Managing the impacts of climate change rainfall decline on vine balance and root activity



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1 ABSTRACT

This project determined the impact on vine performance of irrigation strategies to mitigate low rainfall during winter. Rainfall was excluded using shelters between May and August. Despite top-up winter irrigation to a similar level as average winter rain, a reduction in yield was still observed. Applying irrigation to refill the soil profile in spring generally stimulated vine growth, which negatively affected grape and wine composition without restoring yield. Reduced winter rainfall (one third of average) improved grape and wine composition at the cost of a significant drop in yield. Growers are advised to maintain soil moisture using irrigation throughout winter.

2 EXECUTIVE SUMMARY

In many Australian wine regions, grapevine production relies on soil moisture stored during the winter in addition to supplementary irrigation during the growing season. The combination of winter rainfall decline and restricted water for irrigation (~ 1.5 ML/ha per season) will place increasing strain on these production systems.

This study investigated the effects of winter rainfall exclusion and rainfall replacement options on (i) vine balance, (ii) fruit quality parameters, (iii) wine chemical and sensory characteristics, (iv) root growth and (v) carbohydrate reserves storage. The project commenced in 2013 with the installation of the field trial (shelters and irrigation system); and the results from the 2015/16 to the 2017/18 inclusive are included in this report.

Three seasons of results showed that a reduction in winter rain is associated with major changes in grape production. Despite top-up winter irrigation either using sprinklers or drippers to a similar level as natural winter rain, a reduction in yield was still observed. This is likely to be due to the irregular soil pattern of wetting caused by the irrigation and its influence on root growth and longevity and then vine performance. Unfortunately, root growth and development are very difficult to accurately assess. The irrigation to refill the profile at budburst generally stimulated vine growth across most measured parameters, which negatively affected grape and wine composition without restoring yield. Reduced winter rainfall (in the lowest two deciles) improved grape and wine composition at the cost of a significant drop in yield in the two dryer seasons.

If water is available for irrigation during a dry winter, growers are recommended to maintain soil moisture throughout the season as opposed to waiting until budburst to refill the soil profile. Further research is needed to explore alternative application times and methods which can fully compensate for the yield loss as a result of a reduction in winter rainfall.

This project was completed as a collaboration between the South Australian Research and Development Institute and the Commonwealth Scientific and Industrial Research Organisation. It was supported by Australian grapegrowers and winemakers through their investment body Wine Australia, with matching funds from the Australian Government. The Commonwealth Scientific and Industrial Research Organisation and the South Australian Research and Development Institute are members of the Wine Innovation Cluster in Adelaide.

3 BACKGROUND

Projections from climate change models and trends in data observations (Cai and Cowan 2008) indicate that temperatures will increase and rainfall decline in most winegrowing regions in Australia. While there is less confidence in predictions of rainfall than for warming, observations suggest that rainfall will decline more in autumn and winter than for summer (Murphy and Timbal 2008). In most premium Australian growing regions the average rainfall is significantly greater than the irrigation; and the latter amount is usually less than 1.5 ML/ha (equivalent to 150mm rainfall) during the growing season. The grapevine growth and production in these regions relies on soil moisture stored during the winter, in addition to supplementary irrigation during the growing season. This means that any long term decline in rainfall (even during winter) is likely to need to be replaced with irrigation; drawing from already limited water supplies.

Mendez-Costabel, et al. (2014) demonstrated significant long term impacts of reduced winter rainfall on vine performance, even when vines received irrigation during the growing season. After winter rainfall was excluded for three years there were negative impacts on vine balance as demonstrated by a doubling of the yield to pruning weight ratio which in turn effected fruit and wine quality. The volume of water excluded by Mendez-Costabel, et al. (2014) was less than the total winter/spring rainfall in many Australian vineyards, highlighting the real threat that reduced winter rainfall can have on vine balance and fruit quality. Anecdotal evidence suggests that restricted spring growth, sometimes reported in the Murray valley is a result of soil water deficit during the autumn and winter, possibly due to impacts of the dry conditions on root physiology during dormancy.

Soar and Loveys (2007) highlighted the relationship between water availability in drip irrigated portion of the under vine area and root distribution. Roots are maintained in the inter-row area although it may have a very low soil moisture during summer. During dry winters, drip irrigation isn't able to provide water to a large proportion of the rootzone and the impact of this on vine performance hasn't been investigated.

Sustainable rootzone salinity management is also dependent on sufficient rainfall in winter and early spring to leach salts that are applied as part of irrigation (Stevens, et al. 2013). If reduced winter rainfall means that this is not achieved (as experience during the millennium drought) will impact on productivity and product quality (de Loryn, et al. 2014).

4 PROJECT AIMS AND PERFORMANCE TARGETS

1. Large scale field experiment using rainout shelters to simulate reduced winter rainfall.

Use existing and projected climate information to calculate winter rainfall deciles and place the recent drought in context. This information will be used to establish levels of rainfall exclusion in the field experiment.

2. Effect of winter drought on vine growth and development.

Examine the impacts of dormant season soil water deficit on root growth and vine storage reserves thought the use of existing sampling protocols and mini-rhizotron.

3. Effect of winter rainfall decline on vine balance and grape and wine composition.

Quantify the annual and cumulative effects of reduced winter rainfall on vine balance, fruit and wine composition and wine sensory characteristics.

4. Irrigation management strategies against drier winter.

Integrate seasonal rainfall outlook and impacts of reduced rainfall on vine balance into appropriated management strategies for growers to help minimise impacts of winter rainfall deficits

5. Package information into clear adoptable messages and outcomes for Australian grape growers.

Present project learnings at grower workshops, industry conferences and by publications.

5 A LARGE-SCALE FIELD EXPERIMENT TO SIMULATE REDUCED WINTER RAINFALL.

5.1 Introduction

The trial was established in 2013 in the SARDI's Nuriootpa research station (34 ^{o}S, 139 ^{o}E) in the Barossa Valley of South Australia. The climate in this region is characterised by moderate rain, predominantly in winter, and high summer evaporative conditions (Dry, et al. 2004). The mean January temperature (MJT) is 21.2 ^{o}C and the average annual rainfall is 502 mm. The experimental site has a duplex soil with sandy loam to loam top soil down to 30 cm over a restrictive red clay subsoil from 40 cm (Maschmedt 2004) (Figure 5:1). The Shiraz vines (BVRC30) were planted on own roots in 1998. The row width is 3 m and the vines were planted at 2.25 m apart. The vines were trained to a single cordon, hand pruned and mechanically harvested until the beginning of the trial.

5.2 Treatment details

Five treatments were established with the aim to exclude and then replenish winter rainfall using drippers or sprinklers (Figure 5:2). Treatments were: 1) vines exposed to natural rainfall (*control*) with top-up irrigation using sprinklers, if necessary, to match mean May-August rainfall; 2) rainfall exclusion with irrigation to maintain a wet soil profile throughout winter using sprinklers to irrigate the whole vineyard floor (*sprinkler-rain*) or 3) under the vine using drippers (*dripper-rain*); 4) rainfall exclusion with reduced irrigation using sprinklers (30% of *sprinkler-rain* treatment) applied throughout the winter (*reduced-rain*) and 5) rainfall exclusion with irrigation using sprinklers applied at budburst to *refill* the soil profile (*spring-rain*). The treatments were arranged in a randomised complete block design with four replications (Figure 5:3).



Figure 5:1 Duplex soil with thin sandy loam topsoil over a non-restrictive clayey subsoil from 40 cm.

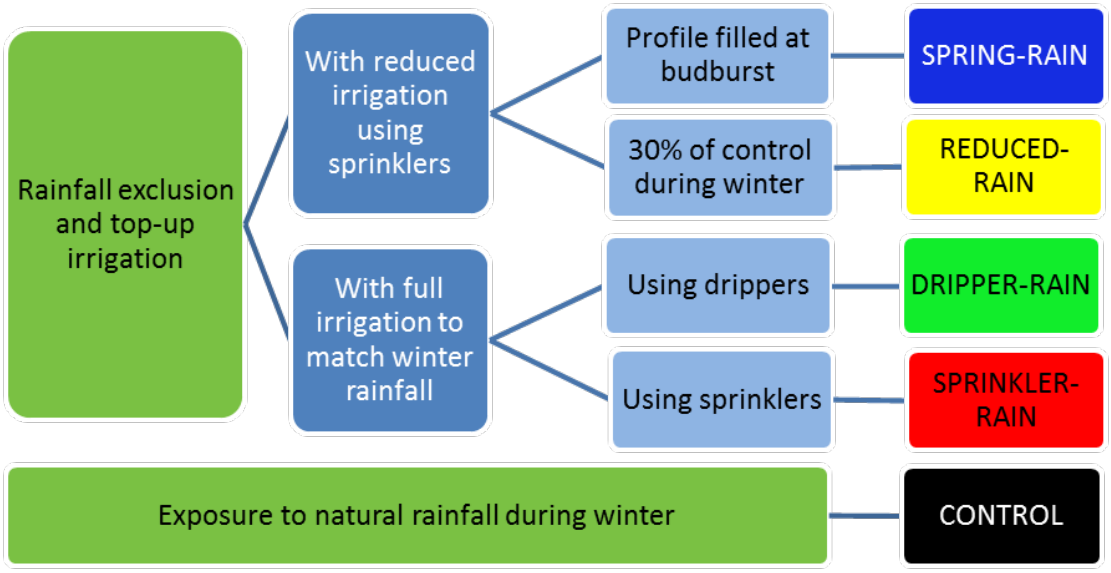


Figure 5:2 Schematic representation of the treatments.

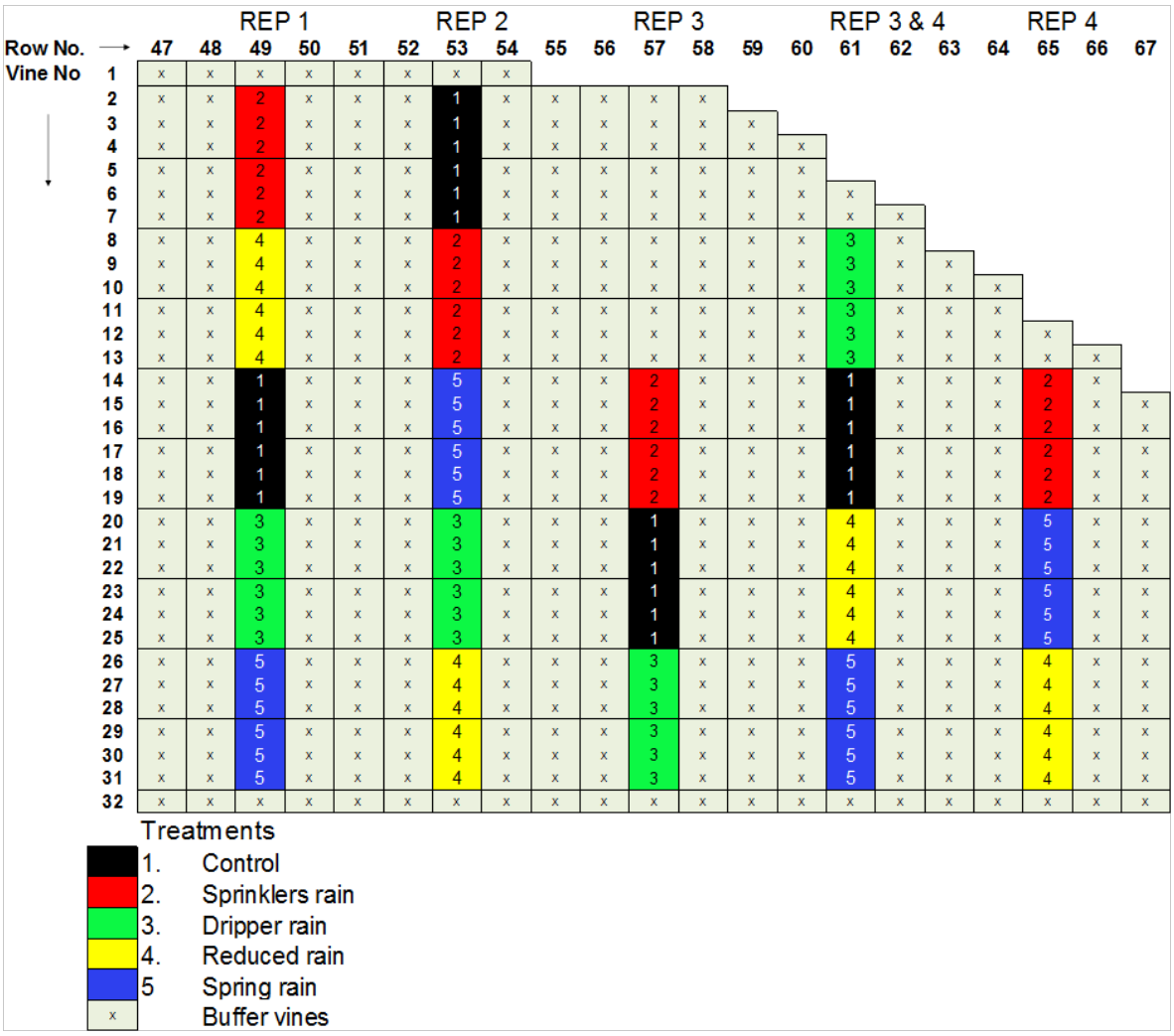


Figure 5:3 Experimental design

5.3 The large-scale rainfall exclusion system

Shelters were used to exclude rainfall from May to August. Figure 5:4a shows an overview of the system, which consists of modular tunnel units (13 m length x 6 m wide x 2.95 high) supported by 50 mm square galvanized steel tube and covered with 210 micron greenhouse film. The walls of the units were left uncovered to allow for free air circulation. Each module covered one central row with the experimental vines and two adjacent rows used as buffers (Figure 5:4b). A drainage system, which consisted of galvanized steel gutters and 100 mm PVC tubes, was installed on each side of the unit to direct rainwater away from the vineyard (Figure 5:4c).

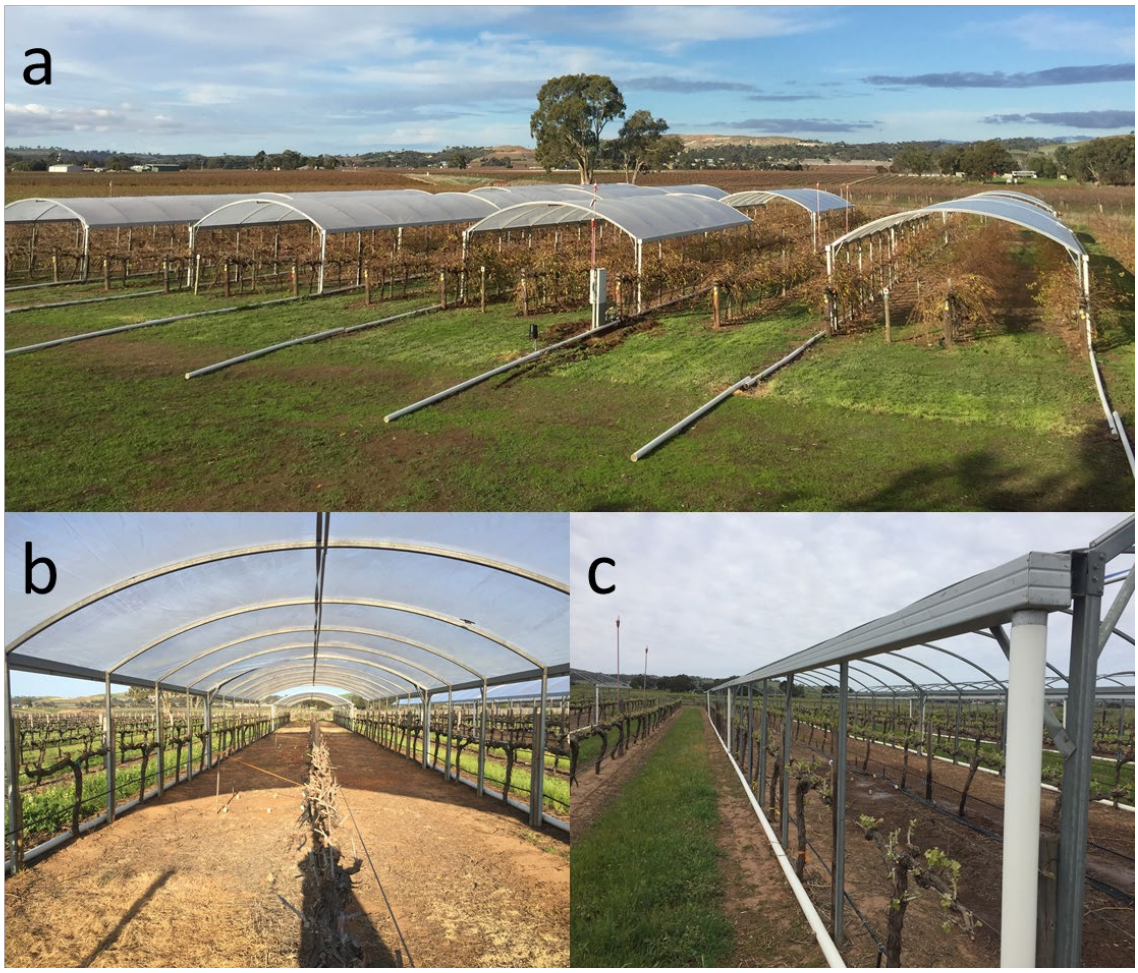


Figure 5:4 Rainout shelter deployed in the vineyard during from May to August.

a) panoramic view of the shelters after their installation in late autumn 2016. b) inside the shelter viewed in mid-winter. c) details of drainage system.

5.4 Rain and supplementary irrigation

The volume of irrigation applied to the *dripper-rain* and *sprinkler-rain* treatments was calculated from average winter rainfall for Nuriootpa (Bureau of Meteorology 2016). The accumulated monthly mean rainfall from May to August in the period 1952-2015 corresponded to approximately 230 mm (Figure 5:5). Irrigation was also applied to the *control* treatment in the event that natural rainfall during winter did not reach the May-August average.

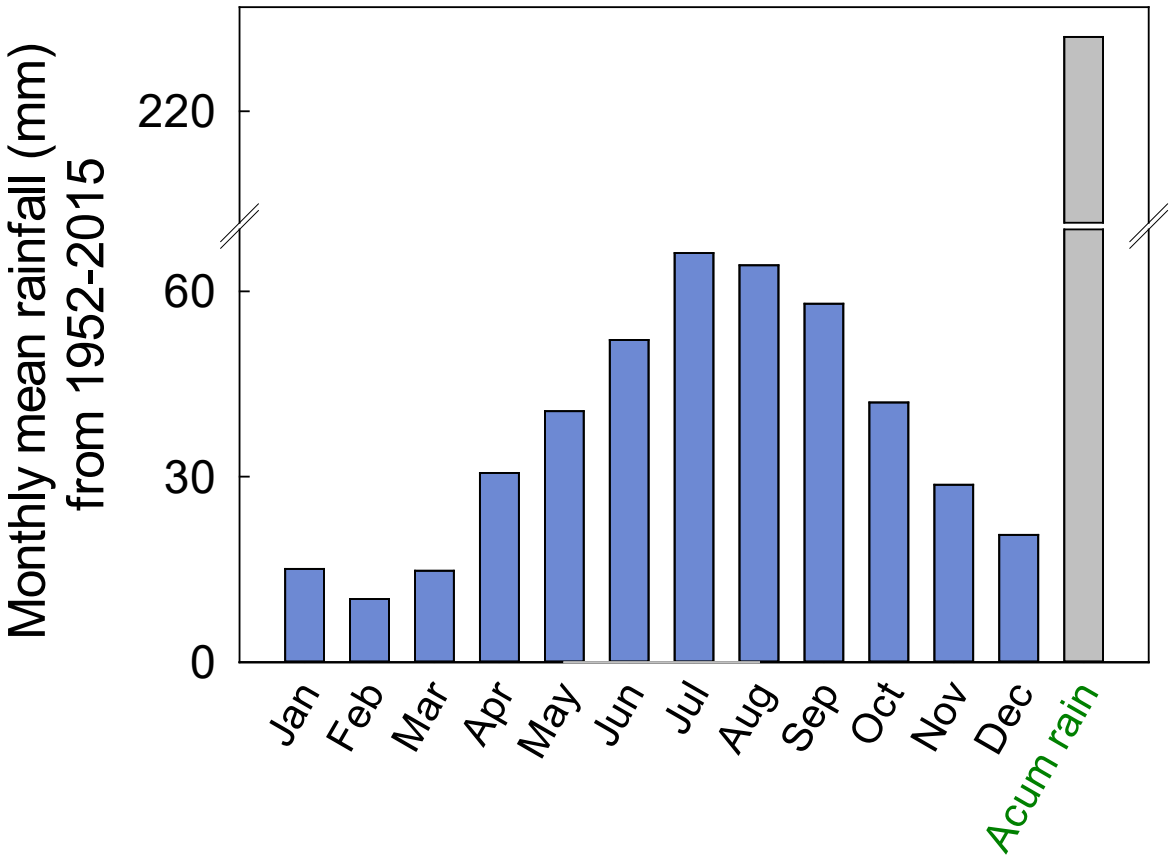


Figure 5:5 Monthly distribution of mean rainfall at the SARDI's Nuriootpa Research Station, SA. Blue bars correspond to mean values for the period 1952-2015, grey bar is the accumulated rain for May to August. Data sourced from the Bureau of Meteorology (2016).

Irrigation for *reduced-rain* vines corresponds to the accumulated May to August rainfall from decile one of the monthly rainfall distribution for the period 1952-2015 (Bureau of Meteorology 2016). The volume of irrigation applied in *spring-rain* treatments corresponded to 150 mm, which is the volume of water necessary to fill the soil profile up to one-meter depth with minimum or no leaching (McCarthy, et al. 2004).

Differential irrigation was applied during the dormant period from May to August. In sprinkler treatments, i.e. *control*, *sprinkler*- and *spring-rain*, the irrigation system consisted of under-vine microjets (Waterbird VI-PC, Toro Ag Irrigation, Beverley, SA, Australia) spaced at 2.25 m alongside the central row of each replicate. For the drip treatment, i.e. *dripper-rain*, a system was installed with a drip line equipped with 2.3 L/h drippers spaced at 0.3 m. During the growing season (from budburst to leaf fall) all the treatments were irrigated using one lateral with pressure-compensated button drippers spaced at one metre interval. Vines were watered at a flow rate of 6.6 L/h per vine, during approximately 24 h per irrigation event based on calendar applications.

5.5 Performance of the system

We assessed the performance of the system based on its capability to effectively exclude rainfall and its effects on soil and air temperature. The shelter was deployed in the field during the dormant period, around leaf fall, and removed just prior to bud burst. There was therefore no secondary effect of the plastic film producing altered intercepted radiation on growing shoots (Berli, et al. 2013).

Soil temperature was continuously measured and recorded approximately every 30-min using thermistor based soil temperature probes (Measurement Engineering Australia, Magill, SA), located at three depths, i.e. 30, 60 and 90 cm (Figure 5:6a and b). Air temperature was measured continuously and recorded at 15-min intervals using shielded TinyTag sensors (Ultra2 loggers, Hastings Dataloggers, Port Macquarie, New South Wales, Australia). Sensors were located at trunk level in the centre of each replicate on both vines exposed to natural rain and vines under the rainout shelters (Figure 5:6c).

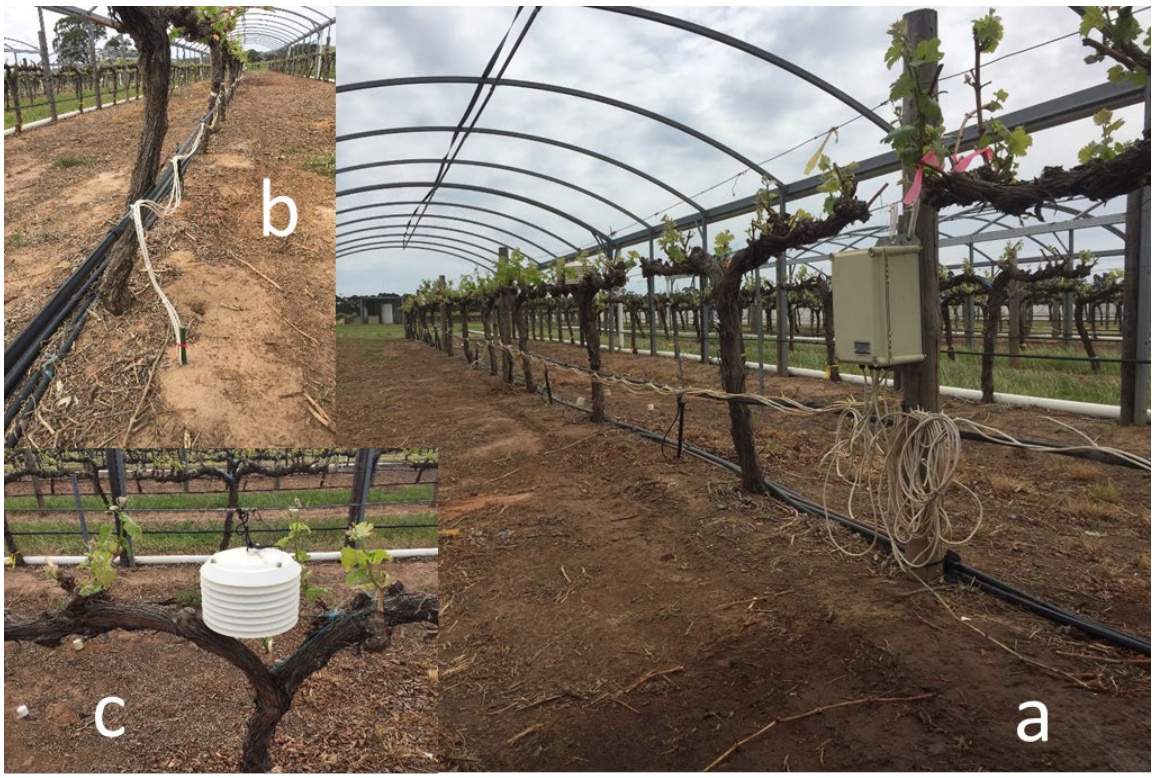


Figure 5:6 Detail of soil and air monitoring system. a) Logging system. b) soil temperature probes positioned adjacent to the central vine of each replicate at three depths (30, 60 and 90 cm). c) shelter containing sensors for air temperature and relative humidity.

The rainout shelters were effective in reproducing daily cycles of temperatures. Comparison of daily records between May to August shows the air under the shelters was only slightly higher in temperature than ambient air at night time (Figure 5:7a). The temperature every 15-min aggregated over a 4-month period captured the effect of higher air temperature at

night time under the shelter (Figure 5:7b). However, there was no significant difference in daily temperatures between ambient and air under the shelters (Table 5:1). Therefore, the biological impact of a transient night time 0.6 ºC increase in air temperature under the shelter on vine development could be mostly dismissed.

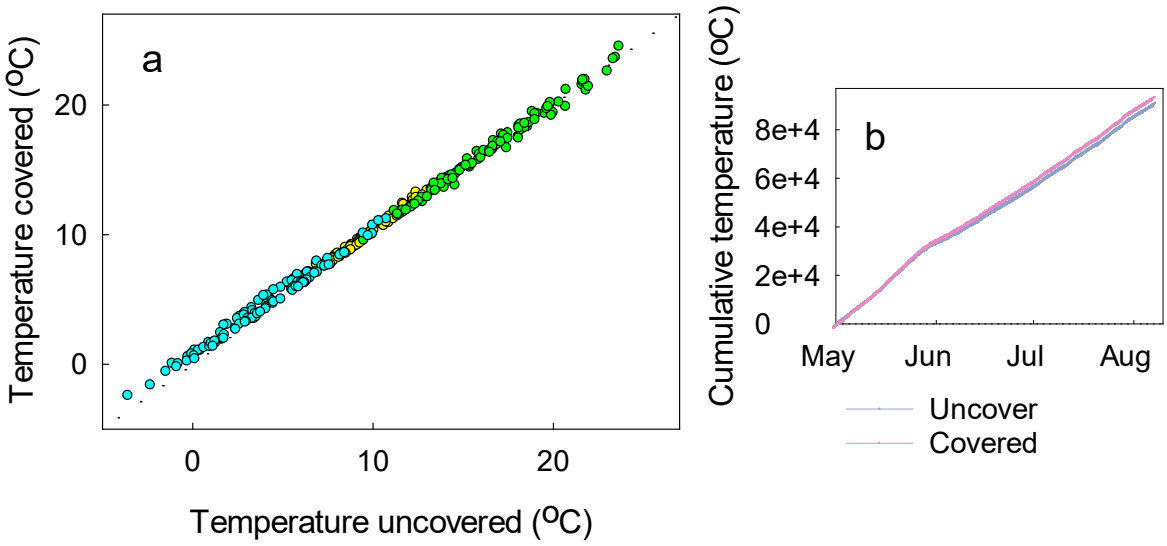


Figure 5:7 Comparison of (a) temperature in covered and uncovered rainout shelters from May to August 2017. Each point is the average of three independent replicates representing minimum (cyan), mean (yellow) and maximum (green) daily temperatures. Reference line corresponds to y = x. (b) shows cumulative temperature between the establishment (late April) and removal of the shelter (early September).

Table 5:1 Daily average air temperatures at vine cordon level recorded from May to August 2017 on vines exposed to natural rain (uncovered) and under the rainout shelters (covered).

Treatment	Minimum temperature	Mean temperature	Maximum temperature
Uncovered	3.8 ± 0.3	9.7 ± 0.2	16.7 ± 0.3
Covered	4.4 ± 0.3	10.0 ± 0.2	16.8 ± 0.3
p value	0.155	0.272	0.838

Soil temperature is most likely influenced by the irrigation treatments, as irrigation will impact on the soil moisture content and in turn its thermal mass and conductivity. During winter the soil in the *spring-rain*, which was also the driest treatment, was the warmest. This trend was reversed in spring when a significant quantity of irrigation was applied to the treatment (Figure 5:8). During summer most of the treatments had similar soil temperatures, except for a short period when the reduced-rain treatment (at 60cm) was warmer than the others. This period coincided with an increased level of water stress for these vines (Figure 5:10).

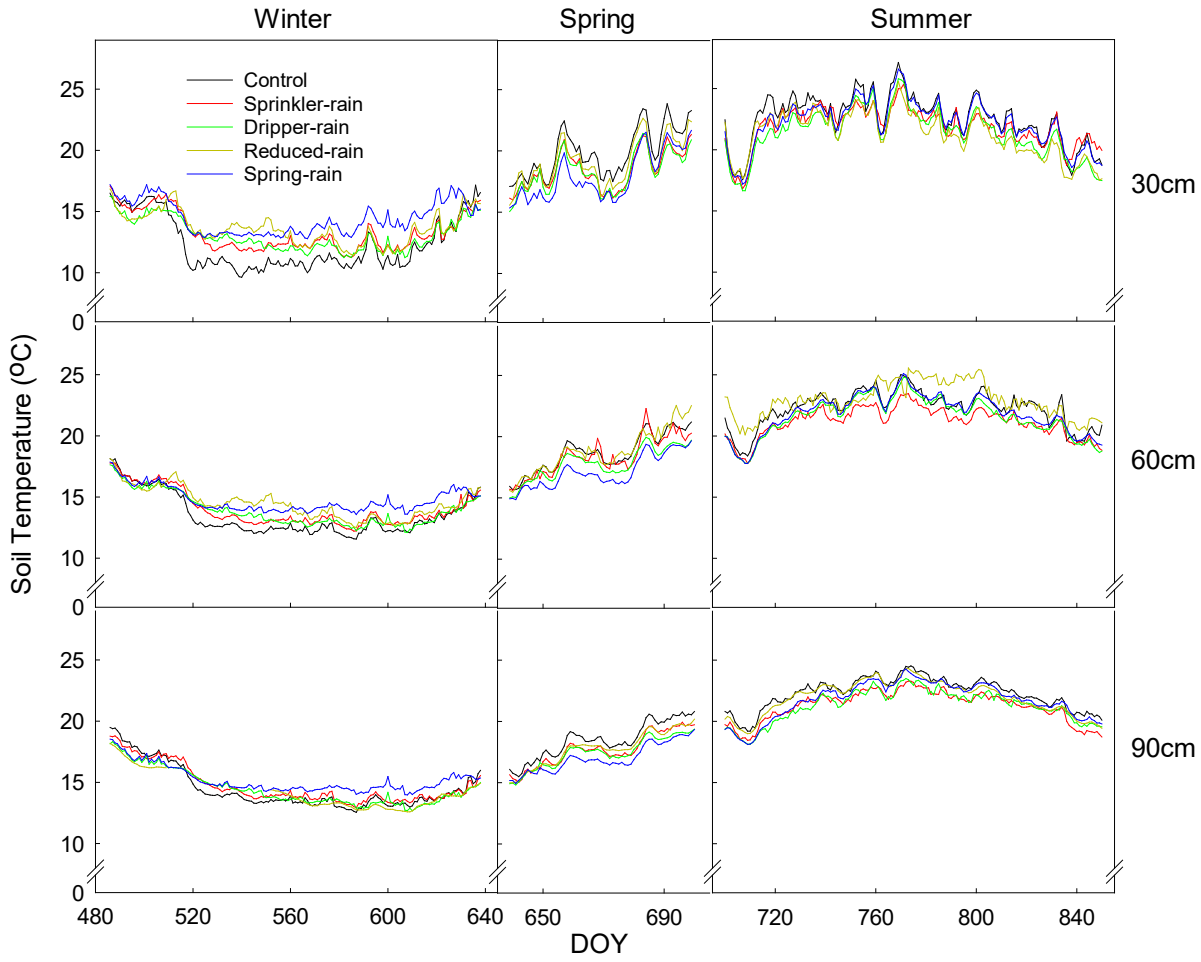


Figure 5:8 Daily average soil temperatures across irrigation treatments recorded at three depths during season 2017/18. In this figure, *Winter* corresponds the period of rainfall exclusion and top-up irrigation, from May to September; *Spring* is the period between October and November, and *Summer* between December to April.

5.6 Plant water relations and gas exchange measurement

Vine water status was assessed using a Scholander type pressure chamber (PMS Instruments, Model 1005, Albany, OR, USA) using the procedures of Hsiao (1990).

Integral water stress ($S\Psi$) was calculated as described in Myers (1988) from the summation of mid-day stem water on every day during each season. Larger $S\Psi$ relates to larger accumulated water stress during the season (Myers 1988).

An LI-6400 gas exchange system (LI-COR, Lincoln, USA) was used to monitor assimilation (A), and stomatal conductance (g) of mature leaves. These measurements were carried out at four times during the same day (9:00am, 11:30am, 2:00pm and 4:00pm) at three points during the season 2016/17 (pre-veraison, veraison and pre-harvest) and four points during the season 2017/18 (pea-size, pre-veraison, veraison and pre-harvest). Two leaves from different vines were taken from each of the three more contrasting treatments, i.e. *control*, *reduced*- and

spring-rain, across three field replicates. Stem water potential was also measured in an adjacent leaf from the same shoot at the time of gas exchange measurements. The CO_2 concentration of the incoming air was maintained at 400 μ mol/mol. The sensor head block temperature and leaf illumination were set to match ambient levels at the beginning of each set of measurements. We presented here dynamics of A and g during both seasons from measurements taken around mid-day, i.e. 11:30am.

5.7 Growing conditions seasons 2015/16, 2016/17 and 2017/18

5.7.1 Winter irrigation treatments

Table 5:2 shows details of irrigation treatments during winter 2015, 2016 and 2017. There were only minor differences between the calculated and the actual volumes of water applied (Figure 5:9a, c and e). *Control* vines exposed to natural winter rain received a total of 257 mm in 2015, 309 mm in 2016 and 274 mm during winter of 2017. Supplementary irrigation was applied to *control* vines in the dry winters of 2015 (91 mm) and 2017 (65 mm) to achieve close to the long-term average for this site (Figure 5:9a and e, and Table 5:2). Water applied was similar between *control* and top-up irrigation treatments either with *sprinkler-rain* or *dripper-rain* on the three years (Figure 5:9a, c and e). *Sprinkler-rain* vines received 246 mm in 2015, 227 mm in 2016 and 230 mm in 2017, whereas, *dripper-rain* vines received 209 mm in 2015, and 229 mm in 2016 and 2017 (Figure 5:9a, c and e). During the three seasons, the number of irrigation events for these treatments ranged between 12 to 17 and between 12.3 and 20.5 mm were applied at each irrigation event (Table 5:2).

Table 5:2 Detail of irrigation treatments during winter 2015, 2016 and 2017.

Irrigation	Control	Sprinkler-rain	Dripper-rain	Reduce-rain	Spring-rain
Winter 2015					
Date first irrigation	30/06/2015	2/06/2015	2/06/2015	5/07/2015	30/09/2015
Date last irrigation	14/07/2015	3/09/2015	10/09/2015	26/08/2015	20/10/2015
Number of irrigation events	7	12	17	2	4
Lenght of irrigation (hours)	4.8	7.5	11.2	13.6	13.9
Frequency	Weekly	Weekly	Weekly	Monthly	Weekly
Water applied per irrigation (mm)	13.0	20.5	12.3	37.2	34.6
Winter 2016					
Date first irrigation	-	30/05/2016	30/05/2016	7/07/2016	21/09/2016
Date last irrigation	-	1/09/2016	1/09/2016	2/09/2016	19/10/2016
Number of irrigation events	-	14	15	3	6
Lenght of irrigation (hours)	-	5.9	13.9	9.1	9.5
Frequency	-	Weekly	Weekly	Monthly	Weekly
Water applied per irrigation (mm)	-	16.2	15.3	25.0	26.0
Winter 2017					
Date first irrigation	25/06/2017	8/06/2017	8/06/2017	10/07/2017	22/09/2017
Date last irrigation	10/07/2017	6/09/2017	7/06/2017	13/09/2017	27/10/2017
Number of irrigation events	4	14	14	3	6
Lenght of irrigation (hours)	6.5	6.9	15.3	9.2	9.9
Frequency	Weekly	Weekly	Weekly	Monthly	Weekly
Water applied per irrigation (mm)	15.7	16.5	16.4	25.1	25.5

Compared to the long-term average rainfall, over the three years the *reduced-rain* treatment received approximately 33% (approx. 75 mm) and *spring-rain* 66% (approx. 152 mm) of the water applied (Figure 5:9a, c and e). Irrigation in *reduced-rain* vines was applied in two irrigation events of 37 mm each in winter 2015 and in three irrigation events of 25 mm each during winter 2016 and 2017 (Table 5:2). Similarly, starting at budburst, four irrigation events of 35 mm each were applied to *spring-rain* vines during winter 2015, and six irrigation events of 26 mm each in 2016 and 2017.

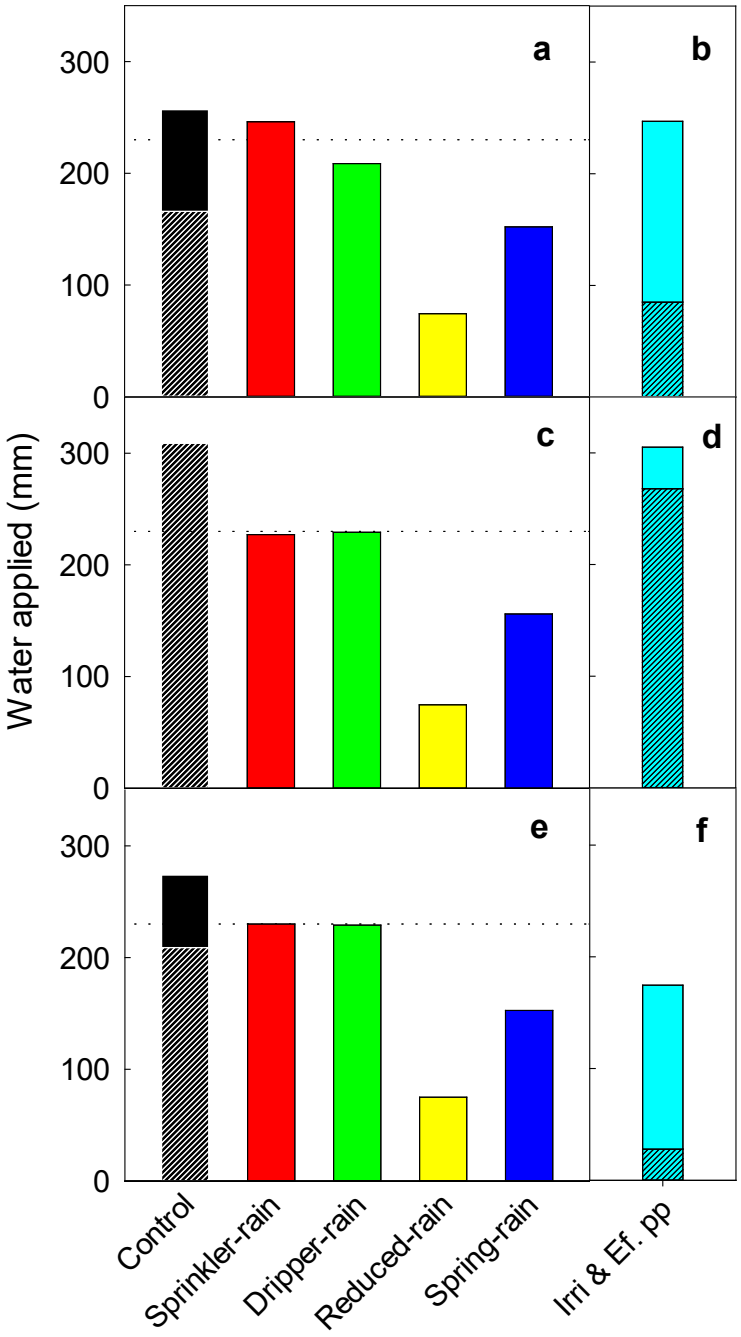


Figure 5:9 (a, c and e) Water received by each irrigation treatment from May to September, and (b, d and f) from October to April during seasons (top) 2015/16, (middle) 2016/17 and (bottom) 2017/18. On the stacked bars, the lined bar corresponds to rain (a and e) and to effective rain – > 10 mm – (b, d and f), and solid bar to supplementary irrigation. The horizontal dotted line indicates the accumulated average rain from May to August (230 mm) during the period 1952-2015 in Nuriootpa, SA.

From October to April seasons 2015/16 to 2017/18 the treatments were irrigated according to standard industry practices; using drip irrigation at a flow rate of 6.6 l/h per vine, and irrigation events of approximately 12 h. Overall, water supply during the summer was similar to the industry standard in the area of study; with effective rainfall (> 10 mm) and supplementary irrigation totalling 247 mm in season 2015/16, 305 mm in season 2016/17 and 175 mm in season 2017/18 (Figure 5:9b, d and f).

5.7.2 Characterisation of vine water status

The mid-day stem water potential reflected the patterns of soil drying and wetting during the contrasting rainfall conditions of seasons 2015/16, 2016/17 and 2017/18 (Figure 5:10a). As observed on Figure 5:10b, the lack of rainfall during the spring of 2015 (71 mm) lead to early signs of water stress (Figure 5:10a). Stem water potentials between -1.1 and -1.3 MPa were reached around berry pea-size and maintained until approximately veraison, when more frequent irrigation was applied to avoid damage to the canopy. In contrast to this, greater rainfall in the spring of 2016 (232 mm) allowed the vines to maintain a lower water potential beyond berry pea-size, and to developed signals of water stress (-1.2 MPa) later in the season from around veraison. In the season 2017/18 spring rainfall ranged around the 130 mm long term average (109 mm) and supplementary irrigation was needed from around veraison. Mild water stress conditions (around -1.1 MPA) developed late in the season from veraison to harvest.

Significant differences in stem water potential between treatments were only detected early in the season 2015/16 around berry pea-size, when *reduced-rain* vines were more water stressed (Figure 5:10a). Likewise, vines from reduced-rain treatments were significantly more water stressed from anthesis to approximately berry pea-size during the season 2016/17, and from around anthesis to early berry ripening in the season 2017/18. Nevertheless, as suggested by the water stress integral (Figure 5:11a and b), there were no significant differences between treatments during the entire growing season during seasons 2015/16 and 2016/17, but there was a significant carry over effect of reduced rainfall in winter on vine water status during the 2017/18 season.

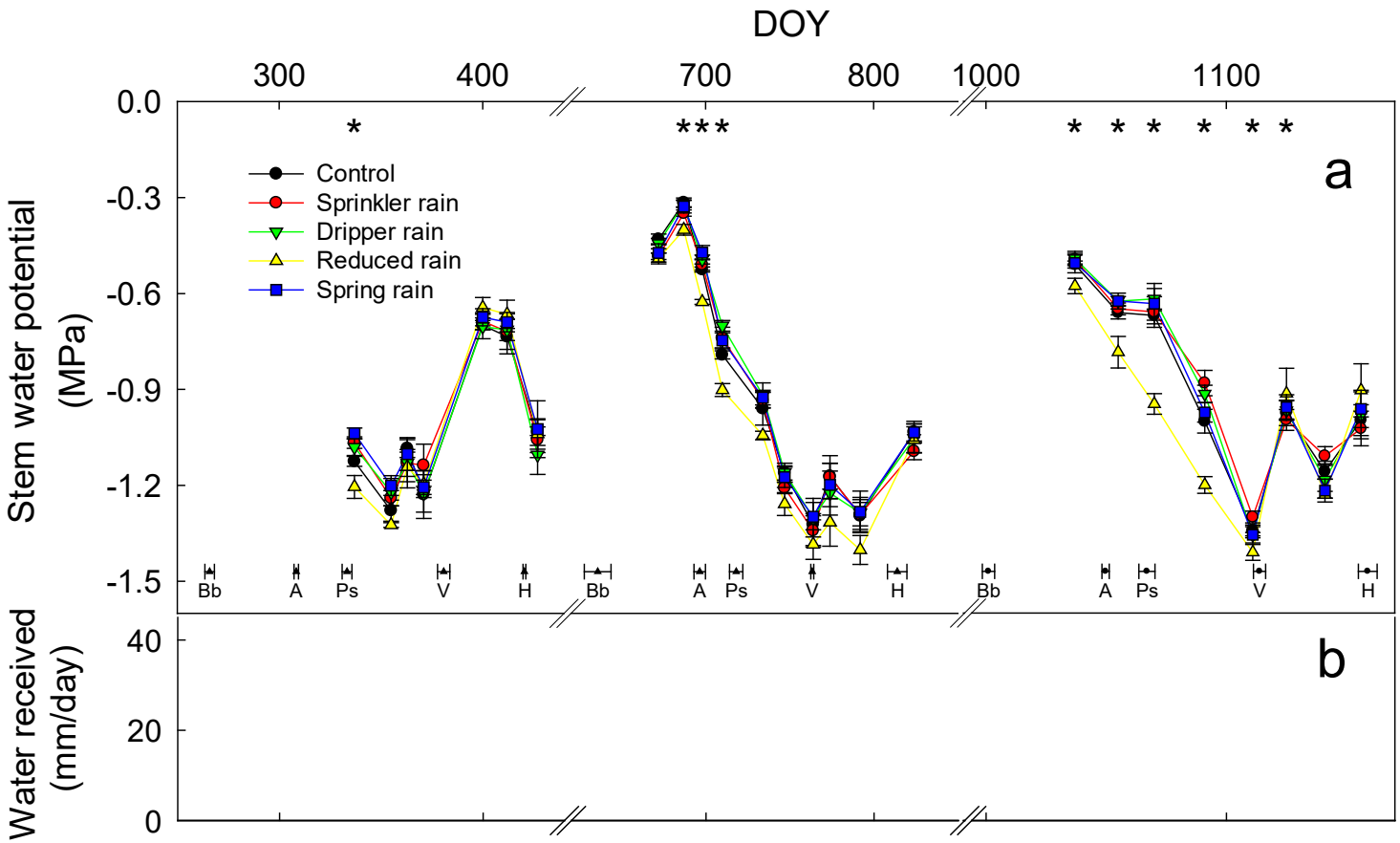


Figure 5:10 (a) Dynamics of mid-day stem water potential of Shiraz vines subject to a range of winter irrigation treatments in chronological time (DOY, days of the year from 01/01/2015). Data are mean from four field replicates. Black circles indicate key phenology stages (mean ± SD): budburst (Bb), anthesis (A), berry pea size (PS), veraison (V) and harvest (H). (*) indicate significant difference between irrigation treatments from the one-way ANOVA at a $p < 0.05$ significant level. (b) water received during the growing season from irrigation (blue bars) and rainfall (cian bars).

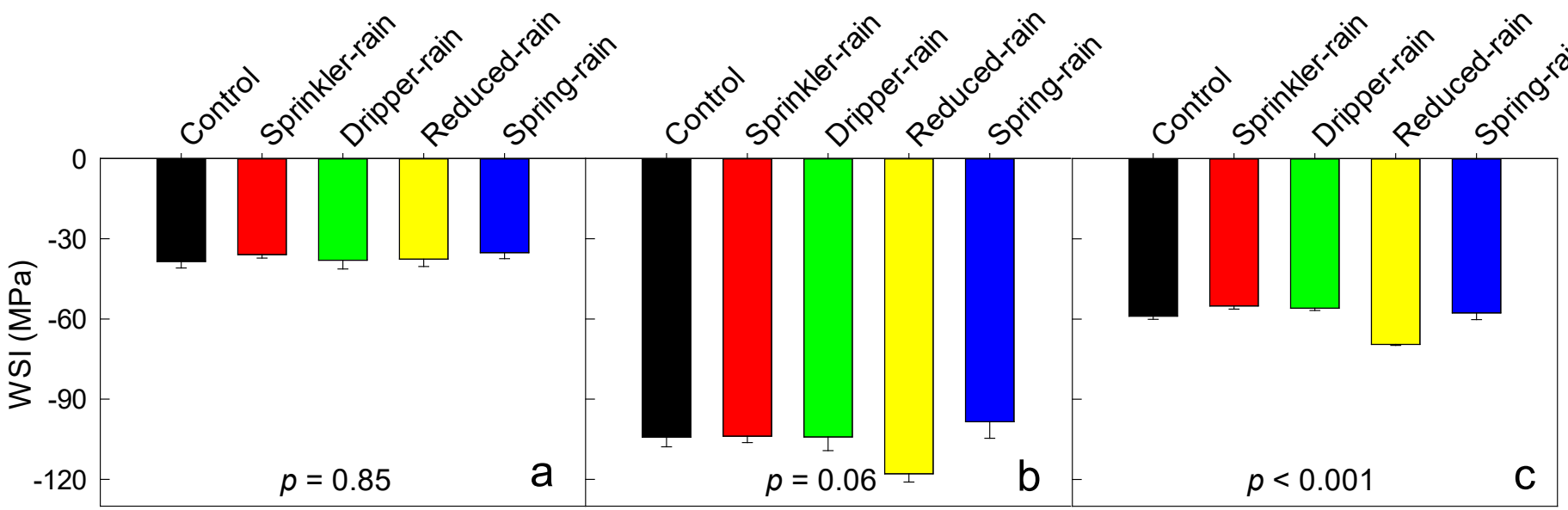


Figure 5:11 The cumulative integral of mid-day leaf water potential over the growing period of Shiraz vines exposed to different irrigation treatments during winter and early spring of 2015/16 (a), 2016/17 (b) and 2017/18 (c). Error bars are one standard error of the mean. *p* values are from analysis of variance (ANOVA).

5.7.3 Vine gas exchange

The stem water potential declined during the season as soil water content decreased from spring to summer months (Figure 5:10 and Figure 5:12). Differences in stem water potential between *reduced-rain* vines and *control* and *spring-rain* vines lasted for most of the ripening period in season 2016/17 (Figure 5:12a) and up to around veraison in season 2017/18 (Figure 5:12b). Overall, stomatal conductance and photosynthesis was lowered in reduced-rain vines at any measured time in season 2016/17 (Figure 5:12c and e) and in the early stages of season 2017/18 (Figure 5:12d and f). Differences in stomatal conductance and photosynthesis between *control* and *spring-rain* vines become apparent during the ripening period. Consistently during both seasons, leaves from *spring-rain* vine showed lower CO_2 assimilation rates pre-harvest (Figure 5:12c and d). Although gas exchange measures at a leaf level cannot be extrapolated to the whole canopy, this reduction of CO_2 assimilation rate observed in *spring-rain* vines during ripening, coupled with the reduction of canopy size suffered by the vines in this same period (Figure 6:7), may explain in part the reduced yield observed for this treatment at harvest in 2017 and 2018 (Figure 7:1).

5.7.4 Soil moisture monitoring

Soil moisture status was monitored approximately every fortnight using a capacitance moisture sensor (Odyssey, Dataflow Systems Ltd., Christchurch, New Zealand). Mini-rhizotron tubes were used as the access tubes, and soil moisture was assessed using three tubes located adjacent to the vine, at 75 cm from the vine trunk and at the middle of the row (Figure 6:3a). In each tube, soil moisture was collected at five depths in the soil profile (20, 30, 50, 70 and 90 cm). At each monitoring time, the readings from two measurement cycles were averaged after the probe had stabilised for 30 seconds.

The calibration of the probe for the local soil type was completed on a plot located approximately 10 metres from the experimental site (Figure 5:13). Scaled frequency readings from the probe, either using the recommended access tubes or the mini-rhizotron tubes, were contrasted against volumetric water content at each measurement depth (20, 30, 50, 70 and 90 cm). The access tubes were installed in the centre of two 4 m^2 sites, three meters apart, in preparation for the calibration (Figure 5:13c). To ensure a range of soil water content was covered the *wet* site was watered until soil saturation occurred, so the probe would give maximum readings. Whereas, the *dry* site was progressively dried using a fast-growing deep-rooted summer crop (sunflowers) and sheltered from the rain until the calibration was performed. On the day of the calibration, after obtaining readings for 15 minutes at each access tube, a trench was dug adjacent the access tubes and soil samples were taken at each depth in triplicate using metal rings (7.3 cm diameter and 7.5 cm depth). At the laboratory, soil was weighed and then dried at 105 ^oC until it reached a constant weight. The values of soil bulk density obtained were used to convert the gravimetric values of soil water from the capacitance sensors to volumetric soil water content. Overall, there was a good agreement

on the normalised readings from the Odyssey access tubes and the mini-rhizotron access tubes (r^2 = 0.76), and between the volumetric water content from the soil samples and normalised reading using mini-rhizotron tubes ($y = 0.5058\ x^{0.1819}$; r^2 = 0.89).

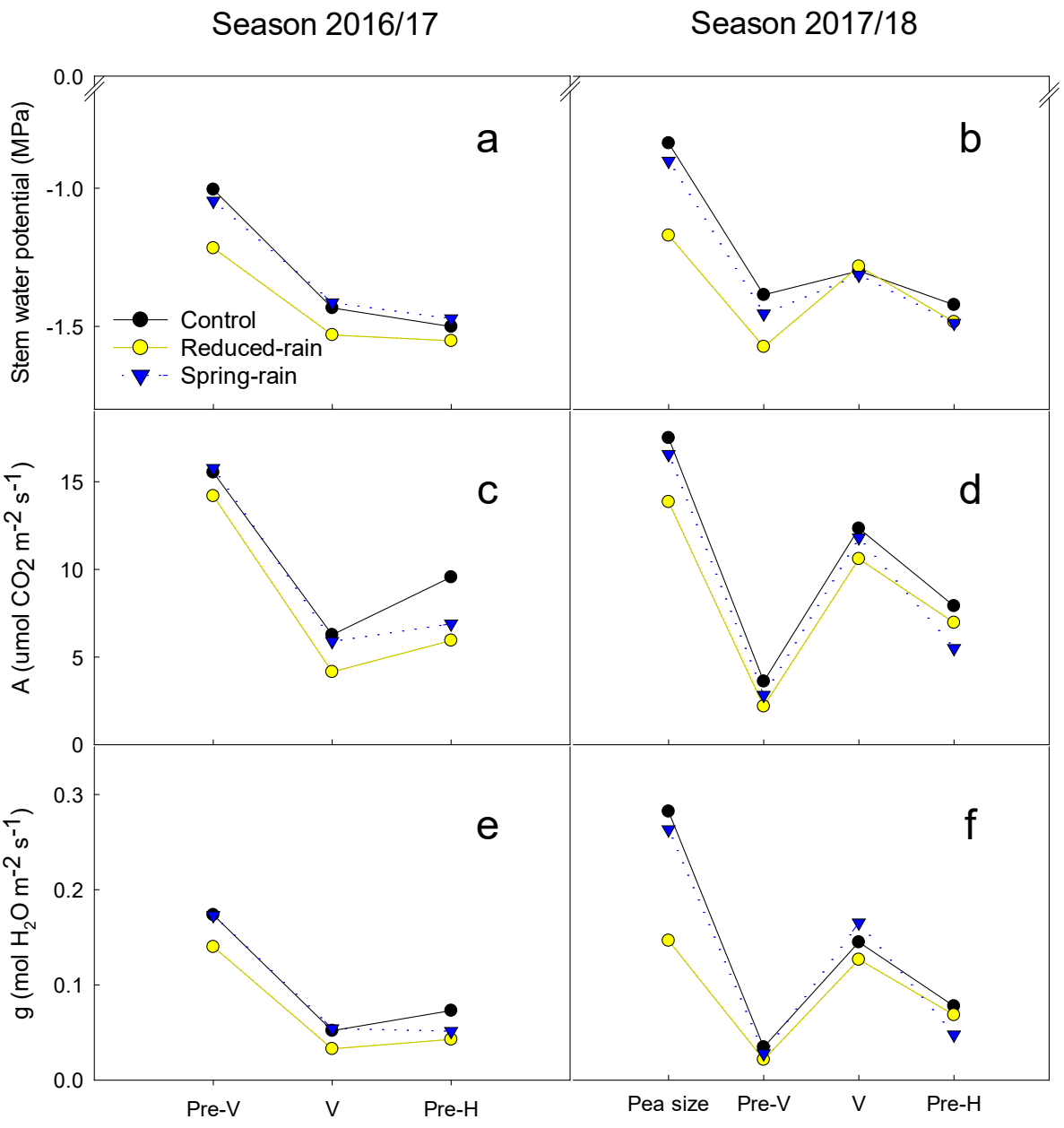


Figure 5:12 (a and b) Mid-day stem water potential, (c and d) leaf photosynthesis (A) and (e and f) stomatal conductance (g) in Shiraz vines during season 2016/17 and 2017/18. Values are averages ± one standard error of three replicates.



Figure 5:13 Field calibration of soil moisture probe. (a) Preparation of sites with contrasting soil water content (b) located close to the current experimental site. (c) The *wet* site was established with artificial ponding around the access tubes whereas sunflowers were stablished in the dry site to extract water from the soil profile. (d) A trench was dug beside access tubes to obtain (e) undisturbed soil samples at five depths for volumetric soil water content determination.

For each treatment and depth, cumulative soil moisture (Csm) was estimated from volumetric water content (Θv) analogously to the plant water stress integral of Myers (1988) and the cumulative soil moisture tension of Zerihun et al. (2010):

$$Csm = \sum_{i=0}^{i=t} \left(\Theta v_{i,i+1} - C\right) \times n$$

where $\Theta v_{i,i+1}$ is the mean Θv for any interval $i, i+1$, C is the minimum Θv measured at a given depth for all treatments and dates, and n is the number of days in the interval $i, i+1$.

Cumulative soil moisture was estimated during three important stages: (i) *winter*, from late autumn to early spring, which comprised the period of rainfall exclusion for all the treatments and top-up irrigation for *sprinkler-*, *dripper* and *reduced-rain* treatments, (ii) spring, from the date the rainout shelters were removed and started irrigation in *spring-rain* treatments to the beginning of summer, and (iii) *summer*, which comprises summer to early autumn months and relates the period in which all the treatments were equally irrigated.

During the spring of season 2015/16, Csm was higher at 30 and 50 cm depth in the *spring-rain* treatments (Figure 5:14a, d and g). However, in season 2016/17, coinciding with the high rainfall observed in spring (Figure 5:10), differences in soil moisture between treatments were only observed on the top soil (Figure 5:14b, e and h). In the dry spring of season 2017/18, *spring-rain* vines had higher Csm at 30 cm (like 2015/16), whereas *reduced-rain* vines had lower Csm consistently at 50 and 70 cm depth (Figure 5:14c, f and i). No differences were observed in Csm between treatments during any of the summer of seasons regardless of the depth measured. Cumulative soil moisture during winter of seasons 2016/17 and 2017/18 mirrored irrigation strategies. At the three depths, soil of the *spring-rain* treatments had the lowest Csm, followed by the *reduced-rain* treatment. The *control*, *sprinkler-* and *dripper-rain* treatments had the highest Csm at all the measured depths (Figure 5:14b, d and f).

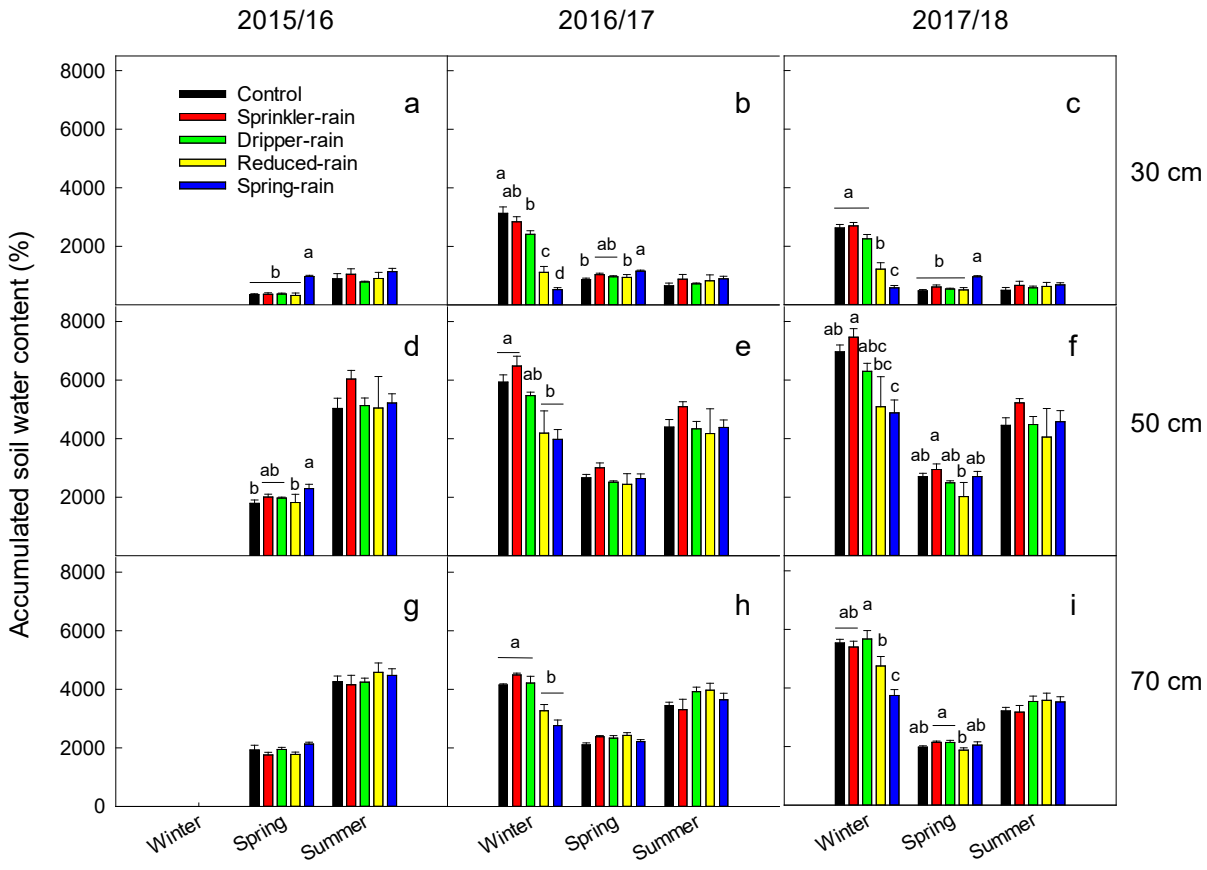


Figure 5:14 The cumulative soil moisture during seasons (a, d and g) 2015/16, (b, e and h) 2016/17 and (c, f, and i) at (a, b and c) 30 cm, (d, e and f) 50 cm and (g, h and i) 70 cm from the ground level. Values are averages ± one standard error of four replicates per treatment. Bars followed by different letters differ significantly at $p < 0.05$ by Fisher's LSD test. In this figure, *winter* corresponds the period of rainfall exclusion and top-up irrigation, from May to September; *spring* is the period between October and November, and *summer* between December to April. Data from Winter 2015/16 is not available as measurements started in October 2015.

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6 EVALUATION OF WINTER RAINFALL DECLINE ON VINE GROWTH AND DEVELOPMENT

6.1 Introduction

Anecdotally, canopy development of Barossa Shiraz in the spring following a dry winter is delayed and the final canopy size is reduced. This section of the project aims to quantify phenology, and canopy and root growth to confirm this relationship under controlled conditions. More importantly it will allow us to relate root volume and growth (and with this the ability to extract water from the soil) to canopy development and hopefully better understand the relationships between dry winters and vine development.

6.2 Materials and methods

6.2.1 Phenology

Phenology was assessed weekly from budburst until harvest. Two complementary approaches were used to characterise the effects of the treatments on phenology (Sadras and Moran 2013). For the period budburst-veraison growth stages were estimated visually using the E-L scale (Coombe 1995). During ripening grape development was quantitatively determined by using berry total soluble solids concentration (TSS). When phenology was assessed using the E-L scale the approximate date at which each treatment reached key phenology stages was calculated and the difference in days between the treatments was analysed using an analysis of the variance. During the period of berry ripening, analysis of variance was also used to assess the difference in TSS between treatments.

6.2.2 Leaf area index

Canopy size was indirectly assessed as leaf area index (LAI) using digital photography and gap fraction analysis. Up-ward looking digital images were taken from canopies approximately every three weeks from budburst to leaf fall using an iPhone mounted in a pole. The camera was configured in automatic mode without zoom. Images were collected on the central vines of each replicate as in Figure 6:1, with the average replicate LAI calculated from four photos. The camera was located at ground level and orientated to ensure that sky was equally visible in each side of the image. Images were taken avoiding direct sunshine (at the evening, early morning or in overcast conditions) which interfere with the analysis of the image as it obscures part of the canopy. The distance from the camera to the cordon was constant between repetitions and obtained using a mounting pole and remote shutter release.



Figure 6:1 Upward-looking digital image taken on October 2016.

6.2.3 Vine roots assessment

We used two complementary approaches to assess root growth and development during the season. Soil coring and root scanning allowed the investigation of the treatment effects on root biomass accumulation and root morphology. To identify peaks of root growth and determine the rate of root turnover during the season, videos were taken from mini-rhizotron tubes and roots tracked during the season.

Root biomass was estimated from soil samples collected up to 100 cm depth using a 5 cm internal diameter hydraulic hammer-driven probe (Figure 6:2). Samples were collected from the central vines at each replicate, mirroring the distribution of mini-rhizotron tubes, i.e. mid-row, 75 cm from the vine and adjacent to the vine, samples were collected at budburst and veraison during each season. Core samples were divided into three equal sections (approximately 33 cm long), bagged and stored at 4 ^{o}C until processed. At each sampling time, fine roots (< 2 mm in diameter) were separated manually in the laboratory, washed and stored in a plastic container with a bleach solution (1% v/v) until analysis could be completed. Root morphology, i.e. length, diameter, surface and volume, were measured using a root analysis software package (WinRHIZO, Regent Instrument Inc., Quebec, Canada) as previously described (Bouma et al. 2000). After scanning, roots were dried in paper bags at 70 °C to a constant mass, and results expressed in dry matter (DM, g).



Figure 6:2 Soil core sampling during spring 2016. (a) 5 cm internal diameter hydraulic hammer-driven probe. (b) one-meter long core sample.

Root development was monitored using 100 cm long acrylic mini-rhizotron tubes with an external diameter of 31mm, installed in autumn 2013. Six tubes were located close to the central vine of each replicate in a rectangular distribution defined by two tubes located in the middle of the row, two at 75 cm from the vine trunk and two adjacent to the vine (Figure 6:3a, b). Tubes were etched with a column of 54 numbered 2.5 x 1.65 cm windows (Figure 6:3c). From August 2015, images of the windows were collected approximately every 3 weeks with a videoscope IPLEX FX series camera (Olympus, Mount Waverley, Victoria, Australia). A total of 24 tubes were examined for each irrigation treatment. The turnover of fine roots (i.e. production and mortality of roots thinner than 2 mm) from each treatment was assessed across multiple sampling dates at the end of the second season using a semi-automatic discriminating tool (Zeng et al. 2008).



Figure 6:3 (a) Distribution of mini-rhizotron tubes in the field. Detail of (b) an acrylic tube one metre buried in the soil and (c) an individual window. In the background of (c) a new grapevine fine root can be observed with the videoscope.

6.2.4 Mini-rhizotron video-based automated tool for image processing and rectification

To improve the processing efficiency for the mini-rhizotron images, a semi-automated system for image pre-processing was developed. The multi-stage method uses mini-rhizotron videos as the input and transforms the video into still images that are compatible with an open source system for the analysis of root turnover (Rootfly). The operation of the software is based on python scripts that perform the following steps: 1) frame extraction and binary classification, 2) window identification, 3) window selection, 4) rectification and naming of the images (Figure 6:4). Stages 1 and 2 identify and extract still images from the videos and align these with the windows in the mini-rhizotron tube. During stage 3 clear images are selected and blurry or incomplete images excluded. Once the images corresponding to each window are sorted, stage 4 of the process involves image rectification to remove distortion due to the curved interior of the mini-rhizotron tubes. During this stage, any of the images that extend beyond the edges of the numbered ‘root window’ are cropped. The final stage of the analysis covers image naming and sorting into files following the convention defined in the Rootfly software.

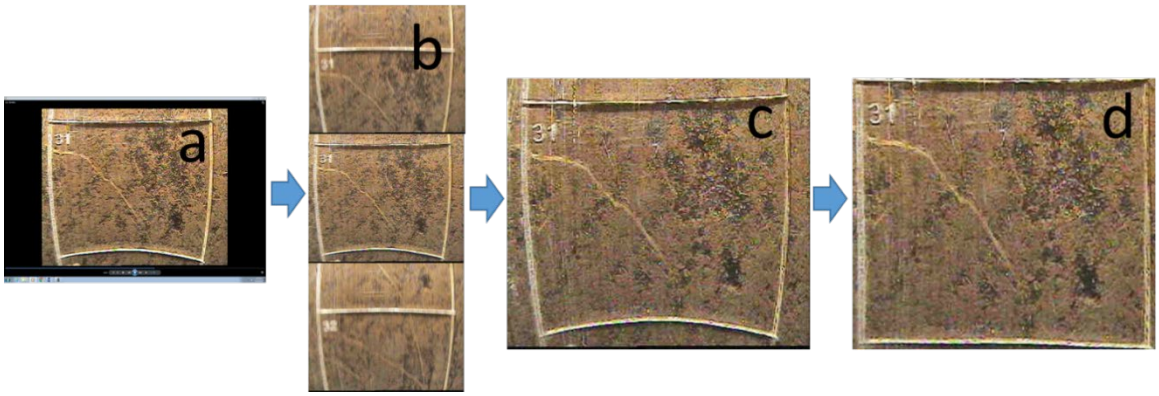


Figure 6:4 Sequence of stages for image processing and rectification. Using (a) mini-rhizotron videos as inputs, the software automatically extracts (b) still images, (c) identifies and selects individual images and (d) rectifies images to account for any deformation caused during the video acquisition.

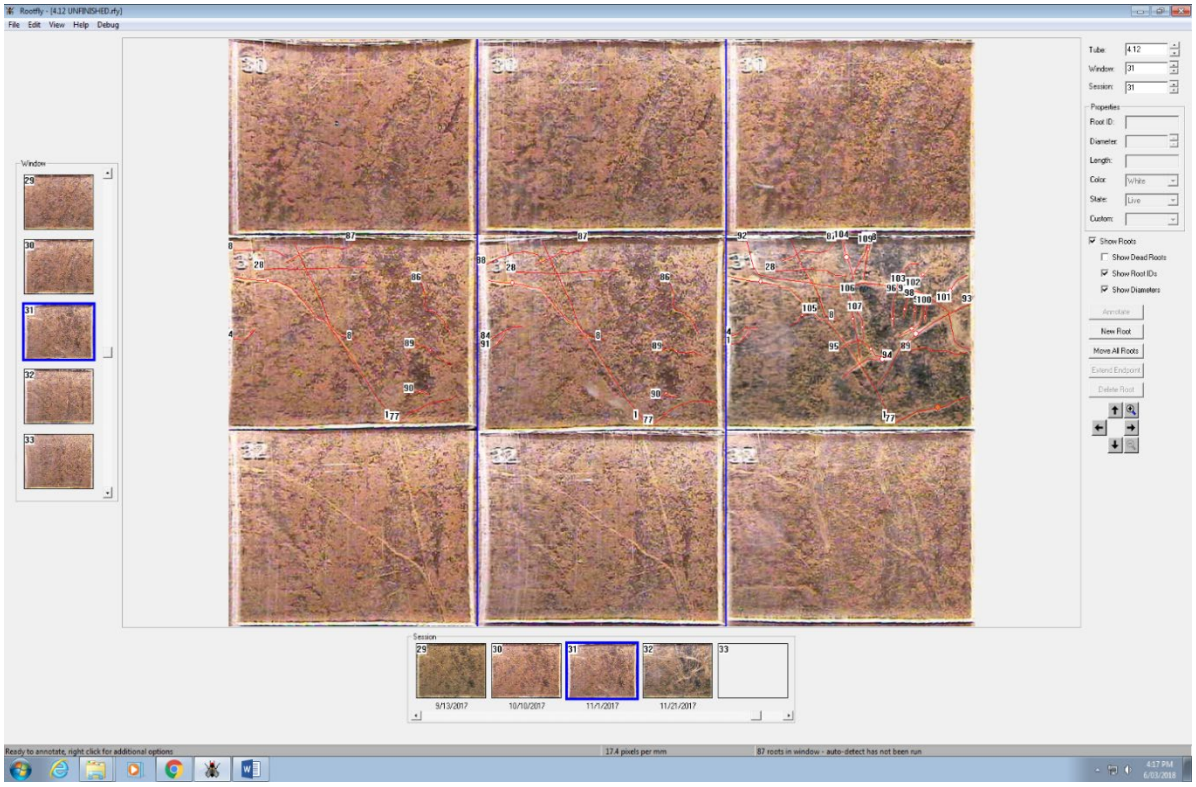


Figure 6:5 Screenshot from the Rootfly software showing the tracking of root at consecutive sampling times. The images in the centre display the current images being analysed. Changes in root number and morphology are annotated progressively over the time. Note in the central array of images how new roots have been tracked in red and labelled as they develop.

6.2.5 Sampling and quantification of abscisic acid (ABA) in the roots

Root samples were taken at budburst in 2015, 2016 and 2017, when first leaf tissue was visible (E-L4) in buds of *control* vines. Fine roots were sampled from the top 0.33m of a one-metre depth core samples taken adjacent to the vine and at 0.75m from the vine trunk. During the second season we sampled roots in the first 33 cm of soil only in the position adjacent to the vine trunk. Roots were swiftly extracted from the soil by hand in the field, loosely cleaned, immediately frozen in liquid nitrogen and then stored at -80°C until use. For 2017, roots were sampled on six occasions during winter and spring (15/5/17, 10/7/17, 16/8/17, 19/9/17, 19/10/17 and 21/11/17) in the same way as at budburst 2016.

ABA analysis was performed as described in Spiers et al. (2013). Briefly, root samples were ground under liquid nitrogen, extracted using 20%(v/v) methanol, to which deutrated internal standards for ABA, phaseic acid (PA), di-hydrophaseic acid (DPA) and ABA-glucose ester (ABA-GE) were added. The extracts were added to a solid phase extraction column and the compounds of interest eluted with 90%(v/v) methanol. The eluate was dried in a vacuum centrifuge and then resuspended in aq. acetonitrile. ABA, PA, DPA and ABA-GE were subsequently quantified using a triple-quad LC/MS/MS.

6.3 Results

6.3.1 Treatments effects on grapevine phenology

Compared to the *control*, the top-up winter irrigation treatments either using sprinklers or drippers advanced budburst in all seasons (Figure 6:6a, c and e), and this difference persisted into the growing season in 2015/16. The s*pring-rain* treatment had the largest impact on development, delaying phenology stages prior to veraison in all seasons and during ripening in the 2015/16 and 2017/18. During ripening the phenology of the *reduced-rain* vines was advanced during the 2015/16 and 2017/18 seasons, but delayed during the 2016/17 season (Figure 6:6b, d and f).

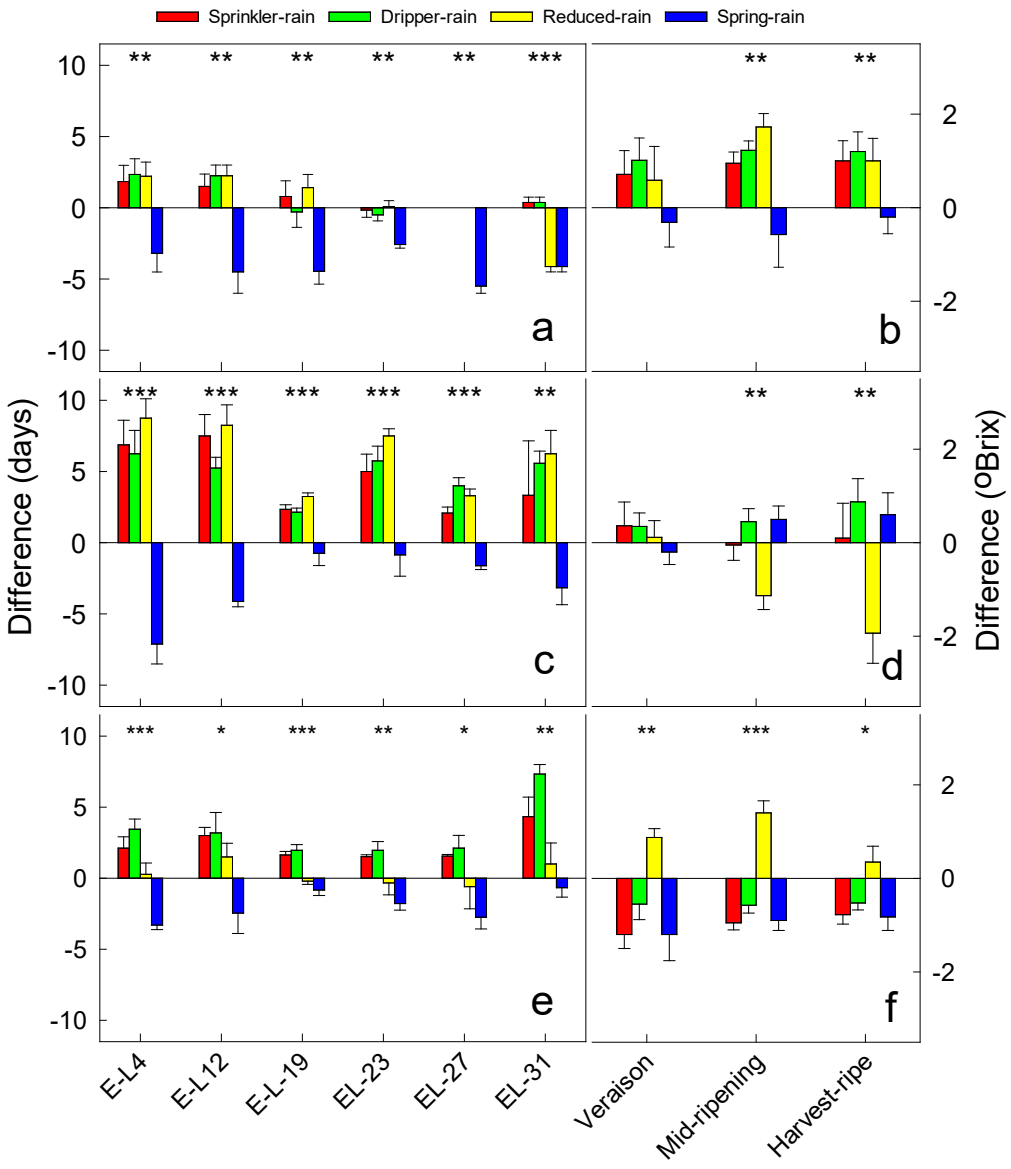


Figure 6:6 Effects of winter irrigation treatments on grapevine phenology (a, c and e) before veraison (b, d and f) and during berry ripening in seasons 2015/16 (a and b), 2016/17 (c and d) and 2017/18 (e and f). In (a, c and e) irrigation effects correspond to the difference in days at which treatments reached key phenological stages in relation to *control* vines: budburst (E-L4), shoots 10 cm (E-L12), flowering begins (E-L19), full bloom (E-L23), setting (E-L27) and berry pea size (E-L31). In (b, d and f) irrigation effects are differences in TSS at veraison, mid-ripening and targeted harvest (26°Brix). Values are averages ± one standard error of four replicates per treatment. Statistical significance from the one-way ANOVA for irrigation effect is indicated by (*) $P < 0.05$, (**) $P < 0.01$ and (***) $P < 0.001$.

6.3.2 Effect of treatments on leaf area index

Leaf area index (LAI) assessed during the season reflected differences in canopy size (Figure 6:7). In the first season (2015/16), since early stages of vine development, *reduced*- and *spring-rain* treatments diverged by LAI; whereas *reduced-rain* decreased canopy size, *spring-rain* boosted shoot growth and canopy density. However, in a dry spring of season 2015/16 (Figure 5:10), soil moisture was insufficient to sustain highly transpiring canopies on *spring-rain* vines, and LAI decreased due to the loss of basal leaves (indicated with an arrow in Figure 6:7, left panel). In the 2016/17 and 2017/18 seasons the *reduced-rain* treatment showed a lower LAI, which was evident from early spring. In the 2017/18 season canopy size decreased between version and harvest (black arrow), while it was maintained until after harvest in the previous two seasons.

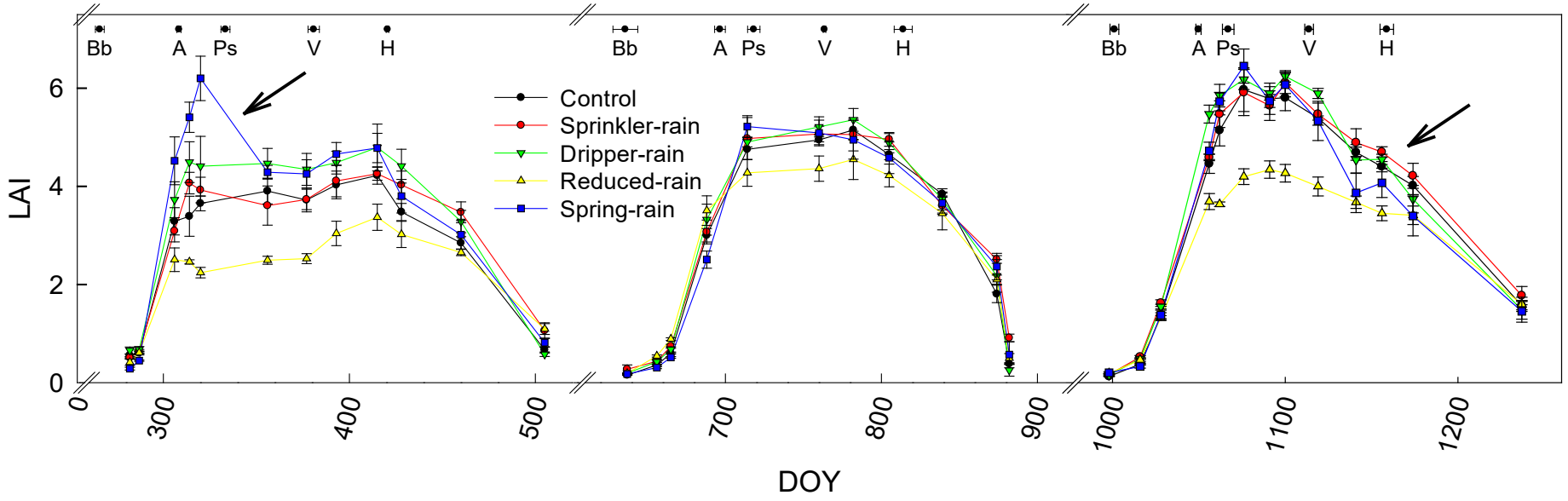


Figure 6:7 Seasonal patterns of LAI during 2015/16, 2016/17 and 2017/18. A continuous time scale where day of year (DOY) starts on 01/01/2015 was used. Values are averages ± one standard error of four replicates per treatment. Black circles indicate key phenological stages (mean ± one standard deviation): budburst (Bb), flowering (A), berry pea size (PS), veraison (V) and harvest (H). Arrows indicate a steady drop in LAI by intense leave basal defoliation in spring-rain treatments due to lack of rainfall during spring season 2015/16 and summer 2017/18.

6.3.3 Root growth and turnover during the seasons

Vine root morphology and total root biomass varied due to the winter irrigation treatments and between seasons (Table 6:1 and Table 6:2). They largely followed the trends observed in canopy size or pruning weight, with the spring-rain treatment reporting the highest values for all the parameters measured (Table 6:2). Likewise; the wetter 2016/17 season corresponded with generally larger root systems, regardless of the parameter considered. The results for the mini-rhizotron images did not align well with the data collected from the soil cores. The reduced-rain treatment reported the smallest canopy size and some of the smaller root parameters from the soil cores; however, it had the largest root length as monitored from the mini-rhizotron tubes (Figure 6:8). Attempts were made to relate the results from the varying depth of the soil cores and the window locations in the mini-rhizotron tubes, but this disparity could not be resolved. We are uncertain if this inconsistency is due to the measurement technique or the relatively small sample size.

Table 6:1 Levels of significance (*p*-value) indicating effect of irrigation treatment, phenological stage (budburst and veraison), season, sampling position (adjacent and at 75 cm from the vine trunk, and at mid-row) and depths (0-33 cm, 33-66 cm and 66-99 cm) upon various root metrics averaged across seasons 2015/16, 2016/17 and 2017/18.

Source of variation	**Fine root biomass (g/core fraction)**	**Fine root length (cm/core fraction)**	**Fine root surface (m^2/core fraction)**	**Fine root diameter (mm/core fraction)**
Treatment (T)	**0.020**	**0.027**	**0.006**	0.305
Phenological stage (E-L)	**< 0.0001**	**0.001**	**< 0.0001**	**< 0.0001**
Season (S)	**0.000**	**< 0.0001**	**< 0.0001**	**< 0.0001**
Position (P)	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
Depth (D)	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.059
T x E-L	0.452	0.981	0.942	**0.014**
T x S	0.516	0.112	**0.041**	0.419
T x P	0.505	**0.002**	**0.001**	0.958
T x D	**< 0.001**	0.685	0.212	0.805
E-L x S	**< 0.0001**	**< 0.0001**	**0.021**	**< 0.0001**
E-L x P	0.198	**0.003**	**0.012**	**0.023**
E-L x D	0.672	**0.184**	0.797	**< 0.0001**
S x P	0.620	0.275	0.170	0.042
S x D	**0.001**	**< 0.0001**	**0.001**	0.664
P x D	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.008**

Table 6:2 Biomass, length, surface area and average diameter of fine Shiraz roots per vine extracted from soil cores collected at budburst (E-L 4) and veraison (E-L 35) during seasons 2015/16, 2016/17 and 2017/18 seasons, from five irrigation treatments and at three sampling positions (adjacent and at 75 cm from the vine trunk, and at mid-row). Values are means ± one standard error; *p* indicates effect of irrigation treatment, sampling position and interaction. Different letters indicate significant differences between treatments or sampling positions, as calculated by Fisher's least significant difference (LSD 5% level).

Source of variation	Fine root biomass (Kg/vine)		Fine root length (km/vine)		Fine root surface (m^2/vine)		Fine root diameter (mm)	
Treatment (T)								
Control	0.23 ± 0.03	b	4.21 ± 0.26	b	7.95 ± 0.56	b	0.54 ± 0.01	ab
Sprinkler-rain	0.19 ± 0.02	c	4.20 ± 0.27	b	7.71 ± 0.49	b	0.55 ± 0.01	a
Dripper-rain	0.22 ± 0.02	bc	3.96 ± 0.28	b	7.86 ± 0.62	b	0.55 ± 0.01	a
Reduced-rain	0.21 ± 0.02	bc	4.32 ± 0.30	b	7.94 ± 0.69	b	0.53 ± 0.01	b
Spring-rain	0.31 ± 0.03	a	5.33 ± 0.35	a	10.30 ± 0.82	a	0.53 ± 0.01	b
p-value	**< 0.001**		**0.001**		**< 0.001**		**0.045**	
Season (S)								
2015/16	0.18 ± 0.01	b	3.69 ± 0.23	c	6.29 ± 0.36	c	0.50 ± 0.01	b
2016/17	0.30 ± 0.02	a	4.21 ± 0.20	b	7.78 ± 0.36	b	0.55 ± 0.01	b
2017/18	0.22 ± 0.02	b	5.22 ± 0.20	a	10.64 ± 0.48	a	0.56 ± 0.01	a
p-value	**< 0.0001**		**< 0.0001**		**< 0.0001**		**< 0.0001**	
Phenological stage (E-L)								
Budburst	0.20 ± 0.01	b	4.03 ± 0.18	b	7.55 ± 0.42	b	0.52 ± 0.01	b
Veraison	0.27 ± 0.02	a	4.77 ± 0.19	a	9.16 ± 0.39	a	0.55 ± 0.01	a
p-value	**< 0.0001**		**0.001**		**< 0.001**		**< 0.0001**	
T x E-L	0.365		0.977		0.632		0.980	
T x S	0.282		0.091		0.074		0.120	
E-L x S	0.074		0.001		0.089		**0.002**	

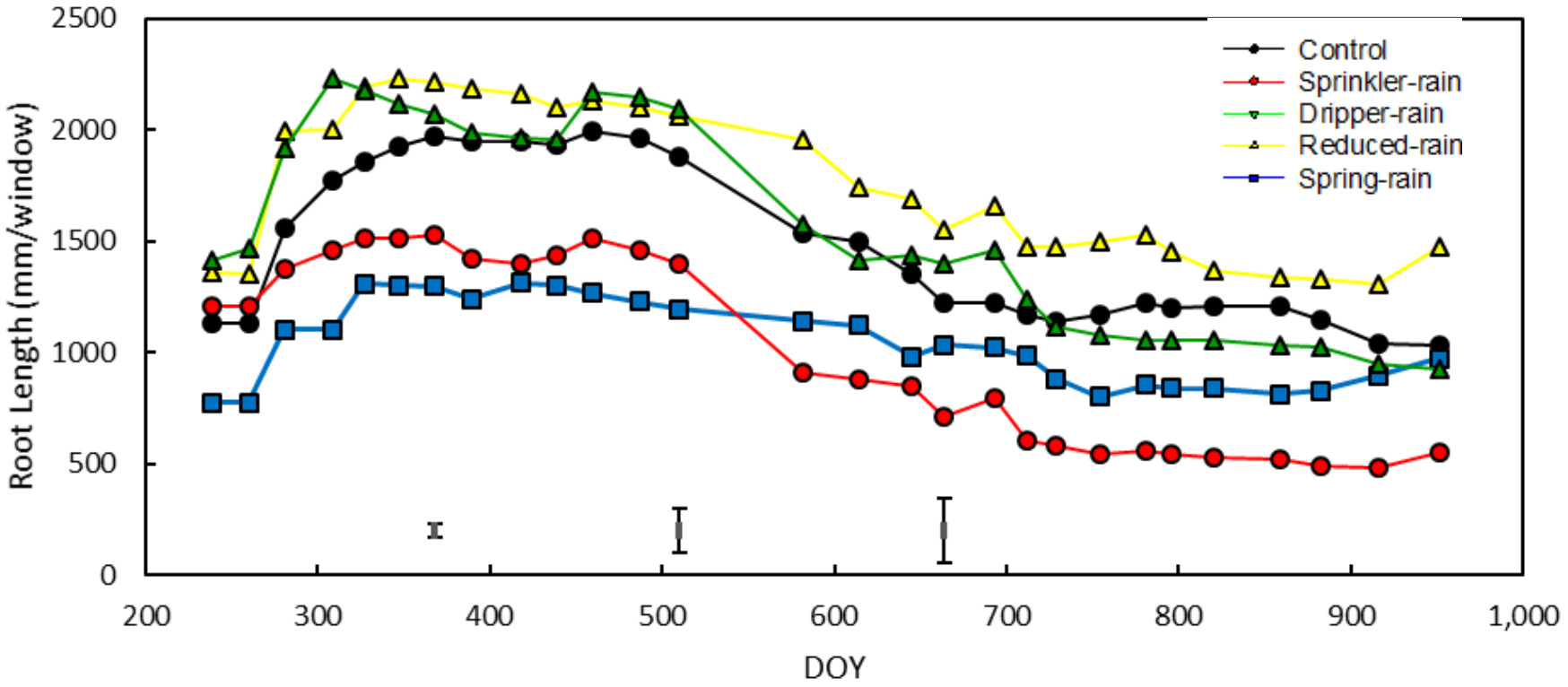


Figure 6:8 Seasonal patterns of root length during 2015/16 and 2016/17. A continuous time scale where day of year (DOY) starts on 01/01/2015 was used. Values are averages of three replicates per treatment. From left to right the bars represents 5% LSD for treatment differences from repeated measures ANOVA for the treatment, sampling date and the treatment by date interaction.

6.3.4 Synthesis and accumulation of ABA (Abscisic Acid) in the roots

At the first sampling date (budburst 2015), the effect of sampling position on root ABA concentration was investigated. There was no significant difference in ABA concentration between roots taken adjacent to the vine trunk and those taken 0.75 m from the vine trunk (data not shown), consequently all future samples were taken adjacent to the vine trunk, within the wetting zone of the drip system.

Overall, there was no consistent treatment effect on root ABA concentration at budburst (Figure 6:9a). However, when the full data set was analysed as a two-way ANOVA, there was a significant impact of treatment (p = 0.027); this was driven by a significantly lower ABA concentrations in the *reduced-rain* treatment relative to the *sprinkler-rain* treatments (p < 0.05) and marginal differences between the *reduced-rain* treatment and the *dripper-rain* and *spring-rain* treatments (p < 0.10). In contrast there was a marked seasonal difference (p = 0.001), with 2016 having the highest root ABA concentrations across all treatments.

PA (phaseic acid) was generally found to have concentrations in the root that were below the limit of quantitation throughout all seasons (data not shown). The next step in the catabolic pathway of ABA, DPA (dihydrophaseic acid) was also significantly affected by season and in 2017 was present in much higher concentrations in the root than ABA (Figure 6:9b).

ABA-GE (abscisic acid-glucose ester) represents a pool of ABA that has been de-activated but is still present in the root cells. This pool was present in much higher concentrations than ABA in all seasons, although there was no significant effect of treatment (Figure 6:9c). In order to examine the possibility that ABA had been produced in high concentrations earlier in the winter, but had been metabolised prior to budburst, regular sampling during winter and spring 2017 was undertaken (Figure 6:10). Over the six time-points there was no significant effect of treatment, but there was a significant effect of time in all three measures. There was a small decrease in ABA, with a matching small increase in ABA-GE, and a large decrease in DPA. These results suggest that the high concentrations of root ABA-GE observed during the experiment are probably built up during the latter part of the growing season (not measured), reflecting the fate of part of the ABA production during the season. Similarly, in these roots, the catabolism of ABA to PA is clearly not a rate-limiting step, with an accumulation of DAP occurring followed by further catabolism that is occurring more slowly.

Overall, there was no evidence to suggest that ABA was accumulating in the roots subjected to dry winter conditions. Consequently, it is unlikely that a flush of ABA into the shoot once irrigation is returned was occurring or that this was the cause of the differences observed in canopy growth.

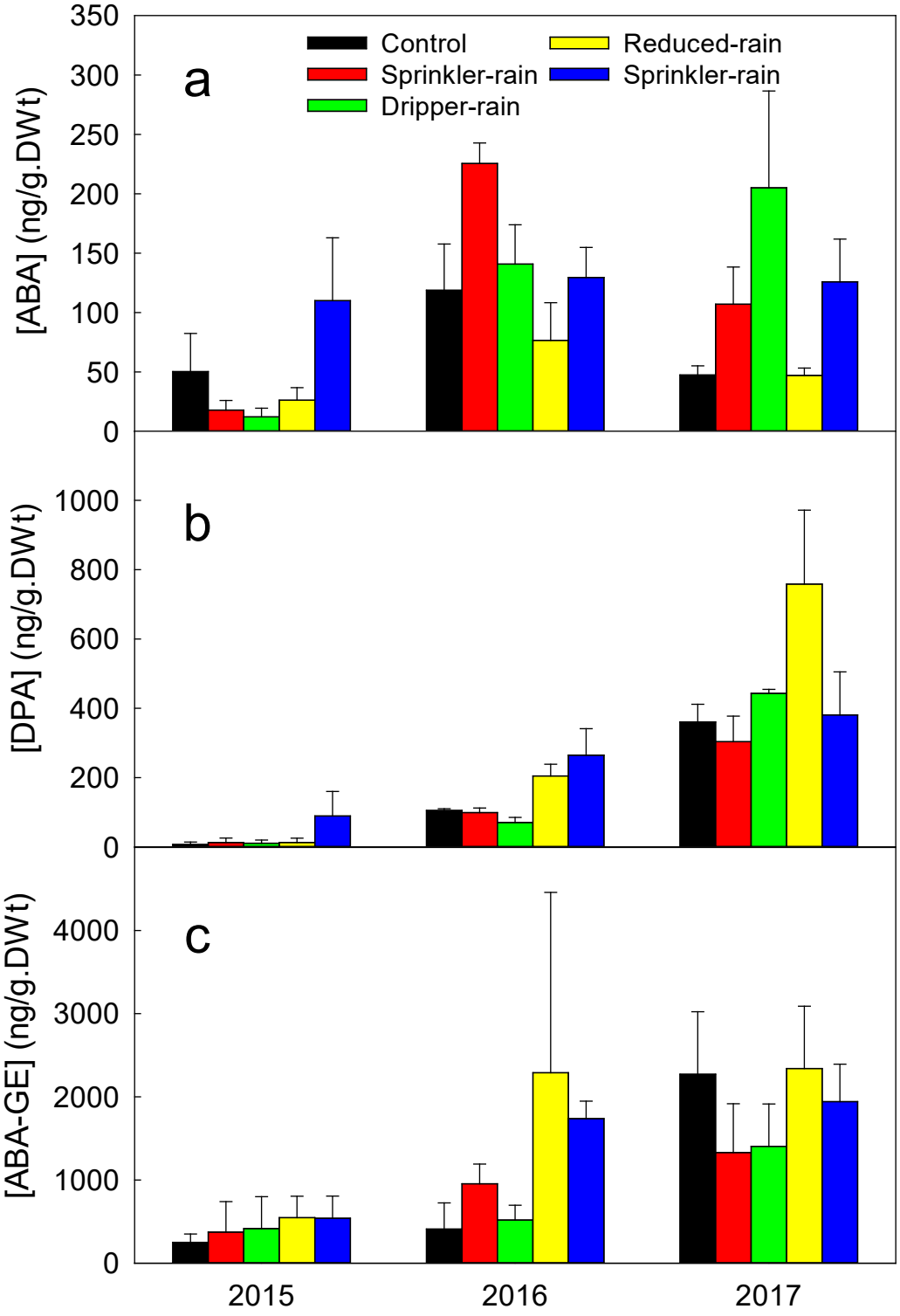


Figure 6:9 Effect of season and treatment on ABA, DPA and ABA-GE concentrations in roots from the top 33 cm of soil adjacent to the vine. Bars are means ± one standard error of four replicates per treatment.

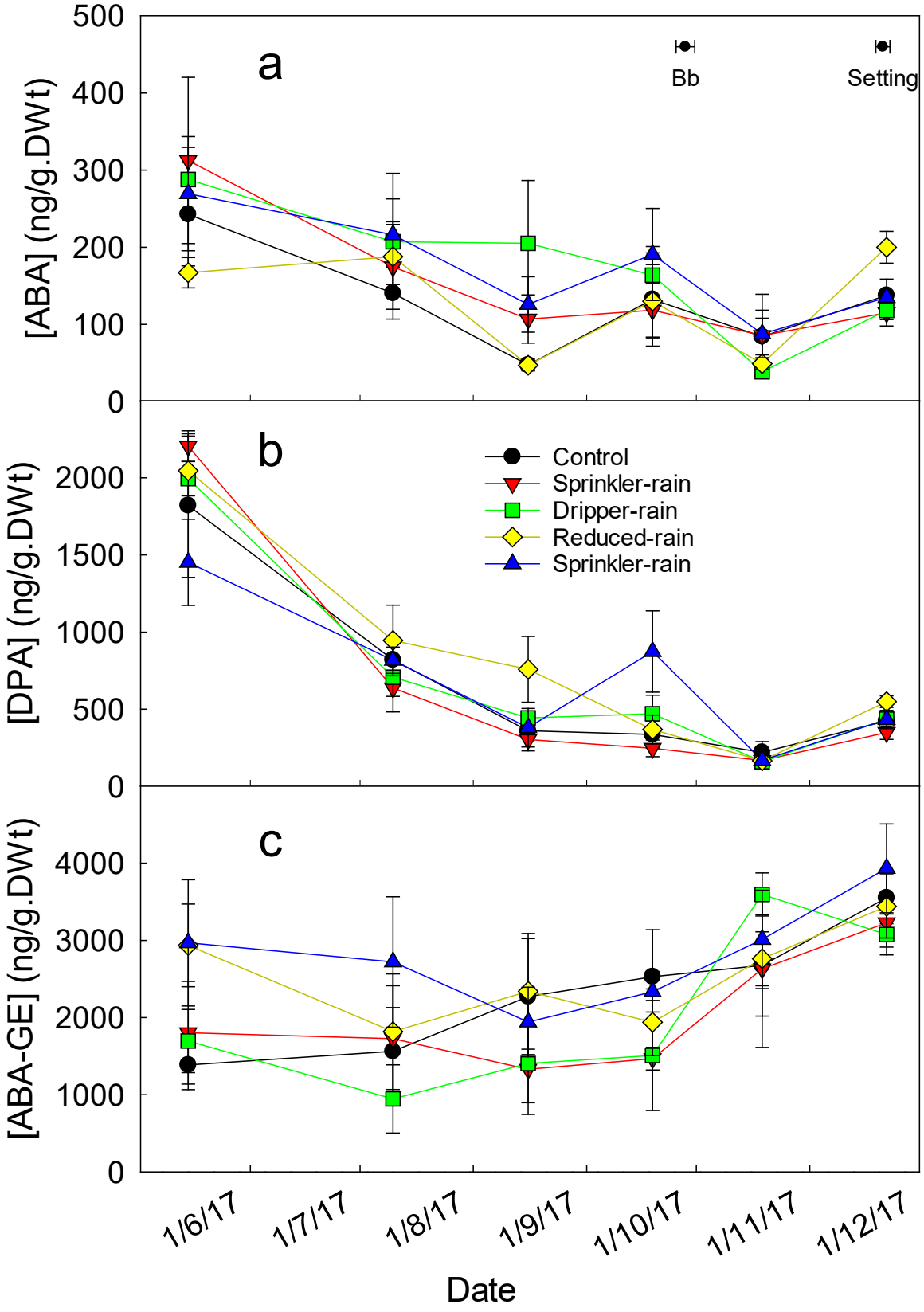


Figure 6:10 Effect of season and treatment on ABA, DPA and ABA-GE concentrations in roots from the top 33 cm of soil adjacent to the vine. Points are means ± one standard error, of four replicates per treatment.

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7 EFFECTS OF WINTER RAINFALL DECLINE AND SUPPLEMENTARY IRRIGATION ON VINE BALANCE

7.1 Introduction

Vine balance is nominally the relationship between three factors; the canopy, the root system and the fruit. The size of the canopy determines its ability to produce the carbohydrates that support the growth of the fruit and the roots. The volume or size of the root system governs its ability to supply water and nutrients to maintain the canopy and ripen the fruit. The fruit acts as a sink for carbohydrates from the canopy, and water and nutrients from the roots. An excess or shortage of any of these three variables can negatively impact on vineyard productivity or fruit quality. Vine balance is normally measured by assessing the yield (fruit) to pruning weight (canopy) ratio as the root system is difficult to assess (see section 6.3.3).

7.2 Materials and methods

7.2.1 Vine yield, pruning weight and vine balance

At harvest we measured fruit yield and the number of bunches per vine, and estimated bunch weight and number of berries per bunch. Prior to harvest average berry weight was measured on a 120-berry sample randomly collected from the four central vines of each replicate. During winter we measured pruning weight per vine and its components. We counted the number of shoots per vine and estimated average shoot weight.

7.2.2 Carbohydrates sampling and analysis

Of the six treated vines per repetition, only the two central vines were used for monitoring carbohydrate concentration, whereas the remaining vines acted as buffers. The trunk samples were collected with a 4.8 mm drill bit to a depth visually estimated as the centre of the trunk. Wood samples were collected in key phenological stages during both seasons (Table 7:1) and then frozen for later analysis of total non-structural carbohydrates (TNC).

Table 7:1 Phenological stages and sampling dates for non-structural carbohydrates on Shiraz vines during season 2015/16 and 2016/17.

Phenological stage (E-L scale)	Season 2015/16	Season 2016/17
Bud-break (E-L 4)	11 September	13 September
Flowering (E-L 23)	10 November	25 November
Veraison (E-L 35)	20 January	2 February
Harvest (E-L 38)	4 March	6 April
Leaf-fall (E-L 47)	30 May	23 May

For analysis of TNC, a 5 mg sub-sample was weighed after grinding to a fine powder (~ 50 µm) with a Rocklabs Benchtop Ring Mill (Sietronics, Canning Vale, WA, Australia). Soluble sugars were extracted using three 0.5 ml washes of 80% aqueous ethanol at 60 ^{o}C for 10 min. After centrifuging between each wash, the three aliquots were combined in a single 1.5 ml tube and dried at ambient temperature using a vacuum centrifuge (Speedvac Plus, Savant Instruments, Farmingdale, NY). The remaining pellet was dried in a heat block to remove any excess supernatant and retained for starch analysis. Resuspended dried supernatant in 500 µl of de-ionised water was used for determination of soluble sugars concentration by enzymatic assay (Megazyme International, Bray, Ireland).

For starch analysis, the dried pellet was resuspended in 0.5 to 1.0 mL deionized water, depending on the expected carbohydrate concentration, and vortexed thoroughly. A 50-µL aliquot was transferred to a new 1.5-mL microcentrifuge tube with 1 mL anthrone reagent (0.2% anthrone in 70% concentrated sulfuric acid) in a cool bath. The mixture was vortexed, then left on ice for 10 min, after which it was heated to 85 ^{o}C for 10 min using a dry-block heater. After the anthrone mix was vortexed to ensure a uniform colour, 300 µL was transferred to a microplate well and absorbance was read at 600 nm on a Labtech FLUOstar Optima microplate reader (BMG Labtech, Mornington, VIC, Aust.) against a fructose standard curve. All extracts were analysed in triplicate and results from anthrone analysis were expressed as mg fructose equivalents per gram.

7.3 Results

7.3.1 Treatments effects on yield and its components

Yield was higher in season 2016/17 than in seasons 2015/16 and 2017/18, notwithstanding treatment differences that ranged from +8% to -42% from the *control* (Figure 7:1). Overall, during three seasons, *control* vines exposed to natural winter rainfall yielded the most. Relative to these vines, neither the top-up irrigation strategies using drippers nor the one that uses micro-sprinklers during winter consistently restored yield. *Sprinkler-rain* vines yielded at the same level of *control* vines in two out of three seasons (2016/17 and 2017/18), whereas *dripper-rain* vines equalled yield of *control* vines only during one season (2017/18). Consistently, during the three seasons *spring-rain* decreased yield in comparison to *control* vine from 8% to 20%. The *reduced-rain* treatment significantly reduced yield during the first (-42%) and third season, when experimental dry conditions in winter matched with a natural dry spring. However, in the second season, *reduced-rain* vines yielded similarly to *control* vines (+8%), when rainfalls were sufficient to refilled soil profile early at spring. This highlights the importance of entering the season with a soil water content that does not limit the early stages of growth and development.

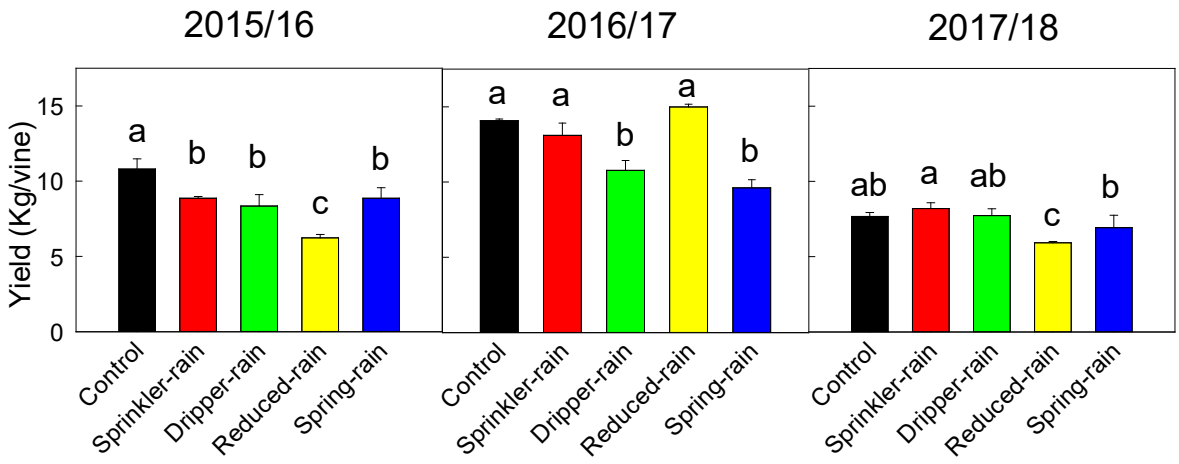


Figure 7:1 Effects of winter irrigation treatments on yield of Shiraz during seasons 2015/16, 2016/17 and 2017/18. Bars are means ± one standard error. Different letters indicate means that differ significantly at $p < 0.05$ by Fisher's LSD test.

Differences in yield between treatments during season 2015/16 were mainly driven by the higher number of bunches in *control* vines and by the lighter bunches of *reduced-rain* vines, which were in turn due to significantly smaller berries (Table 7:2). *Reduced-rain* vines and *control* vines yielded similarly the second season (2016/17), which was driven by the significantly higher number of bunches of *reduced-rain* vines, although their berry weights were also lower. During season 2017/18 there was a similar number of bunches per vine between treatments; however, lighter bunches with smaller berries in *Reduced-* and *Spring-rain* treatments, as indicated by the lower berry mass, translated into lower yield per vine at harvest in these treatments. It is likely the microclimatic conditions in the smaller and more open canopies of the *reduced-rain* vines (Figure 6:7 and Figure 7:2) favoured bud differentiation and fruitfulness, as verified by the consistent higher number of bunches per shoot in the three seasons (Table 7:3).

Table 7:2 Effects of winter irrigation treatments on yield components of Shiraz at harvest during seasons 2015/16, 2016/17 and 2017/18. Means followed by different letters differ significantly at $p < 0.05$ by Fisher's LSD test. *P* values correspond to the one-way ANOVA.

Season	Treatment	Bunch number (per vine)		Bunch weight (g)		Berry weight (g)	
2015/16	Control	102 ± 1.3	a	108 ± 6.4	a	0.9 ± 0.04	a
	Sprinkler rain	82 ± 2.8	bc	109 ± 3.9	a	1.0 ± 0.01	a
	Dripper rain	76 ± 3.1	c	110 ± 10.7	a	1.0 ± 0.04	a
	Reduced rain	88 ± 2.7	b	71 ± 3.4	b	0.8 ± 0.03	b
	Spring rain	84 ± 5.1	bc	105 ± 3.4	a	1.0 ± 0.03	a
	P value	0.001		0.002		0.011	
2016/17	Control	103 ± 1.1	b	137 ± 1.3		1.1 ± 0.03	a
	Sprinkler rain	94 ± 4.6	bc	139 ± 3.0		1.1 ± 0.01	a
	Dripper rain	85 ± 2.8	cd	127 ± 6.8		1.1 ± 0.06	a
	Reduced rain	120 ± 3.1	a	125 ± 2.7		0.9 ± 0.02	b
	Spring rain	78 ± 3.6	d	124 ± 7.7		1.1 ± 0.02	a
	P value	<0.001		0.159		0.030	
2017/18	Control	70 ± 1.0		111 ± 3.6	a	1.4 ± 0.03	a
	Sprinkler rain	73 ± 3.7		114 ± 5.9	a	1.4 ± 0.02	a
	Dripper rain	72 ± 3.3		111 ± 2.8	a	1.4 ± 0.02	a
	Reduced rain	67 ± 2.0		87 ± 2.0	b	1.3 ± 0.03	b
	Spring rain	75 ± 3.0		95 ± 3.9	b	1.3 ± 0.03	b
	P value	0.383		0.001		0.001	

7.3.2 Effects on vegetative growth and vine balance

A consistent number of buds were retained across the treatments at pruning in the three seasons. Vine vigour, as estimated from pruning weight, was significantly affected by irrigation treatments (Figure 7:2). In the first two seasons, top-up irrigation using drippers during winter (*dripper-rain*) and micro-sprinklers at budburst (*spring-rain*) increased pruning weights, due to a higher weight of individual shoots in these treatments (Table 7:3). In the third season (2016/17) all of the treatments except *reduced-rain* performed similarly to the *control*. In each of the three seasons *reduced-rain* during winter decreased vine vegetative growth and individual shoot weight (Figure 7:2, Table 7:3).

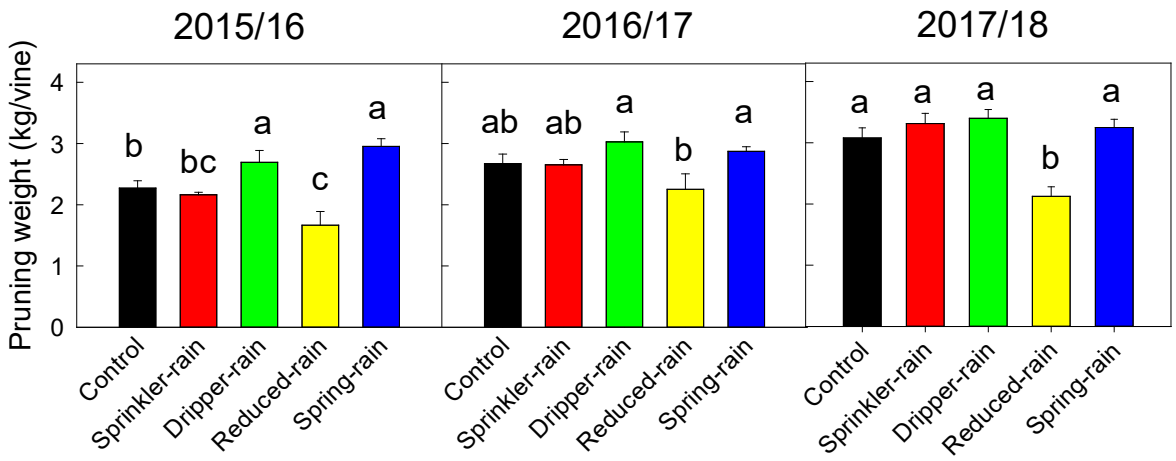


Figure 7:2 Effects of winter irrigation treatments on pruning weight of Shiraz during seasons 2015/16, 2016/17 and 2017/18. Bars are means ± one standard error. Different letters indicate means that differ significantly at $p < 0.05$ by Fisher's LSD test.

Table 7:3 Effects of winter irrigation treatments on vegetative growth and sink/source ratio of Shiraz during season 2015/16, 2016/17 and 2017/18. Values are means. *p* values correspond to the one-way ANOVA. Means followed by different letters differ significantly at $p < 0.05$ by Fisher's LSD test.

Season	Treatment	Shoot number (vine)	Weight per shoot (g)		Bunch per shoot		Yield/pruning wt.	
2015/16	Control	68.9 ± 3.0	33.1 ± 1.2	b	1.5 ± 0.1	a	5.1 ± 0.2	a
	Sprinkler-rain	62.0 ± 2.1	35.1 ± 1.8	b	1.3 ± 0.1	ab	4.2 ± 0.1	b
	Dripper-rain	62.6 ± 3.7	43.5 ± 3.1	a	1.2 ± 0.1	b	2.7 ± 0.2	d
	Reduced-rain	64.5 ± 1.6	25.7 ± 3.3	c	1.4 ± 0.1	ab	3.4 ± 0.3	c
	Spring-rain	68.2 ± 3.2	43.6 ± 1.3	a	1.3 ± 0.1	b	3.3 ± 0.3	c
	P value	0.346	<0.001		0.050		<0.001	
2016/17	Control	74.0 ± 1.8	36.5 ± 2.3	bc	1.3 ± 0.1	bc	4.6 ± 0.3	b
	Sprinkler-rain	65.1 ± 1.3	41.1 ± 1.1	ab	1.5 ± 0.1	ab	5.2 ± 0.1	b
	Dripper-rain	71.8 ± 1.0	42.6 ± 2.5	a	1.2 ± 0.1	c	3.6 ± 0.2	c
	Reduced-rain	71.6 ± 4.9	32.4 ± 1.7	c	1.7 ± 0.1	a	6.1 ± 0.2	a
	Spring-rain	70.3 ± 1.7	40.8 ± 1.7	ab	1.2 ± 0.1	c	3.7 ± 0.3	c
	P value	0.202	0.011		0.002		<0.001	
2017/18	Control	67.7 ± 2.7	45.8 ± 2.9	b	1.0 ± 0.1		2.7 ± 0.1	a
	Sprinkler-rain	65.4 ± 1.2	50.7 ± 2.9	ab	1.2 ± 0.1		2.5 ± 0.2	a
	Dripper-rain	63.7 ± 1.4	53.6 ± 2.2	a	1.1 ± 0.0		2.4 ± 0.1	ab
	Reduced-rain	60.9 ± 4.9	35.6 ± 2.0	c	1.2 ± 0.1		2.7 ± 0.2	a
	Spring-rain	67.2 ± 2.6	48.8 ± 2.2	ab	1.1 ± 0.0		2.0 ± 0.3	b
	P value	0.472	0.001		0.150		0.100	

The yield:pruning weight ratio was also significantly affected by the treatments. Overall, the ratio increased for all the treatments during the 2016/17 season due to the higher yield. Over the three seasons, *dripper*- and *spring-rain* vines had the lowest yield:pruning weight ratio, due to their relatively large canopies. The *reduced-rain* vines, which had a higher yield during the 2016/17 season, also had a higher yield:pruning weight ratio.

7.3.3 Effects on reserves of total non-structural carbohydrates

The impact of the irrigation treatments on non-structural carbohydrates was relatively small and inconsistent in the 2015/16 season. The *sprinkler-rain* treatment reduced starch concentrations at flowering, but no other effects were observed (Figure 7:3). From veraison in the 2016/17 greater treatment effects were seen. The *reduced-rain* treatment, with the smallest canopy and highest yield showed a significant reduction in starch concentration (Figure 7:3) as reserves were drawn down in order to ripen the fruit.

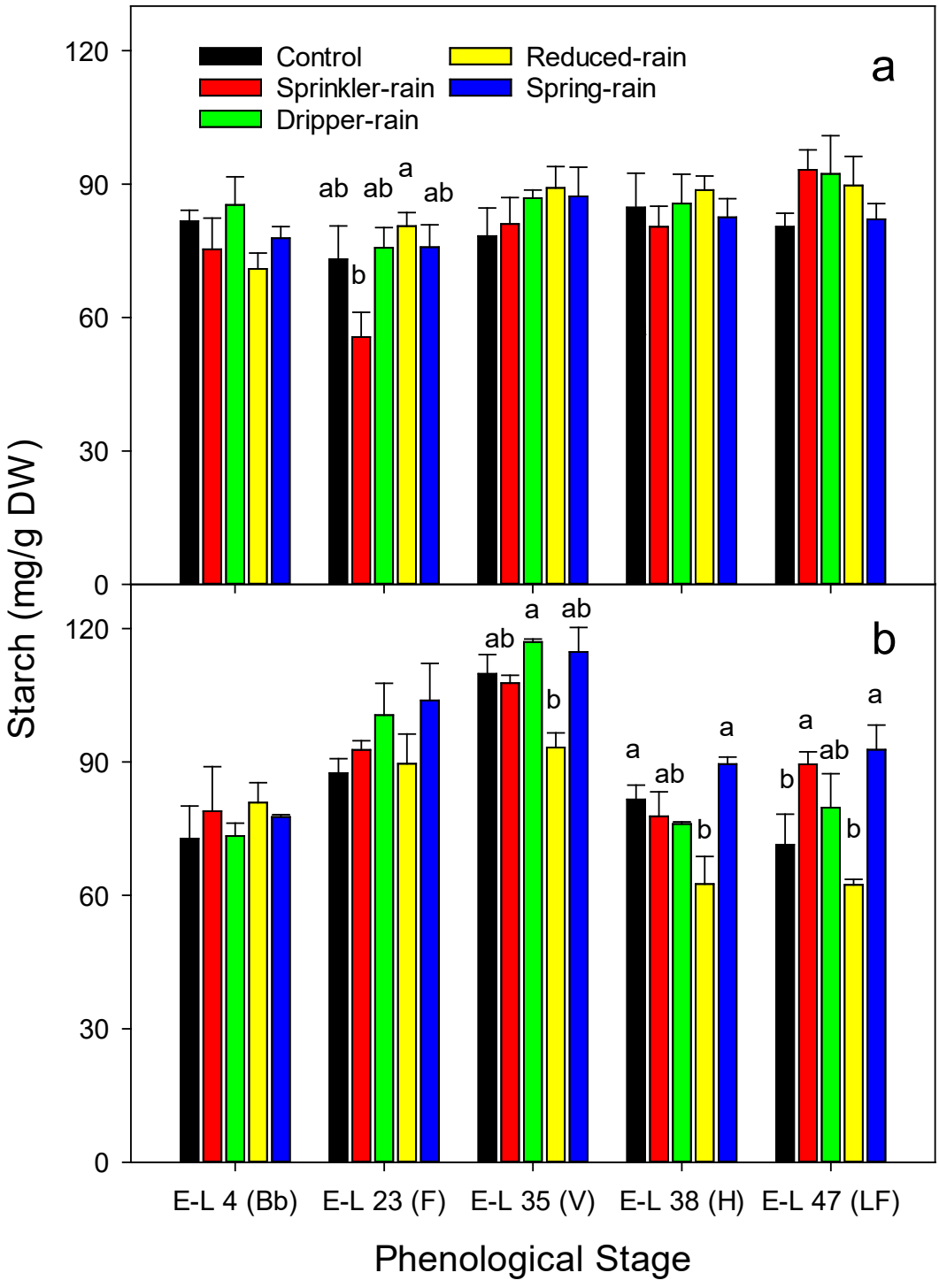


Figure 7:3 Effects of winter irrigation treatments on starch concentration of trunk wood from Shiraz grapevines during season (a) 2015/16 and (b) 2016/17 at key phenological stages: budburst (E-L 4 - Bb), full bloom (E-L 23 - F), veraison (E-L5 - V), harvest (E-L 38 - H) and leaf fall (E-L 47 - LF). Values are averages ± one standard error of four replicates per treatment. Different letters differ significantly at $p < 0.05$ by Fisher's LSD test.

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8 EVALUATION OF WINTER RAINFALL DECLINE ON GRAPE AND WINE CHEMICAL COMPOSITION AND WINE SENSORY ATTRIBUTES

8.1 Introduction

Anecdotally, dry winters and limited spring growth can have a dramatic impact on grape and wine quality. This is potentially due to either direct effects; most likely water stress; or indirect effects such as the increased fruit exposure due to smaller canopies. A better understanding of the causes and impacts of dry winter on grape and wine quality will aid the development of management practices.

8.2 Materials and methods

8.2.1 Assessment of berry ripening and composition

Samples for grape composition were taken weekly from veraison to harvest and analysed using standard analytical technics (Iland, et al. 2004). Samples of 120 berries were generated by sampling from bunches on one side of the vine from the top, middle, bottom, back and front of the bunch. The samples were transported from the field to the laboratory in chilled insulated containers for analysis. Each 120-berry sample was divided into two lots of 60 berries in the laboratory. Juice from one 60-berry sample was extracted using a juice press and clarified by centrifuging at 4000 rpm for 5 minutes. Total soluble solids (TSS) and juice pH and TA (g/L) were measured with an Oenofoss FTIR spectrophotometer (FOSS, Hillerod, Denmark). The Oenofoss parameter ^{o}Brix was calibrated against a bench refractometer (ATAGO PR-101, Tokyo, Japan), and juice pH and TA (g/L) against an automatic titrator (TitraLab 80, Radiometer Copenhagen, Lyon, France). Berry total anthocyanins and phenolic substances were determined according to the method described by Mercurio et al. (2007) using a 96 well plate reader (Spectra Max M2/M2e, Molecular Devices Corporation, California, USA).

8.2.2 Winemaking and wine analysis

Harvest date was defined as the point where juice TSS reached 26 ^{o}Brix. After harvest yield estimation, small scale standardised winemaking was completed on 25 kg of fruit from three field replicates (15 wines in total) by WIC Winemaking Services. Field replicate identity was maintained during the vinification process. One field replicate was eliminated to reduce winemaking cost, based on the highest variability in yield within the vines of the replicate in the 2015/16 season. For the sake of consistency, the same replicate was eliminated in the remaining seasons (2016/17 and 2017/18).

After overnight storage at 0 ^{o}C following harvest, the fruit was destemmed and crushed prior to transfer to 50-L plastic bins. 50ppm SO_2 were added to the must upon crushing and pH correction to 3.6 with tartaric acid. *Saccharomyces cerevisiae* yeasts were inoculated to

conduct primary fermentation (strain Lalvin EC-1118, Lallemand Inc., Montréal, QC, Canada). The juice was fermented on skins at 18 ^{o}C, with yeast assimilable nitrogen adjusted to 200 mg/L after two days with DAP. Lactic acid bacteria (Oenococcus oeni Lalvin VP 41, Lallemand Inc.) were inoculated on day two of alcoholic fermentation, and wines were maintained at 20 ^{o}C until malolactic fermentation was completed. After sugar (< 2 g/L combined glucose and fructose) and malolactic fermentation (< 0.1 g/L malic acid) was completed, wine was treated with potassium metabisulfite to maintain 40 ppm of free SO_2. Cold stabilisation was induced by adding 2 g/L of KHT and placing the wine in the 0 ^{o}C room for a minimum of 28 days. Wines were racked off fining lees and filtered with a cartridge membrane filter prior to bottling.

Wine anthocyanin equilibria and phenolic composition were determined using the modified Somers colour assay (Mercurio, et al. 2007) to coincide with both bottling and the descriptive analysis. Control samples prepared as part of the methyl cellulose precipitable (MCP) tannin assay were used for quantifying phenolic substances at 280 nm in the wine samples. Total tannin concentration was expressed as epicatechin equivalents (mg/L) using an 8-point epicatechin standard curve. The chromatic CIELab coordinates L* (lightness), a* (green/red component) and b* (blue/yellow component) were calculated using the Spectral Colour softwae, version 1.5 (GBC Scientific Equipment Pty Ltd, Braeside, Vic., Australia). Measurements were undertaken at room temperature (21–23 ^{o}C) using a Cintra 40 spectrophotometer (GBC Scientific Equipment Pty Ltd). Wine samples were centrifuged for 5 min at 4000 rpm prior to analysis, prior to being scanned from 380–780 nm at 0.43 nm intervals in a 1-mm quartz cuvette (Starna, Baulkham Hills, NSW, Australia). The daylight illuminant D65, a 10-degree observer angle, and a Milli-Q water blank were used.

8.2.3 Wine sensory assessment

Training for sensory descriptive analysis

A panel of ten (2016), nine (2017) and twelve (2018) assessors with an average age of 50 years was convened to evaluate the wines on both seasons. All panellists were part of the external AWRI trained descriptive analysis panel and had extensive experience in wine sensory descriptive analysis. In both years, assessors attended three two-hour training sessions to determine appropriate descriptors for rating in the formal sessions. All the wines from the study were progressively used during training sessions to generate and refine appropriate descriptive attributes and definitions through a consensus-based approach. Wines were assessed by appearance, aroma and palate. In the second session, standards for aroma attributes were presented and discussed and these standards were also available during subsequent training sessions, the booth practice session and the formal assessment sessions.

Following the third training session, tasters participated in a practice session in the sensory booths under the same conditions as those for the formal sessions. After the practice session, any terms which needed adjustment were discussed and the final list of terms and standards were determined. For the formal sessions, this list was refined to include one appearance terms, fourteen and sixteen aroma terms (last one defined as 'Other' term), fourteen and sixteen palate terms (last one defined as 'Other' term), for seasons 2015/16 and 2016/17 respectively. The final list of attributes, definitions/synonyms and reference standards for both years are shown in Table 8:1.

Sensory assessment

All samples were presented to panelists in 30 mL aliquots, in 3-digit-coded, covered, ISO standard wine glasses at 22–24 ^{o}C, in isolated booths under daylight-type lighting, with randomised presentation order, except in the practice sessions where there was a constant presentation order. All samples were expectorated. In practice booth sessions the assessors were presented with four trays of three wines per tray. In formal booth sessions of two hours duration the assessors were presented with five trays of three wines per tray. The assessors were required to have a 60 second rest between samples and a minimum ten-minute rest between trays. During the ten-minute break assessors were requested to leave the booths. Samples were evaluated over two days of formal sessions.

Fifteen wines were evaluated for each year of this study, presented to assessors twice in a modified Williams Latin Square incomplete random block design generated by the Fizz sensory acquisition software (version 2.47B, Biosystemes, Couternon, France).

The intensity of each attribute was rated using an unstructured 15 cm line scale from 0 to 10, with indented anchor points of 'low' and 'high' placed at 10% and 90% respectively. Data was acquired using Fizz sensory software (version 2.47B, Biosystemes, Couternon, France).

Panel performance was assessed using Fizz, Senstools (OP&P, The Netherlands) and PanelCheck (Matforsk) software, and included analysis of variance for the effect of judge and presentation replicate and their interactions, degree of agreement with the panel mean and degree of discrimination across samples. All judges were found to be performing to an acceptable standard.

Analysis of variance (ANOVA) was carried out using Minitab (Minitab Inc., Sydney, NSW). Following ANOVA, Fishers least significant difference (LSD) value was calculated (p = 0.05). Principal component analysis (PCA) was conducted on the mean values for the treatments averaged over viticultural replicates, panelists and replicates, on the correlation matrix, using the statistical package XLSTAT-Pro, version 2018.6 (Addinsoft SARL, Paris, France).

Table 8:1 Attributes, definitions and reference standards evaluated by panellists in formal sessions for the wines during descriptive analysis in 2016, 2017 and 2018.

Attribute	Definition/Synonyms	Standard*	Year		
			2016	2017	2018
Appearance					
Opacity	Colour intensity, the degree to which light is not allowed to pass through a sample		X	X	X
Aroma					
Blackcurrant	Intensity of the aroma of blackcurrant/Ribena	5 µL of 170 mg/L dimethyl sulfide and 1 mL blackcurrant syrup (Ribena®)			X
Bruised fruit	Intensity of the aroma of bruised fruit and cooked fruit	30 ml control wine left overnight	X		
Capsicum	Intensity of the aroma of capsicum	7 µL of 53.82 mg/L isopropyl-methoxypyrazine (IPMP)		X	
Chocolate	Intensity of the aroma of chocolate	1 g of 70% dark chocolate chips (Absolute Organic)		X	X
Confection	Intensity of the aroma of confection and red lollies	1 red lolly and ¼ musk lolly, not in wine	X	X	X
Dark fruit aroma	Intensity of the aroma of dark fruits and berries: blackberries, plums, black currants, black cherries, blueberries	3 frozen blueberries, 1 frozen blackberry, (Sara Lee brand)	X	X	X
Drain	Intensity of the aroma of dirty drains (natural gas) reminiscent of cooked vegetables and boiled eggs	20 µL of mercaptoethanol 2 % v/v, 1 µL of dimethyl disulfide 0.1% v/v and 0.001 g wood ash		X	X
Dried/Cooked fruit	Intensity of the aroma of 'dusty' dried fig, and dried fruits	4 g dried fig, 2 g red snake lolly (Allen's), and 0.2 g molasses (Beerenberg Family Farm), not in wine		X	
Earthy	Intensity of the aroma of earth, beetroot, leather and mushroom	30 µL of 4mg/L geosmin	X	X	X
Floral	Intensity of the aroma of flowers: roses, violets and honeysuckle	40µL of 100 mg/L linalool, 25µL of 200 mg/L 2-phenyl ethanol	X	X	X
Herbs	Intensity of the aromas of various herbs, dried and fresh: mint, oregano, nutmeg and menthol	1 leaf fresh mint, 1/16 T dried oregano	X		
Medicinal	Intensity of the aroma of leather and medical surgery	30 µL of 4.969 g/L meta-cresol and 10 µL of 10.061 g/L meta-cresol		X	
Mint/Eucalypt	Intensity of the aroma of eucalypt and mint	40 µL of 0.98 g/L 1,8 cineole and 50 µL of Menta Fabbri mint syrup (Sienna foods)		X	X
Overall fruit aroma intensity	Intensity of the fruit aromas in the sample		X	X	
Plastic	Intensity of the aroma of plastic, burnt rubber, chemical and bandaid	50 µL 100 µg/L 1,6 dichlorophenol	X		
Pungent	Intensity of the aroma and effect of alcohol	4 mL of 95% food grade ethanol (Tarac Technologies)	X	X	X
Red fruit aroma	Intensity of the aroma of red fruits and berries: raspberries, strawberries, cranberries and red cherries	3 frozen raspberries (Sara Lee brand)	X	X	X
Savoury	Intensity of the aroma of savoury notes and vegemite	0.1 g beef bouillon cube (OXO)			X
Spice	Intensity of the aroma of mixed spice (baking or cooking) including pepper and aniseed (fennel)	2 dashes of mixed baking spice, pepper corns and 1 piece of aniseed (Master foods)		X	
Stalky	Intensity of the aroma of green stems and stalks, tomato stalks and leaves	1 tomato stalk, 4 x 1 cm pieces of rhubarb, 4 x 1cm pieces of fresh green bean, not in wine	X	X	X
Vanilla	Intensity of the aroma of vanilla	0.1 g whole vanilla bean (Taylor and Colledge brand)		X	X
Vanilla/Chocolate	Intensity of the aroma of vanilla and chocolate	1/8 tsp vanilla paste (Queen brand)	X		
Vegetal	Intensity of the aroma of cooked vegetables, green beans, asparagus, vegetable water and drains	Edgell mixed vegetables, tinned	X		
Palate					
Acidity	Intensity of acid taste in the mouth including aftertaste	2 g/L L-(+)-tartaric acid (Chem-Supply) in water	X	X	X
Astringency	The drying and mouth-puckering sensation in the mouth. Low=coating teeth; Medium=mouth coating & drying; High=puckering, lasting astringency	0.43 g/L alum sulfate (Ajax fine Chem Supply PTY LTD in water	X	X	X
Bitterness	The intensity of bitter taste perceived in the mouth, or after expectoration	0.15 g/L Quinine sulfate (Sigma Aldrich) in water	X	X	X
Blackcurrant	Intensity of the aroma of blackcurrant/Ribena				X
Chocolate	Intensity of the aroma of chocolate			X	
Dark fruit flavour	Intensity of the flavour of various dark fruits: blackberries, currants and plums		X	X	X
Dried/Cooked fruit	Intensity of the flavour of 'dusty' dried fig, sultanas, raisins, jam and stewed fruit confection			X	
Fruit Aftertaste	Intensity of the lingering flavour perceived in the mouth after expectorating		X	X	X
Green	Intensity of the flavour of green stalks and stems, leaves and tomato leaves		X		
Hotness	The intensity of alcohol hotness perceived in the mouth, after expectoration. Low = warm; High = hot. Includes the burning sensation after expectorating	8% food grade alcohol (Tarac Technologies) in water	X	X	X
Mint/Eucalyptus	Intensity of the flavour of eucalypt and mint character, including aftertaste			X	
Overall fruit flavour intensity	Intensity of the overall fruit flavours in the sample		X	X	
Red confection	Intensity of the flavour of red snake lolly				X
Red fruit flavour	Intensity of the flavour of red fruits and berries: raspberries, strawberries, cherries and cranberries		X	X	X
Salty	Intensity of the salty taste of the sample, including aftertaste	1 g/L sodium chloride (brand) in water	X	X	
Spritz	The perception of the spritz, tingling, bubbling experience in the mouth.		X		
Stalky	Intensity of the flavour of green stalks, rhubarb stalks, fresh tomato leaf and stalk			X	X
Sweetness	Intensity of the sweet taste of the sample	8 g/L table sugar (Woolworths essentials) in water	X	X	X
Vanilla	Intensity of the aroma of vanilla			X	X
Viscosity	The perception of the body, weight or thickness of the wine in the mouth. Low=watery, thin mouth feel. High=oily, thick mouth feel	1.5 g/L carboxymethylcellulose sodium salt (Sigma Aldrich) in water	X	X	X

*All aroma standards were added to 30 ml of 2015 Yalumba Classic Dry Red unless otherwise noted

8.3 Results

8.3.1 Berry ripening and fruit composition

During the ripening period and at harvest (targeting 25-26 Brix), quality/style parameters were significantly affected by the irrigation treatments (Table 8:2). Anthocyanin concentrations were affected by the irrigation treatments during the 2015/16 and 2016/17 seasons; generally, the *dripper-rain* and *reduced-rain* treatments recorded the higher anthocyanin concentrations and *sprinkler-rain* the lowest. Tannin concentrations were also significantly affected during the 2015/16 and 2016/17 seasons. However, in this case there wasn't a consistent treatment effect. During the 2015/16 and 2017/18 seasons the *reduced-rain* treatment recorded the highest tannin concentration while in 2016/17 the reverse of this occurred; with the *reduced-rain* recording the lowest tannin concentration. The tannin concentrations were likely responding to the yield in the treatments, which followed an inverse trend (Figure 7:1). The *spring-rain* treatment followed the opposite trend to the *reduced-rain* treatment; the tannin concentration was the highest of the treatments in 2016/17 and lowest in 2015/16 and 2017/18. Across all three seasons the *sprinkler-rain* treatment recorded some of the lowest tannin concentrations.

Phenolic substances only showed a significant treatment effect in 2015/2016 when the *reduced-rain* treatment had the highest values; and the *control*, *sprinkler-rain*, and *spring-rain* the lowest. As is normally observed the anthocyanin concentrations increased as the grapes ripened and the concentrations of tannin and total phenolic dropped (Figure 8:1). The magnitude of these changes varied between seasons, with larger changes seen during the 2015/2015 and 2017/2018 seasons compared to the 2016/2017 season. Generally, the influence of the treatments remained consistent across the sampling points. We successfully selected the harvest date so there was not a significant difference in total soluble solids between the treatments at harvest in 2016/17 and 2017/18; however, in 2015/16 the fruit of the *control* and *spring-rain* were less ripe compared to the other treatments when they were picked. The pH was consistent between treatments in each season and the titratable acidity was only affected by the *reduced-rain* treatment in 2016/17 and the *reduced-rain* and *spring-rain* treatments in 2017/18.

Table 8:2 One-way ANOVA of the effects of winter irrigation treatments on must composition of Shiraz at harvest in 2016, 2017 and 2018.

Parameters	Control	Sprinkler-rain	Dripper-rain	Reduced-rain	Spring-rain	Statistical difference[a]
Season 2015/16						
Anthocyanins (mg/g)	2.0 c[a]	2.0 c	2.3 ab	2.4 a	2.1 bc	*
Anthocyanins (mg/berry)	1.9 b	1.9 b	2.2 a	1.9 b	2.0 b	*
Tannins (mg/g homogenate)	1.5 d	1.6 cd	2.2 b	2.9 a	1.8 c	***
Phenolic substances (au/berry)	10.2 b	10.7 b	12.1 a	11.0 b	11.0 b	*
Phenolic substances (au/g)	11.1 b	11.2 b	12.6 a	13.5 a	11.5 b	***
Total soluble solids (°Brix)	24.6 b	26.0 a	26.1 a	26.1 a	24.8 b	**
Titratable acidity (g/L)	3.7	3.6	3.7	3.7	4.0	ns
pH	3.9	3.9	4.0	4.0	4.0	ns
Season 2016/17						
Anthocyanins (mg/g)	1.4	1.3	1.5	1.4	1.4	ns
Anthocyanins (mg/berry)	1.6	1.5	1.6	1.4	1.5	ns
Tannins (mg/g homogenate)	2.3 ab	2.2 bc	2.3 ab	2.0 c	2.5 a	*
Phenolic substances (au/berry)	7.0 a	6.4 bc	6.3 bc	5.9 c	6.3 bc	*
Phenolic substances (au/g)	6.1	5.7	5.9	6.0	5.8	ns
Total soluble solids (°Brix)	26.5	26.0	26.0	25.6	26.3	ns
Titratable acidity (g/L)	3.4 a	3.3 a	3.3 a	2.7 b	3.2 a	***
pH	4.1 a	4.0 a	4.0 b	4.0 a	4.0 b	*
Season 2017/18						
Anthocyanins (mg/g)	1.5	1.5	1.5	1.5	1.4	ns
Anthocyanins (mg/berry)	2.1 a	2.1 a	2.1 ab	1.8 b	1.8 b	*
Tannins (mg/g homogenate)	3.2	2.9	3.0	3.3	2.9	ns
Phenolic substances (au/berry)	9.4 a	8.9 ab	8.9 ab	8.6 bc	7.9 c	*
Phenolic substances (au/g)	6.6	6.4	6.4	6.9	6.2	ns
Total soluble solids (°Brix)	25.2	25.2	25.1	25.1	25.2	ns
Titratable acidity (g/L)	2.9 c	2.9 c	3.0 bc	3.5 a	3.2 b	**
pH	4.2	4.2	4.2	4.1	4.1	ns

[a] Results for ANOVA conducted on data collected at harvest. Statistical significance of treatments is given by (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$, and (ns) not significant.

[b] Values are means from four repetitions. Within a row, values followed by the same letter are not significantly different according to Fisher's LSD test at $p < 0.05$.

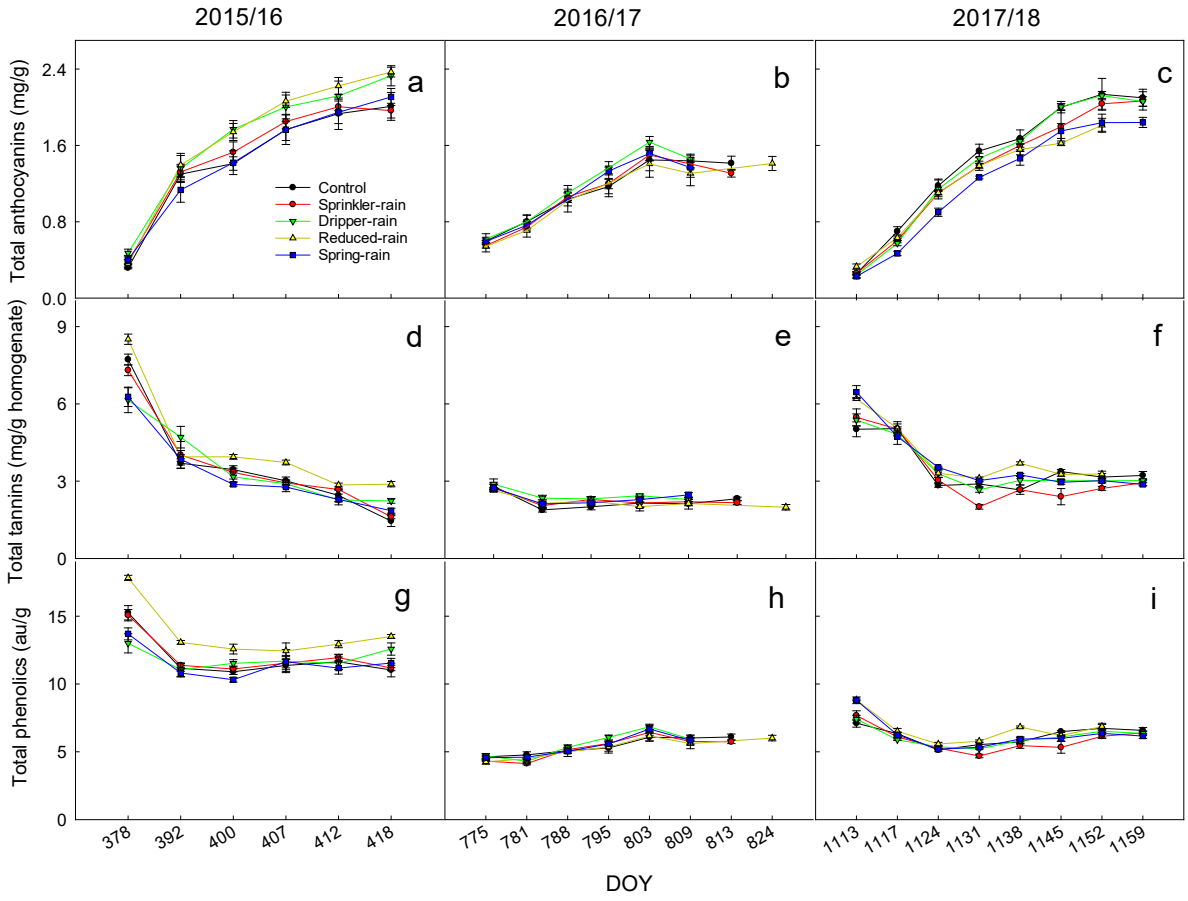


Figure 8:1 Dynamics of (a, b and c) total anthocyanins, (d, e and f) total tannins and (g, h and i) total phenolic substances concentrations on Shiraz during berry ripening in seasons 2015/16 (a, d and g), 2016/17 (b, e and h) and 2017/18 (c, f and i). Values are averages ± one standard error of four replicates per treatment.

8.3.2 Wine composition and sensory attributes

The study includes a chemical characterisation of the wines three-month post bottling, to coincide with the time of the sensory analysis, and approximately nine months after harvest.

To further explore the impact of the irrigation treatments on wine composition, data from the three seasons and from traits where a significant difference ($p < 0.05$) between treatments occurred were subject to principal components analysis (Figure 8:2). The first two principal components (PCs), with eigenvalues greater than one were retained, accounting for between ~92% and ~96% of the observed variation in wine composition and CIELab chromatic differences across the three seasons. The third PC explained less than ~7% of the observed variability in season 2015/16, ~3% in season 2016/17 and ~2% in season 2017/18; therefore, PC3 was excluded from the analysis to simplify the interpretation.

Observed differences in grape phenolic composition between treatments in the season 2015/16 (Table 8:2) were mirrored by the differences in the wines (Figure 8:2). The PCA component loadings on the negative side of PC1 associated *control* and *spring-rain* treatments with the CIELab lightness parameter ($r \geq 0.92$). PC1 segregates the *reduced-rain* treatment on the positive side, and strongly associated this treatment ($r \geq 0.97$) with free anthocyanin, total phenolics, tannins and pigments, and colour density. *Reduced-rain* wines were also associated with the CIELab parameters red tones and colour saturation ($r \geq 0.86$) and with pH a total acid concentration ($r \geq 0.48$). *Sprinkler-* and *dripper-rain* treatments located at the central part of PC1.

The PCs showed a clear separation of treatments within the compositional and chromatic space. Reduced rain in winter caused higher water stress early in the season at the stage when both berry development and canopy growth occur. Smaller berries under *reduced-rain* vines (Table 7:2) lead to a concentration, as opposed to a higher synthesis, of phenolic substances in the berries (Table 8:2), which translated into higher wine phenolic composition and colour. The effect of early water stress on canopy size was also noticeable on *reduced-rain* vines, which showed higher canopy porosity (Figure 6:7) and lower pruning weight (Table 7:3). Although high light interception at bunch level may have favoured the synthesis and accumulation of phenolic substances since early stages of berry development, this effect was not evident in this first season as shown by the overall lower concentration of berry secondary metabolites on a per berry bases (Table 8:2). In contrast, wines from vines with natural winter rain (*control*) had a lower concentration of phenolic substances, which translated to their lighter colour. Interestingly, wines from *spring-rain* vines, which received only half the water applied to the *control*, were chemically and chromatically similar to *control* wines. This suggests that, different from *reduced-rain*, the timing of irrigation in this treatment, i.e. budburst, did not induce early water stress conditions and its beneficial impact in wine phenolic composition. Top-up winter irrigation treatments either using sprinklers or drippers were in an intermediate situation between *control*, *spring-rain* and *reduced-rain* treatments.

PCs component analysis of data from the 2016/17 season showed a higher dispersion of wine composition and irrigation treatments across PC1 than PC2. The PCA component loadings on the negative side of PC1 associated the *reduced-rain* and *sprinkler-rain* treatments with pH ($r \geq 0.87$). PC1 segregate *dripper-* and *spring-rain* treatments on the positive side, and strongly associated these treatments ($r \geq 0.95$) with the percent of pigmented tannins, chemical age and total acidity. Wines from these treatments were also associated to a higher colour saturation and intensity of red tones.

The PCs analysis of the data during season 2017/18 also showed a good separation of irrigation treatments in the compositional and chromatic space. The PCA component loadings on the positive side of PC1 strongly associated ($r \geq 0.95$) the *reduced-rain* and *control* treatments with free anthocyanin and total pigments. *Sprinkler-, dripper- and spring-rain* treatments located at negative part of PC1, and were associated ($r \geq 0.71$) with the percent

of pigmented tannins, chemical age 1 and 2, and with the higher intensity of blue tones and hue angle. PC2 separated *Dripper*- and *Reduce-rain* treatments on its positive side, due to their higher concentration of total tannins and phenolic substances. Reduced-rain treatments also showed a higher total acidity in the grapes (Table 8:2) and in the finished wines (Figure 8:2c). *Spring-rain* and *Control* treatments, on the negative side of PC2, were correlated (r = 0.82) with the CIELab lightness parameter; reflecting the lighter colour of wines from these treatments.

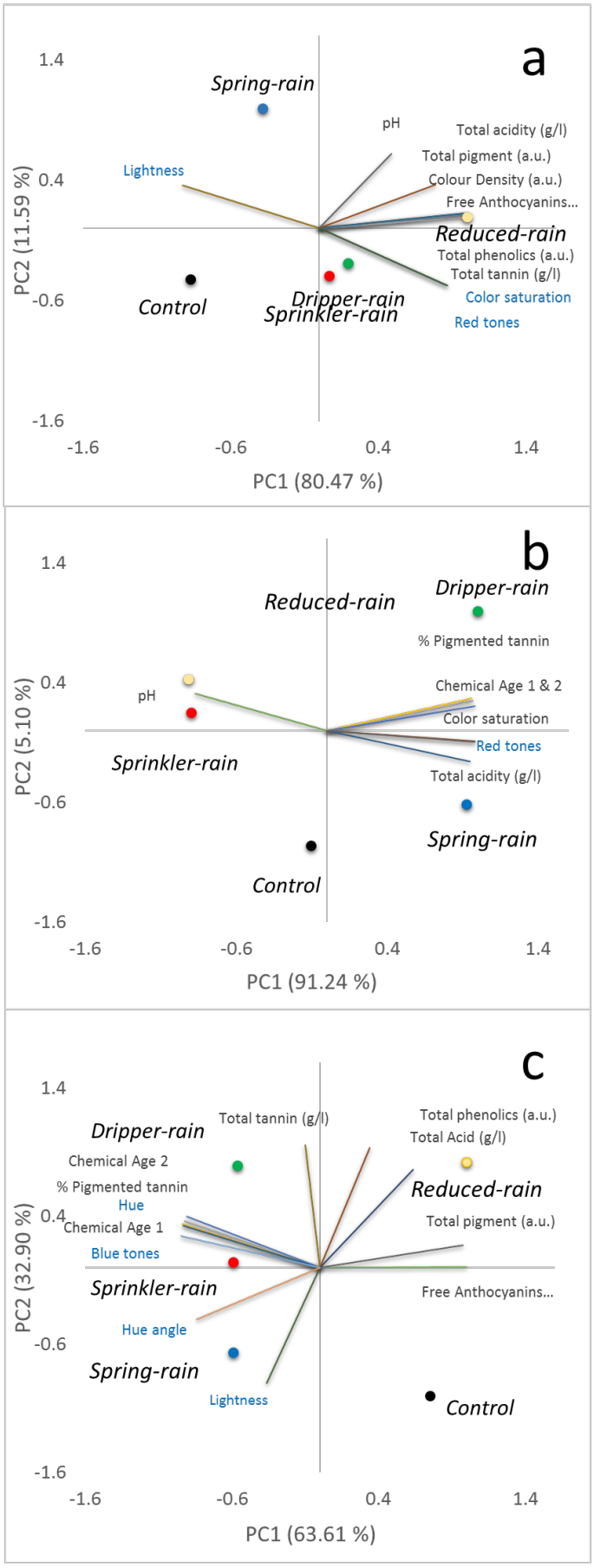


Figure 8:2 Principal component (PC) analysis of Shiraz wine that had been bottled for three months, compositional (black font) and chromatic (blue font) data during vintages (a) 2015/16, (b) 2016/17 and (c) 2017/18.

8.3.3 Wine sensory composition

The ANOVA showed that eight of the twenty-seven attributes assessed in 2016 treatments were rated as significantly different ($p \leq 0.05$) (opacity, dark fruit aroma, red fruit aroma, viscosity, dark fruit flavour, earthy aroma, vegetal aroma and spritz), and one at a near significant level $p \leq 0.10$ (green flavour). Principal Component Analysis (PCA) was performed on the significant sensory attributes and those close to significance for the mean values for each treatment. The first two PCs were important in showing the variation in the dataset. Figure 8:3 shows the scores and loadings for PC1 and 2, which account for ~87% of the variance. Wines from *sprinkler-*, *dripper-* and *reduced-rain* treatments were all found to be similar, aggregating together on the positive side of PC1. These wines exhibited high opacity, earthy aroma, viscosity, dark fruit aroma and flavour, and relatively low red fruit aroma and green flavour. Wines from *control* vines were the most different to the other treatments and were the highest in red fruit aroma and green flavour, as well as being the lowest in all other significant attributes. Wines from spring-rain vines were rated second lowest in opacity, dark fruit aroma and flavour, and viscosity; and were rated highest in spritz and vegetable aroma, both undesirable attributes in finished wines.

From the ANOVA for the Shiraz wines from 2017, eleven attributes were rated by the panel as significantly ($p \leq 0.05$) different among the treatments. These attributes included: opacity (colour intensity), red fruit aroma, dark fruit aroma, red confection aroma, floral aroma, vanilla aroma, mint/eucalyptus aroma, dank drain aroma (reduction) and earthy aroma, sweetness and astringency. Three attributes, dark fruit flavour, dried fruit flavour and vanilla flavour, were close to being significant ($p \leq 0.10$). The PCA for the Shiraz wines was created using the fourteen attributes that were significantly different ($p \leq 0.10$) across the five treatments (Figure 8:3). The first two PCs were important in showing the variation in the dataset and accounted for ~81% of the variance. Wines from *sprinkler- and spring-rain* treatments were all found to be similar and aggregated closer on the positive side of PC1. These wines exhibited high drain and earthy aromas, opacity, dark fruit aroma and astringency. The attributes red fruit aroma, red confection aroma, mint/eucalypt aroma and floral aroma were negatively loaded on PC1. Wines from *reduced-rain* vines located on the far left of PC2 were most associated with these attributes. The attributes vanilla aroma and flavour, floral aroma and dark fruit flavour were most positively loaded on PC2 while sweetness was most negatively loaded on PC2. These attributes contribute the most to the vertical axis separation on *control* and *sprinkler-rain* wines. Wines from *control* vines were the highest in vanilla and floral aromas, whereas wines from *dripper-rain* vines were rated the highest in sweetness.

From the ANOVA for the wines from 2017/18, six attributes were rated by the panel as significantly different ($p < 0.05$) among the irrigation treatments. These attributes included: *opacity* (colour intensity)*, mint/eucalyptus aroma, drain aroma* (reduction), *savoury aroma*, *astringency* and *dark fruit flavour.* Three attributes: *blackcurrant aroma, stalky aroma,* and *bitterness* were close to being significant ($p < 0.10$). The PCA plots for the wines were created

using the nine attributes that were significantly different ($p < 0.05$) and close to significant ($p < 0.10$) across the five irrigation treatments. PC1 and 2 explained ~44% and 31.2% of the variation in the data. Beyond the second principal component eigenvalues approached or were below 1 and explained little variability in the data and were therefore excluded from the analysis. Wine from the *dripper*- and *deficit-rain* treatments were rated highly for the attributes that were positively loaded on PC1, notably astringency, mint/eucalypt aroma, opacity and blackcurrant aroma. Conversely, wine from *control* and *spring-rain* treatments were plotted to the negative site of PC1, being rated lower in these attributes and rated highly in attributes negatively loaded on PC1, notably stalky and drain (reduction) aromas. The vertical separation of the treatments was determined by the intensity of attributes most positively or negatively loaded on PC2. Notably, the *sprinkler-rain* treatment wines were positioned higher, being rated high in bitterness, while wines from the other treatments were rated lower in this attribute.



Figure 8:3 Principal Component (PC) analysis of Shiraz wine that had been bottled for three months, descriptive data during vintages (a) 2015/16, (b) 2016/17 and (c) 2017/18. Attribute name followed by A refers to aroma and F to flavour.

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9 WINTER RAINFALL DECLINE AFFECTS THE ACCUMULATION OF SALTS IN THE SOIL OF THE VINEYARD

9.1 Introduction

Vineyard soils in the Barossa Valley are characterised by an increase in salinity due to added salt from the irrigation water during the dry summer months, followed by the flushing of salts from the soil due to winter rainfall. Therefore, the salinity of the soil is indicative of the balance between salts added with irrigation and salts flushed out from the soil by natural rain. As observed in other studies, winter rains leach about 75% of the salt from soils under the vine and help to maintain soil salinity below the threshold for salinity damage to occur (Stevens, et al. 2012). Insufficient winter rainfall may therefore lead to the build-up of salts, bringing soil salinity closer to the threshold for salinity damage, especially if water with high salt content is used for irrigation. In this context, we hypothesised that supplementary irrigation during winter that restored winter rainfall may prevent salt accumulation, while reduced rainfall would allow salt accumulation.

9.2 Material and methods

9.2.1 Soil sampling

Soil samples were collected twice during the season. The first sampling was conducted around budburst, coinciding with the period when soil moisture is expected to be at its maximum in the *control* treatments. The second sampling time, at veraison, occurred when the profile is expected to be dry. Samples were collected up to one-metre depth using a 5 cm internal diameter hydraulic hammer-driven probe and at three positions from the central vine of each replicate, i.e. mid-row, 75cm from the vine and adjacent to the vine. Core samples were divided into three equal sections (approximately 33 cm long) and bagged.

9.2.2 Soil salinity and pH

Soil salinity was measured as the electrical conductivity of 1:5 soil:water extracts (EC1:5) following the method described in Stevens *et al.* (2012) using a temperature compensated conductivity meter (model CON510, Eutech, Singapore) and reported at 25 ^{o}C. The soil pH was measured on the 1:5 soil:water extract using a temperature compensated pH meter (model pH 510, Eutech, Singapore) and reported as pH (1:5 soil:water) at 25 ^{o}C.

9.2.3 Gravimetric soil water content

Water content of soils was assessed gravimetrically. The values of soil bulk density used to convert gravimetric values of soil water content to volumetric were determined in the vineyard in summer 2016. Volumetric samples of soil were obtained with brass rings (0.07 m diameter and 0.07 m depth). Soil was dried at 105 ^{o}C until it reached a constant weight.

9.3 Results

9.3.1 Seasonal variation in soil salinity

We assessed soil salinity at spring and mid-summer in seasons 2015/16, 2016/17 and 2017/18. For all the irrigation treatments and sampling dates, soil EC1:5 was below the threshold value of 2100 us/cm for salinity damage in own-rooted vines (Figure 9:1). Although it was below the level at which damage is expected to occur, the reduced-rain treatment consistently had the highest EC1:5.

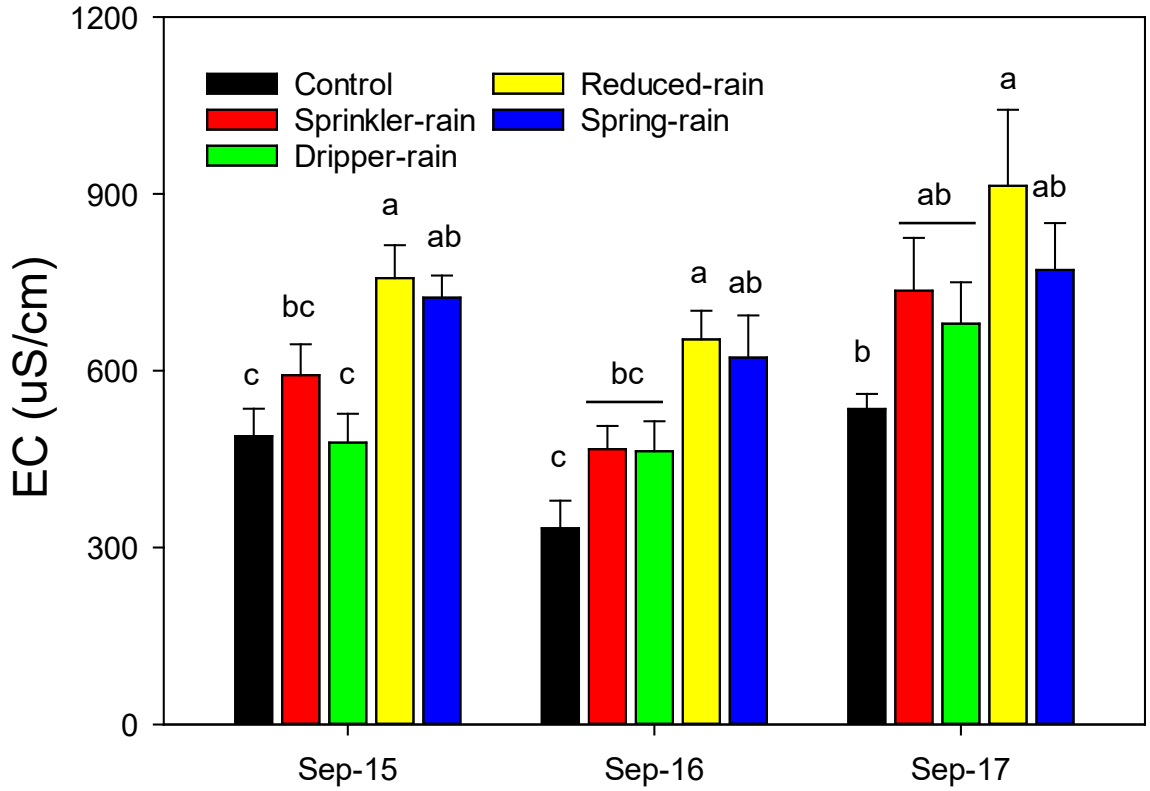


Figure 9:1 Effects of winter rainfall and supplementary irrigation on the dynamics of soil salts accumulation during spring of seasons 2015/16, 2016/17 and 2017/18. Bars are means ± one standard error of four replicates per treatment. Different letters indicate means that differ significantly at $p < 0.05$ by Fisher's LSD test.

Table 9:1 summarises results from the ANOVA comparing soil EC1:5 between irrigation treatments, seasons, sampling times, positions of soil cores, sample depths, and their interactions. There was a significant seasonal effect on soil EC1:5 ($p < 0.001$); dry seasons, such as 2015/16 and 2017/18, with reduced rainfall in spring and summer, contributed to the build-up of salts in the soil. However, as suggested by the also high order interaction between season x depth ($p = 0.004$) and between season and sampling time ($p = 0.016$), during dry

years, in duplex soils (see section 5.1) salts accumulated more at subsoil level, from 30 to 100 cm depth, and soil salinity content increased towards summer months as the soil dried.

Table 9:1 Effect of winter irrigation treatments on soil EC1:5 and pH during seasons 2015/16, 2016/17 and 2017/18. Values are means. *P* values correspond to the one-way ANOVA. Means followed by different letters differ significantly at $p < 0.05$ by Fisher's LSD test.

Source of variation	EC1:5	pH
Treatment (T)		
Control	571.8 c	7.7 b
Sprinkler-rain	659.7 b	7.8 b
Dripper-rain	566.3 c	7.6 c
Reduced-rain	771.9 a	7.7 ab
Spring-rain	699.5 b	7.8 a
p-value	**< 0.001**	**< 0.001**
Season (S)		
2015/16	666.5 b	7.8 b
2016/17	537.7 c	7.9 a
2017/18	757.4 a	7.5 c
p-value	**< 0.001**	**< 0.001**
Sampling time (ST)		
Budburst	631.8 b	7.8 a
Veraison	675.9 a	7.6 b
p-value	**0.012**	**< 0.001**
Depth (D)		
0 to 33	461.7 c	7.3 c
33 to 66	620.2 b	7.7 b
66 to 99	879.6 a	8.2 a
p-value	**< 0.001**	**< 0.001**
Position (P)		
Adj Vine	666.5 b	7.8 a
75 cm	708.8 a	7.6 b
Mid Rw	586.2 c	7.8 a
p-value	**< 0.001**	**< 0.001**
T x S	0.545	0.081
T x ST	0.067	0.882
T x D	**0.005**	**< 0.001**
T x P	**< 0.001**	0.171
S x ST	**0.016**	0.096
S x D	**0.004**	**0.013**
S x P	0.121	0.451
ST x D	0.508	0.867
ST x P	0.978	0.919
D x P	**< 0.001**	**< 0.001**

Coinciding with the period when soil moisture was at its maximum, i.e. end of winter (Figure 5:14), during the three seasons, the average salinity of *reduced-* and *spring-rain* treatments, which simulate reduced winter rainfall, was significantly higher than the treatments that aim to fully replenish natural winter rainfall (Figure 9:1). As indicated by the significant treatment x depth (p = 0.005) and treatment x sampling position (p < 0.001) interactions (Table 9:1), under these treatments, salt accumulation was greater at the subsoil, from 30 to 100 cm, and up to 75 cm from the vine trunk, correlating with the outer edge of the irrigation wetted area and the root zone. These same treatments also lead to the accumulation of salts between seasons, even in a situation where water used for irrigation was low on salt content. Not surprisingly, irrigation in winter with drippers decreased soil salt content under the dripper line and up to 100 cm depth (data not shown).

10 OUTCOMES AND CONCLUSIONS

This project successfully developed and implemented experimental treatments designed to replicate winter drought for the three seasons 2015-16 through to 2017-18. A shelter system was erected so that rainfall was excluded during winter, with the covers being installed in May and removed in August. Irrigation treatments that were designed to replicate rainfall or irrigation programs designed to respond to low winter rainfall were implemented; and vine response in terms of phenology, growth (canopy, roots and fruit) and physiology were monitored. Generally (as reported above) the experimental program performed as expected. The root monitoring using the mini-rhizotron system proved challenging and did not provide definitive results as compared to root sampling using soil cores or observations that could be expected based on canopy growth. We are uncertain why this occurred. Given the high labour requirements for the sample collection and image processing from the mini-rhizotron system; for future projects these resources may be better deployed by collecting soil cores at higher intensity or more often during the season.

Vines that received natural winter rain had the highest yield. A reduction in winter rain to approximately one third of the historical average had a major impact; reducing yield between 20 to 40%. Irrigation during winter (to replace rainfall), either using sprinklers or drippers to refill the soil profile, did not prevent a decline in yield by around 7 to 23%. Likewise, irrigation to refill the soil profile at budburst did not prevent a yield reduction by around 10 to 32% and promoted vegetative growth.

The method and timing of winter irrigation were also important factors altering vine balance. Refilling the soil profile in spring using sprinkler irrigation during dry winters delayed development and stimulated vegetative growth over yield resulting in vines that were out of balance. A similar effect on vegetative growth was observed with drip irrigation that replaced 100% of winter rain. In contrast, when natural rain or sprinkler irrigation provided water during winter the vines showed better balance as measured by a higher yield to pruning weight ratio.

The winter irrigation treatments had a major impact on berry composition at harvest; which translated into the phenolic composition of young wines. This was especially evident in the *reduced-rain* treatment. It is likely the altered canopy microclimatic due to the irrigation treatments caused the differences in grape composition.

Seasonal conditions also impacted on the results; this was especially evident for the *reduced-rain* treatment. The 2015-16 and 2017-18 seasons had relatively dry springs; however, more rainfall occurred in the 2016-17 spring. This meant that the soil profile was filled shortly after the rain exclusion covers were removed. The yield of the *reduced-rain* treatment was significantly reduced compared to the control in the two dry years; but in the wetter year was similar to the control.

Prior to the initiation of the project the awareness by the industry of the impact of dry winters on vine performance was anecdotal and generally low. This project has demonstrated the

negative impacts dry winters have on vine yield. More importantly it has shown that the most common management practice; that is refilling the soil profile in spring, is likely to be counterproductive and result in an increase in canopy size and a reduction in yield. Although maintaining some moisture in the soil profile throughout the winter did not consistently restore yield to the level of the control, this is currently our best management option.

11 RECOMMENDATIONS

Virtually all Australian vineyards are irrigated using drip-based systems. The methods trialled to restore winter rainfall (and drip irrigation-based treatment) did not consistently restore yield to a level that was similar to the control (natural rain). A new Wine Australia-supported project 'Climate adaptation: developing irrigation strategies to combat dry winters' has been initiated from the 2018-2019 season. The key focus of this project is the evaluation of drip-irrigation based methods to supplement low winter rainfall; with the aim to maintain yield following dry winters (Figure 10:1). An experimental plan has been developed that will alter the soil wetting pattern by using multiple rows of drippers and extend the irrigation period at the beginning of spring. Based on results described above, the expectation is that these management options will restore vine performance to a similar level to the control treatment.



Figure 10:1 Relocation of structure for rain out shelter during autumn 2018. Structures were relocated and secured in their new positions to accommodate the new experimental design.

12 COMMUNICATION

Presentations:

- Bonada, M., Petrie, P.R., Edwards, E.J. and McCarthy, M.G., (2016) Assessing the impact of winter drought on vine balance and root activity. 16th Australian Wine Industry Conference (AWITC). Adelaide, Australia, 24-28 July.

- Bonada, M., Petrie, P.R., Edwards, E.J. and McCarthy, M.G., (2017) Managing winter drought. Effects on vine balance, grape and wine composition and root growth. 2017 Vintage update & Barossa Grape & Wine Association (BGWA) forum. Nuriootpa, Australia, 8 June.

- Bonada, M., Petrie, P.R., Edwards, E.J. and McCarthy, M.G., (2017) Managing winter drought. Effects on vine balance, wine composition and sensory traits. Crush 2017 the grape and wine science symposium. Adelaide, Australia, 13-14 November.

- Bonada, M., Petrie, P.R., Edwards, E.J. and McCarthy, M.G., (2017) Managing the impacts of climate change rainfall decline on vine balance, grape and wine composition and root growth. SARDI Waite Seminar Series 2017. Focus on viticulture. Adelaide, Australia, 16 November.

- Bonada, M. Latest drought / Irrigation data in vineyards. ELDERS Viticulture. A Growers Information Evening. Tanunda, SA, 26th June 2018.

- Bonada, M., Petrie, P.R., Edwards, E.J. and McCarthy, M.G., (2018) Managing vineyard irrigation during dry winters. Crush 2018 the grape and wine science symposium. Adelaide, Australia, 25-26 September.

Radio interviews:

- Petrie P.R. and Bonada, M. 2017. What do you do when it doesn't rain in winter? Wine Australia News. Wine Australia, Australia.

Workshops and technology transfer

- Bonada M. and Edwards, E.J. held a field day in the SARDI's Nuriootpa Research Station to show the winter drought trial and discuss best practices for root phenotyping in field trials. The field day carried out the 5th of October was attended by 23 scientists in the context of The 5th International Plant Phenotyping Symposium, titled 'From plant, to data, to impact', held in Adelaide, from 2-5 October 2018.

- Wine Australia RD&E News Article, April 2018. Replacing rain can't be a one-off exercise. https://www.wineaustralia.com/news/articles/replacing-rain-can%e2%80%99t-be-a-one-off-exercise

- Wine Australia RD&E News article, August 2017. What do you do when it doesn't rain in winter? https://www.wineaustralia.com/news/articles/what-do-you-do-when-it-doesnt-rain-in-winter

Industry journals:

- Bonada, M. and Petrie, P.R. 2018. Watering down the impact of climate change on vineyards. Australian and New Zealand Grapegrower & Winemaker September (644): 41-43.

- Bonada, M. and Petrie 2018. Watering down the impact of climate change on vineyards. The Lead. August 29th.

- Bonada, M., Petrie, P.R., Edwards, E.J. and McCarthy, M.G., 2017. The impact of winter drought on vine growth and wine quality. Australian and New Zealand Grapegrower & Winemaker October (657): 60-62.

13 STAFF

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Advisors: Mark Sosnowski and Victor Sadras

SARDI technical assistance: Gaston Sepulveda, Bruce Henderson, Anthony Pearce and Matthew Hay

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Tim Pitt (SARDI) for reviewing the final report.

15 REFERENCES

Berli, F.J., R. Alonso, R. Bressan-Smith, and R. Bottini (2013) UV-B impairs growth and gas exchange in grapevines grown in high altitude. Physiologia Plantarum 149, 127–140. doi: 10.1111/ppl.12012.

Bouma, T.J., K.L. Nielsen, and B. Koutstaal (2000) Sample preparation and scanning protocol for computerised analysis of root length and diameter. Plant and Soil 218, 185-196. doi: 10.1023/a:1014905104017.

Bureau of Meteorology, "Climate statistics for Australian locations", edited by B.o. Meteorology (National Climate Centre, Melbourne, Australia, 2016), Vol. 2013.

Cai, W. and T. Cowan (2008) Dynamics of late autumn rainfall reduction over southeastern Australia. Geophysical Research Letters 35. doi: 10.1029/2008GL033727.

Coombe, B.G. (1995) Growth stages of the grapevine: adoption of a system for identifying grapevine growth stages. Australian Journal of Grape and Wine Research 1, 104–110.

de Loryn, L.C., P.R. Petrie, A.M. Hasted, T.E. Johnson, C. Collins, and S.E.P. Bastian (2014) Evaluation of Sensory Thresholds and Perception of Sodium Chloride in Grape Juice and Wine. American Journal of Enology and Viticulture 65. doi: 10.5344/ajev.2013.13088.

Dry, P.R., D.J. Maschmedt, C.J. Anderson, E. Riley, S.-J. Bell, and W.S. Goodchild (2004) The grapegrowing regions of Australia. In: Viticulture. Volume 1 – Resources, Eds. P.R. Dry and B.G. Coombe (Winetitles: Adelaide, SA, Australia) pp. 17–55.

Hsiao, T.C. (1990) Measurements of plant water status. In: Irrigation of agricultural crops, Eds. B.A. Stewart and D.R. Nielsen (ASA, CSSA, SSSA: Madison) pp. 243–279.

Iland, P., N. Bruer, A. Edwards, S. Weeks, and E. Wilkes (2004) Chemical analysis of grapes and wine: techniques and concepts. (Patrick Iland Wine Promotions: Campbelltown, SA).

Maschmedt, D.J. (2004) Soil and Australian Viticulture. In: Viticulture. Volume 1 – Resources, Eds. P.R. Dry and B.G. Coombe (Winetitles: Adelaide, SA, Australia) pp. 56-89.

McCarthy, M.G., L.D. Jones, and G. Due (2004) Irrigation - Principles and practices. In: Viticulture. Volume 2 – Practices, Eds. P.R. Dry and B.G. Coombe (Winetitles: Adelaide, SA, Australia) pp. 104-128.

Mendez-Costabel, M.P., K.L. Wilkinson, S.E.P. Bastian, C. Jordans, M. McCarthy, C.M. Ford, and N. Dokoozlian (2014) Effect of winter rainfall on yield components and fruit green aromas of Vitis vinifera L. cv. Merlot in California. Australian Journal of Grape and Wine Research 20, 100-110. doi: 10.1111/ajgw.12060.

Mercurio, M.D., R.G. Dambergs, M.J. Herderich, and P.A. Smith (2007) High throughput analysis of red wine and grape phenolics−adaptation and validation of methyl cellulose precipitable tannin assay and modified Somers color assay to a rapid 96 well plate format. Journal of Agricultural and Food Chemistry 55, 4651–4657. doi: 10.1021/jf063674n.

Murphy, B.F. and B. Timbal (2008) A review of recent climate variability and climate change in southeastern Australia. International Journal of Climatology 28, 859-879. doi: 10.1002/joc.1627.

Myers, B.J. (1988) Water stress integral-a link between short-term stress and long-term growth. Tree Physiology 4, 315-323.

Sadras, V.O. and M.A. Moran (2013) Nonlinear effects of elevated temperature on grapevine phenology Agricultural and Forest Meteorology 173 107–115.

Soar, C.J. and B.R. Loveys (2007) The effect of changing patterns in soil-moisture availability on grapevine root distribution, and viticultural implications for converting full-cover irrigation into a point-source irrigation system. Australian Journal of Grape and Wine Research 13, 2-13. doi: 10.1111/j.1755-0238.2007.tb00066.x.

Speirs, J., A. Binney, M. Collins, E. Edwards, and B. Loveys (2013) Expression of ABA synthesis and metabolism genes under different irrigation strategies and atmospheric VPDs is associated

with stomatal conductance in grapevine (*Vitis vinifera* L. cv Cabernet Sauvignon). Journal of Experimental Botany 64, 1907-1916. doi: 10.1093/jxb/ert052.
Stevens, R.M., T.R. Pitt, and C. Dyson, "Managing soil salinity in groundwater irrigated vineyards", (SARDI, 2012).
Stevens, R.M., T.R. Pitt, and C. Dyson (2013) Changes in vineyard floor management reduce the Na+ and Cl- concentrations in wine grapes grown with saline supplementary drip irrigation. Agricultural Water Management 129, 130-137. doi: 10.1016/j.agwat.2013.07.009.
Zeng, G., S.T. Birchfield, and C.E. Wells (2008) Automatic discrimination of fine roots in minirhizotron images. New Phytologist 177, 549-557. doi: 10.1111/j.1469-8137.2007.02271.x.
Zerihun, A., D.M. Lanyon, and M.R. Gibberd (2010) Vine vigour effects on leaf gas exchange and resource utilisation. Australian Journal of Grape and Wine Research 16, 237-242. doi: 10.1111/j.1755-0238.2009.00080.x.