2007) explain that the point (C, D) at which crop yield begins to decrease due to excess water is largely dependent on soil properties and thus is more site-specific than the yield-water deficit response.

Grimes and Williams (1990) determined crop water production functions based on studies of Thompson Seedless grapevines in California and presented their results in terms of relative yield and relative crop evapotranspiration. While several other authors present data indicating positive relationships between grapevine yield and ET_a or water supply (van Rooyen et al. 1980, Shellie 2006, Chalmers 2007, Intrigliolo and Castel 2008, 2010a, 2010b, Williams et al. 2010) they seldom normalise these responses for Y_m or ET_m, limiting the ability to predict yield responses to deficit irrigation in seasons or environments different to those used in the studies.