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

INTERIM REPORT for period April 2013 – August 2017

Project number: SAR 1302

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Research Organisations: SARDI and CSIRO Agriculture and Food

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1 INTRODUCTION

This project aims to determine the impact of low rainfall during winter on (i) vine balance, (ii) fruit quality parameters, (iii) wine chemical and sensory characteristics, (iv) root growth and (v) carbohydrate reserves storage. Outcomes of the project will be used to develop management strategies for growers to help minimise negative impacts of winter rainfall deficit. The project commenced in 2013 with the installation of the field trial (shelters and irrigation system); and the results from the first experimental season (2015/16) are the subject of this report.

2 SUMMARY OF THE PROJECT PROGRESS TO DATE

A. Successfully established and operated a field trial to simulate reduced winter rainfall during seasons 2015/16 and 2016/17.
   
   • Rain-out shelters were deployed in the field (May 2015 and 2016) and winter irrigation treatments imposed from May to August 2015 and 2016.
   
   • Phenology and soil water content were monitored on a weekly basis throughout the season.
   
   • Physiological measurements (photosynthesis, stomatal conductance and stem water potential) and canopy development (leaf area index, LAI) were characterised at key phenological stages throughout the growing season (September – March). Only evolution of stem water potential over seasons one and two are reported here.
   
   • Yield and its components were assessed at harvest.
   
   • Sampling for carbohydrate analysis was conducted at budburst, flowering, veraison, harvest and leaf fall. Samples from both seasons have been pre-processed and analysed.
   
   • Sampling for abscisic acid (ABA) analysis was conducted at budburst during seasons 2015/16 and 2016/17. Extra root sampling was conducted during winter of season 2016/17 with the aim of revealing patterns of ABA synthesis and storage before budburst. Samples from budburst have been pre-processed and analysed by HPLC.
   
   • Berry sampling from pre-veraison through to harvest to determine the impact of treatments on berry maturation and phenolic composition. Berry composition analysis has been completed.
   
   • In both seasons, small scale ferments have been made using fruit from three field replicates of each treatment.
• Analysis of phenolic substances on wines at bottling and with the descriptive sensory analysis (three months after bottling) have been completed on wines from season 2015/16. Descriptive analysis has been completed on wines from both seasons. Only results from the first season are reported here.

• Mini-rhizotron images were collected approximately every three weeks from budburst in September 2015. Complementary soil core sampling at budburst and veraison to assess root growth, soil water content and salts was undertaken in both seasons.

• Winter pruning was conducted in June and July 2016 and 2017, respectively, and vegetative growth assessed.

B. Datasets combining viticulture and fruit composition provide an initial understanding of the effects of winter rainfall deficits on vine balance, vegetative growth and grape and wine composition. Preliminary project outcomes have been delivered to industry through industry magazines, conference presentations, presentations to growers and a media interview. See Communication section at the end of this document.

C. A new image processing tool has been developed to hasten the initial stage of processing and sorting root images from the mini-rhizotron.

• A root image library has been created. Images are sorted, pre-processed and progressively loaded to the library. The turnover of roots is being assessed in parallel with root image acquisition and processing.


• Rain-out shelters were successfully deployed in the field (May 2017) and irrigation treatments successfully imposed (May to early September 2017).
3 SIGNIFICANT OUTCOMES OF YEAR 1 (2015/16)

Direct effect of treatments on yield. 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 by 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 approximately 20%. Likewise, irrigation to refill the soil profile at budburst did not prevent a yield reduction and promoted vegetative growth.

Treatments altered vine balance. The method and timing of winter irrigation were also important factors altering vine balance (yield to pruning weight ratio). Refilling the soil profile in spring using sprinkler irrigation advanced 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.

Effects of winter irrigation on berry and wine composition

The winter irrigation treatments had a major impact on berry composition at harvest; which translated into the phenolic composition of young wines. It is likely the altered canopy microclimate due to the irrigation treatments caused the differences in grape composition.

Industry applicable outcomes

Based on the first season’s results a reduction in winter rain is associated with major changes in grape production.

- Treatments that maintained the soil profile during winter using irrigation did not fully offset the decline in production.
- Refilling the soil profile at the end of winter increased vigour over yield and did not improve fruit and wine composition.
- Reduced canopy growth early in the season due to rainfall exclusion appeared to improve grape quality, but yield was markedly lower.
- Alternative application times and methods that can fully compensate for a reduction in winter rainfall will need to be explored.

The project successfully achieved its milestones during the first experimental season; these included the imposition of the reduced rainfall treatments and the collection of data on canopy and root growth and development, yield and yield components and vine physiology. The carbohydrate analyses remain to be completed and the root images need to be collated and analysed. The experimental plan for the 2016/17 season followed a similar pattern to
2015/16. This was to account for the interaction of seasonal variation and the rainfall reduction treatments, as well as investigating the cumulative effects on vine growth and salinity.

Results from the first season showed that none of the rainfall replacement methods trialled were able to maintain vine yield at a level similar to the control. The cause of the yield reduction and methods to prevent it occurring remained the focus of the following season and additional strategies to maintain yields following low winter rainfall will become the subject of future work.
4 PROJECT AIMS AND PERFORMANCE TARGETS

1. Large scale field experiment using rain-out 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 through the use of existing sampling protocols and mini-rhizotrons.

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 for dry winters.

Integrate seasonal rainfall outlook and impacts of reduced rainfall on vine balance into appropriate 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.
5 PRELIMINARY RESULTS FROM SEASONS 2015/16 AND 2016/17

5.1 General Introduction

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 restricted water for irrigation (~1.0 ML/ha season) and predictions of winter rainfall decline will place increasing strain on these production systems. This makes anticipating the effects of climate-driven shifts in rainfall on vineyard performance a strategic aim of the wine industry. This study investigates the effects of winter rainfall exclusion and rainfall replacement options on vine phenology, vine balance and fruit and wine quality parameters. The impact of dormant season soil water deficit on root development is being investigated using soil core sampling and mini-rhizotrons.

6 LARGE SCALE FIELD EXPERIMENT USING RAIN-OUT SHELTERS TO SIMULATE REDUCED WINTER RAINFALL

6.1 Introduction

The trial was established in 2013 at the SARDI Nuriootpa Research Station (34 °S, 139 °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°C and the average annual rainfall is 502 mm. The experimental site has a duplex soil with thin sandy loam over a restrictive red clay subsoil (Maschmedt 2004). 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.

6.2 Treatment details

Five treatments were arranged in a randomised complete block design with four replications which aimed to exclude and then replenish winter rainfall using drippers or sprinklers and included:

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 \((spring-rain)\).

<table>
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<th>Vine No</th>
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<th>REP 2</th>
<th>REP 3</th>
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</tbody>
</table>

Treatments
1. Control
2. Sprinklers rain
3. Dripper rain
4. Reduced rain
5. Spring rain

Buffer vines

**Figure 6:1** Experimental design

*Rainfall exclusion and top-up irrigation*  
With reduced irrigation using sprinklers  
Profile filled at budburst  
30% of control during winter  
Using drippers  
With full irrigation to match winter rainfall  
Using sprinklers  
Exposure to natural rainfall during winter

**Figure 6:2** Schematic representation of the treatments.
6.3 Large scale system to exclude rainfall in field conditions

Shelters were used to exclude rainfall from May to August. Figure 6:3 shows an overview of the system, which consists of modular tunnel units (13 m length x 6 m wide x 2.95 m high) supported by 50 mm square galvanised 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 6:3b). A drainage system, which consisted of galvanised steel gutters and 100 mm PVC tubes, was installed on each side of the unit to direct rainwater away from the vineyard (Figure 6:3c).

![Image of rain-out shelter](image)

**Figure 6:3** Rain-out 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 and c) details of drainage system.

6.4 Levels of irrigation applied

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 1952-2015 corresponded to
approximately 230 mm (Figure 6:4). Irrigation was also applied to the control treatment in the event that natural rainfall during winter did not reach the May-August average.

**Figure 6:4** Monthly distribution of mean rainfall at the SARDI 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 (shaded area). 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-metre depth with minimal 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 1 m intervals. 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.
6.5 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. Only air temperature is reported here. We deployed the shelter in the field during the dormant period, around leaf fall, and removed it just prior to bud burst, therefore, we did not consider the obvious secondary effect that plastic film may produce on growing shoots due to altered intercepted radiation (Berli et al. 2013).

Soil temperature was continuously measured and recorded averaging measures every 30 min using thermistor based soil temperature probes (Measurement Engineering Australia, Magill, South Australia), located at three depths, i.e. 30, 60 and 90 cm (Figure 6:5a 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 vines exposed to natural rain and vines under the rain-out shelters (Figure 6:5c).

Figure 6:5 Detail of soil and air monitoring system. a) Logging system and 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 rain-out shelters were effective in reproducing daily temperature cycles. Comparison of daily temperature records between May to August shows the air temperature under the shelters was only slightly higher than ambient air at night time (Figure 6:6a). The temperature
every 15 min aggregated over a four month period captured the effect of higher air temperature at night time under the shelter (Figure 6:6b). However, there were no significant differences in daily temperatures between ambient and air under the shelters (Table 6:1). Therefore, the biological impact that the transient night time 0.6°C increase in air temperature under the shelter may have on vine development could be mostly dismissed.

![Temperature comparison graph](image)

**Figure 6:6** Comparison of (a) temperature in covered and uncovered rain-out 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. The reference line corresponds to y = x. (b) shows cumulative temperature between the establishment (late April) and removal of the shelter (early September).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Minimum temperature</th>
<th>Mean temperature</th>
<th>Maximum temperature</th>
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</thead>
<tbody>
<tr>
<td>Uncovered</td>
<td>3.8 ± 0.3</td>
<td>9.7 ± 0.2</td>
<td>16.7 ± 0.3</td>
</tr>
<tr>
<td>Covered</td>
<td>4.4 ± 0.3</td>
<td>10.0 ± 0.2</td>
<td>16.8 ± 0.3</td>
</tr>
<tr>
<td>p value</td>
<td>0.155</td>
<td>0.272</td>
<td>0.838</td>
</tr>
</tbody>
</table>

**Table 6:1** Daily average air temperatures at vine cordon level recorded from May to August 2017 on vines exposed to natural rain (uncovered) and under the rain-out shelters (covered).

6.6 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 midday stem water stress every day during each season. Larger $S\Psi$ relates to larger accumulated water stress during the season (Myers 1988).
Leaf stomatal conductance was assessed on five fully expanded and well-lit leaves per replicate using a steady-state leaf porometer (Decagon SC1, Pullman, WA, USA). An LI-6400 gas exchange system (LI-COR, Lincoln, USA) was used to monitor assimilation (A), transpiration (E) and stomatal conductance (g) of mature leaves. Measurements were carried out at four times during the same day (9:00am, 11:30am, 2:00pm and 4:00pm) at four points during the first season (pre-veraison, veraison, mid-ripening 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. The CO₂ concentration of the incoming air was maintained at 400 µmol/mol. The sensor head block temperature and leaf illumination were set to match ambient levels at the beginning of each set of measurements.

6.7 Growing conditions in seasons 2015/16 and 2016/17

6.7.1 Winter irrigation treatments

Table 6:2 shows details of irrigation treatments during winter 2015 and 2016. There were only minor differences between the calculated and the actual volumes of water applied (Figure 6:7a and c). Control vines exposed to natural rain received a total of 257 mm during winter 2015 and 309 mm during winter of 2016. Supplementary irrigation (91 mm) was applied to control vines in the dry winter (2015) to achieve close to the long-term average for this site (Figure 6:5a and Table 6:2). Water applied was similar between control and top-up irrigation treatments either with sprinkler-rain or dripper-rain on both years (Figure 6:5a and c). Sprinkler-rain vines received 246 mm in 2015 and 227 mm in 2016, whereas dripper-rain vines received 208 mm in 2015 and 229 mm in 2016 (Figure 6:7a and b). For both 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 6:2).
### Table 6.2: Detail of irrigation treatments during winter 2015 and 2016.

Compared to the long-term average rainfall, in both years the *reduced-rain* treatment received approximately 32% (approx. 74 mm) and *spring-rain* 67% (approx. 154 mm) of the water applied (Figure 6:5a and c). Irrigation in *reduced-rain* vines was applied in two and three irrigation events of 37 and 25 mm each, respectively, during winter 2015 and 2016. Similarly, starting at budburst, four and six irrigation events were applied to *spring-rain* vines during winter 2015 and 2016, respectively.
Figure 6: Water received by each irrigation treatment from May to September, and (b and d) from October to April during seasons (top) 2015/16 and (bottom) 2016/17. On the stacked bars (a, b and d), the lined bar corresponds to rain 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 and 2016/17 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 and supplementary irrigation totalling 267 mm in season 2015/16 and 169 mm in season 2016/17 (Figure 6:5b and d).
6.7.2 Characterisation of vine water content

The mid-day stem water potential reflected the patterns of soil drying and wetting during the contrasting rainfall conditions of seasons 2015/16 and 2016/17 (Figure 6:8a). As observed on Figure 6:8b, the lack of rainfall during the spring of 2015 led to early signals of water stress (Figure 6:8a). 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. On the contrary, more rainfall in the spring of 2016 allowed the vines to maintain a lower water potential beyond berry pea-size, and developed signs of water stress later in the season from around veraison.

Figure 6:8 (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
Significant differences in stem water potential between treatments were only detected early in season 2015/16 around berry pea-size, when reduced-rain vines were more water stressed (Figure 6:8a). Likewise, during season 2016/17, vines from reduced-rain treatments were significantly more water stressed from anthesis to approximately berry pea-size. Nevertheless, as suggested by the water stress integral (Figure 6:9a and b) there were no significant differences between treatments during the entire growing season during both years.

**Figure 6:9** 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) and 2016/17 (b). Error bars are one standard error of the mean. *p* values are from analysis of variance (ANOVA).

### 6.7.3 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 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 7:3a). In each tube, soil moisture monitoring was done at four depths in the soil profile (20, 30, 50, 70 and 90 cm). At each monitoring time, the reading from two measurement cycles was 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 6:10b). 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 measuring depth (20, 30,
50, 70 and 90 cm). Two 4 m² sites were prepared three metres apart before the calibration to ensure a variation of soil water content (Figure 6:10a). Access tubes were installed before the site preparation. The wet site was watered until soil saturation occurred and the probe gave consistent maximum readings; whereas the dry site was progressively dried using a fast-growing deep-rooted summer crop and sheltered from the rain until the calibration was performed. At 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 dried at 105°C until it reached a constant weight. The values of soil bulk density obtained were used to convert gravimetric values of soil water content to volumetric soil water content. Overall, there was a good agreement on the normalised reading between the Odyssey and mini-rhizotron access tubes ($r^2 = 0.76$), and between volumetric water content and normalised reading using mini-rhizotron tubes ($r^2 = 0.89$).
Figure 6:10 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 established 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 ($\Theta v$) analogously to the plant water stress integral of Myers (1988) and the cumulative soil moisture tension of Zerihun et al. (2010):

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

where $\Theta v_{i,i+1}$ is the mean $\Theta v$ for any interval $i, i + 1$, $C$ is the minimum $\Theta v$ 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 rain-out 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 were all the treatments were equally irrigated.

During the spring of season 2015/16 Csm was higher at all the measured depths in the spring-rain treatments (Figure 6:11a, c and e). However, in season 2016/17, coinciding with the high rainfall observed in spring (Figure 6:7), differences on soil moisture between treatments were only observed in the top soil (Figure 6:11b, d and f). No differences were observed in Csm between treatments during summer of season 2015/16 and 2016/17 regardless of the depth measured. Cumulative soil moisture during winter of season 2016/17 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 6:11b, d and f).
**Figure 6:11** The cumulative soil moisture during seasons (a, c and e) 2015/16 and (b, d and f) 2016/17 at (a and b) 30 cm, (c and d) 50 cm and (e and f) 70 cm from the ground level. Values are averages ± one standard error of four replicates per treatment: (black) control, (red) sprinkler-rain, (green) dripper-rain, (yellow) reduced-rain and (blue) spring-rain. 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.
7 EVALUATION OF WINTER RAINFALL DECLINE ON VINE GROWTH AND DEVELOPMENT

7.1 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 aimed to quantify phenology, and canopy and root growth to confirm this relationship under controlled conditions. More importantly it allowed us to relate root volume and growth (and with this the ability to extract water from the soil) to canopy development, to better understand the relationships between dry winters and vine development.

7.2 Materials and method
7.2.1 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.

7.2.2 Leaf area index
Canopy size was indirectly assessed as leaf area index (LAI) using digital photography and gap fraction analysis. Upward-facing digital images were taken from canopies approximately every three weeks from budburst to leaf fall using an iPhone mounted on a pole. The camera was configured in automatic mode without zoom. Images were collected on the central vines of each replicate as in Figure 7:1, with the average replicate LAI calculated from four pictures. 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 (in the evening, early morning or in overcast conditions), which can interfere with the analysis of the image as it obscures part of the canopy.
Figure 7:1 Upward-facing digital image taken in November 2016.

The distance from the camera to the cordon was constant between repetitions and images were obtained using a mounting pole and remote shutter release.

7.2.3 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 at up to 100 cm depth using a 5 cm internal diameter hydraulic hammer-driven probe (Figure 7:2). Samples were collected from the central vines in 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°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 (length, diameter, surface and volume) was 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 as dry matter (DM, g).

**Figure 7:2** Soil core sampling during spring 2016. (a) 5 cm internal diameter hydraulic hammer-driven probe. (b) one-metre long core sample.

Root development was monitored using 100 cm long acrylic mini-rhizotron tubes with an external diameter of 31 mm, 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 7:3 a, b). Tubes were etched with a column of 54 numbered 2.5 x 1.65 cm windows (Figure 7:3 c). From August 2015, images of the windows were collected approximately every three weeks with a videoscope IPLEX FX series camera (Olympus, Mount Waverley, Victoria, Australia). A total of 24 tubes was examined for each irrigation treatment. The turnover of fine roots, i.e. production and mortality of roots thinner than 2 mm, across multiple sampling dates from each treatment was assessed at the end of the second season using a semi-automatic discriminating tool (Zeng et al. 2008).
Figure 7.3 (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 observed with the videoscope.

7.2.4 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. 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 image that extends 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 7.4 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.
7.2.5 Sampling and quantification of abscisic acid (ABA) in the roots

Root samples were taken at budburst, when first leaf tissue was visible (E-L 4) in buds of control vines. In the first season we sampled roots separately from two different positions perpendicular to the row. Roots between 3 to 5 mm in diameter were sampled from one-metre depth core samples taken adjacent to the vine and at 0.75 m 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. Cleaned roots from soil at each depth fraction were pooled into plastic containers and immediately frozen with liquid nitrogen.

7.3 Results
7.3.1 Treatments effects on grapevine phenology

Compared to the control, the top-up winter irrigation treatments, either using sprinklers or drippers, advanced budburst in both seasons (Figure 7:6a and c), and this difference persisted up to approximately berry set (E-L 27). However, no statistical differences were found between the dripper- and sprinkler-rain treatments and the reduced-rain treatment. The spring-rain treatment had the biggest impact on development, delaying phenology stages prior to veraison in both seasons and during ripening in the first season. During the season
2016/17, berry ripening of reduced-rain vines, was delayed in relation to control and top-up irrigation treatments (Figure 7:6d).

**Figure 7:6** Effects of winter irrigation treatments on grapevine phenology (a and c) before veraison (b and d) and during berry ripening in seasons 2015/16 (a and b) and (c and d). In (a and c) irrigation effects correspond to the difference in days at which treatments reached key phenological stages in relation to control vines: budburst (E-L 4), shoots 10 cm (E-L 12), flowering begins (E-L 19), full bloom (E-L 23), setting (E-L 27) and berry pea size (E-L 31). In (b and c) 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: (●) control, (●) sprinkler-rain, (Δ) dripper-rain, (Δ) reduced-rain and (■) spring-rain. Statistical significance from the one-way ANOVA for irrigation effect is indicated by (*) P < 0.05, (**) P < 0.01 and (***) P < 0.001.

7.3.2 Treatment effects on leaf area index

Leaf area index (LAI) assessed during the season reflected differences in canopy size (Figure 7:7). In the first season, from the 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 the dry spring of season 2015/16
(Figure 6:8), soil moisture was insufficient to sustain highly transpiring canopies in spring-rain vines, and LAI decreased due to the loss of basal leaves (indicated with an arrow in Figure 7:7). In the second season only, the reduced-rain treatment showed a lower LAI from early spring.

**Figure 7:7** Seasonal patterns of LAI during seasons 2015/16 and 2016/17. 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 error): budburst (Bb), flowering (A), berry pea size (Ps), veraison (V) and harvest (H). Arrow indicates a steady drop in LAI by intense leave basal defoliation in spring-rain treatments due to lack of spring rainfall during season 2015/16.

7.3.3 Root growth and turnover during the seasons
Vine root morphology and total root biomass varied due to the winter irrigation treatments and between seasons. 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. Likewise; the wetter 2016/17 season corresponded with generally larger root systems, regardless of the measurement parameter used.
Table 7: Biomass, length, surface area and average diameter of fine Shiraz roots extracted from soil cores collected at budburst (E-L 4) and veraison (E-L 35) during seasons 2015/16 and 2016/17 seasons, from five irrigation treatments and at two sampling positions (adjacent and at 75 cm from the vine trunk). 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).

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Fine root biomass (g/vine)</th>
<th>Fine root length (km/vine)</th>
<th>Fine root surface (m²/vine)</th>
<th>Fine root diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment (T)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.26 ± 0.03 ab</td>
<td>4.06 ± 0.28 ab</td>
<td>7.40 ± 0.55 ab</td>
<td>0.54 ± 0.02 a</td>
</tr>
<tr>
<td>Sprinkler-rain</td>
<td>0.19 ± 0.02 c</td>
<td>4.03 ± 0.39 ab</td>
<td>6.93 ± 0.59 bc</td>
<td>0.53 ± 0.02 a</td>
</tr>
<tr>
<td>Dripper-rain</td>
<td>0.21 ± 0.02 bc</td>
<td>3.25 ± 0.23 b</td>
<td>6.18 ± 0.45 bc</td>
<td>0.53 ± 0.01 a</td>
</tr>
<tr>
<td>Reduced-rain</td>
<td>0.23 ± 0.02 bc</td>
<td>3.71 ± 0.34 b</td>
<td>6.00 ± 0.52 c</td>
<td>0.50 ± 0.02 b</td>
</tr>
<tr>
<td>Spring-rain</td>
<td>0.31 ± 0.04 a</td>
<td>4.61 ± 0.41 a</td>
<td>8.43 ± 0.70 a</td>
<td>0.51 ± 0.02 b</td>
</tr>
<tr>
<td><em>p</em>-value</td>
<td>0.008</td>
<td>0.041</td>
<td>0.004</td>
<td>0.056</td>
</tr>
<tr>
<td>Season (S)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015/16</td>
<td>0.18 ± 0.01 b</td>
<td>3.67 ± 0.23 a</td>
<td>6.24 ± 0.36 b</td>
<td>0.50 ± 0.01 b</td>
</tr>
<tr>
<td>2016/17</td>
<td>0.29 ± 0.02 a</td>
<td>4.19 ± 0.20 a</td>
<td>7.74 ± 0.36 a</td>
<td>0.55 ± 0.01 a</td>
</tr>
<tr>
<td><em>p</em>-value</td>
<td>&lt; 0.001</td>
<td>0.062</td>
<td>0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Phenological stage (E-L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Budburst</td>
<td>0.22 ± 0.01 b</td>
<td>3.57 ± 0.20 b</td>
<td>6.09 ± 0.31 b</td>
<td>0.50 ± 0.01 b</td>
</tr>
<tr>
<td>Veraison</td>
<td>0.26 ± 0.02 a</td>
<td>4.29 ± 0.23 a</td>
<td>7.88 ± 0.39 a</td>
<td>0.55 ± 0.01 a</td>
</tr>
<tr>
<td><em>p</em>-value</td>
<td>0.030</td>
<td>0.010</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>T x E-L</td>
<td>0.224</td>
<td>0.964</td>
<td>0.679</td>
<td>0.029</td>
</tr>
<tr>
<td>T x S</td>
<td>0.086</td>
<td>0.597</td>
<td>0.713</td>
<td>0.233</td>
</tr>
<tr>
<td>E-L x S</td>
<td>0.357</td>
<td>0.001</td>
<td>0.035</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

7.3.4 Synthesis and accumulation of ABA in the roots
In the 2015/16 season, the differences between the sampling positions (see section 7.2.3) were tested. There was no effect of the sampling position for the variables analysed, so in the second season, roots were only sampled from the position adjacent to the vine in the first ~ 33 cm. For the ANOVA in the first season (Table 7:1) results from the mid-row samples were removed because unexpected interactions between treatment and sampling position occurred, but did not reveal any treatment effects and are most likely due to the roots from the partially treated vines in the adjacent rows. In addition, during the first season, although we sampled the roots from each depth (0-33, 33-66, 66-99 cm), prior to analysis the subsamples from the same core were pooled to provide sufficient material for the analysis.

In the first season, both ABA and ABA GE were significantly higher in spring-rain vines, but the other catabolites were unaffected.
Table 7:2 ABA and catabolite profile of thin (3-5 mm) Shiraz roots sampled at budburst (E-L 4) during season 2015/16, from five irrigation treatments and at two sampling positions (adjacent and at 75 cm from the vine trunk). 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).

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>ABA (ng/g)</th>
<th>DPA (ng/g)</th>
<th>PA (ng/g)</th>
<th>neo PA (ng/g)</th>
<th>ABA GE (ng/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatment (T)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>17.7 ± 3.3 b</td>
<td>76 ± 23.4</td>
<td>2.3 ± 0.3</td>
<td>2 ± 0.4 b</td>
<td>446.8 ± 134 b</td>
</tr>
<tr>
<td>Sprinkler-rain</td>
<td>12.8 ± 2.9 b</td>
<td>61 ± 40.3</td>
<td>0.8 ± 0.0</td>
<td>5 ± 3.7</td>
<td>662.6 ± 149 ab</td>
</tr>
<tr>
<td>Dripper-rain</td>
<td>17.1 ± 2.0 b</td>
<td>104 ± 25.6</td>
<td>0.4 ± 0.1</td>
<td>2 ± 0.6</td>
<td>593.4 ± 60 ab</td>
</tr>
<tr>
<td>Reduced-rain</td>
<td>16.5 ± 3.0 b</td>
<td>40 ± 16.5</td>
<td>4.8 ± 2.6</td>
<td>3 ± 0.9</td>
<td>358.1 ± 92 b</td>
</tr>
<tr>
<td>Spring-rain</td>
<td>34.8 ± 8.7 a</td>
<td>89 ± 36.7</td>
<td>0.8 ± 0.4</td>
<td>2 ± 0.5</td>
<td>928.8 ± 196 a</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td><strong>0.011</strong></td>
<td>0.542</td>
<td>0.377</td>
<td>0.811</td>
<td></td>
</tr>
<tr>
<td><strong>Position (P)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjacent</td>
<td>21.6 ± 3.3</td>
<td>58.3 ± 14.0</td>
<td>1.5 ± 0.7</td>
<td>2.6 ± 0.4</td>
<td>588.4 ± 98.7</td>
</tr>
<tr>
<td>75 cm</td>
<td>18.0 ± 2.8</td>
<td>89.6 ± 27.9</td>
<td>2.1 ± 0.9</td>
<td>3.1 ± 1.9</td>
<td>607.4 ± 88.3</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td>0.349</td>
<td>0.257</td>
<td>0.712</td>
<td>0.774</td>
<td>0.894</td>
</tr>
<tr>
<td><strong>T x P</strong></td>
<td>0.578</td>
<td>0.212</td>
<td>0.934</td>
<td>0.565</td>
<td>0.088</td>
</tr>
</tbody>
</table>

Interestingly, in the second season, although ABA was not higher in *spring-rain* vines, two of the three forms of hydroxylated ABA catabolites (DPA and PA), which are biologically active, were significantly higher in *spring-rain* vines at budburst.

Table 7:3 ABA and catabolite profile of thin (3-5 mm) Shiraz roots sampled between 0 to 33 cm depth, adjacent to the vine trunk at budburst (E-L 4) during season 2016/17. Values are Means ± one standard error and *p* indicates effect of irrigation treatment. Different letters indicate significant differences between treatments or sampling positions, as calculated by Fisher’s least significant difference (LSD 5% level).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>ABA (ng/g)</th>
<th>DPA (ng/g)</th>
<th>PA (ng/g)</th>
<th>neo PA (ng/g)</th>
<th>ABA GE (ng/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>117 ± 34 b</td>
<td>105 ± 5</td>
<td>1.0 ± 1.34 b</td>
<td>1.2 ± 0.58</td>
<td>579.5 ± 196 b</td>
</tr>
<tr>
<td>Sprinkler-rain</td>
<td>225 ± 29 a</td>
<td>99 ± 13 bc</td>
<td>1.0 ± 1.34 b</td>
<td>1.3 ± 0.0</td>
<td>954.3 ± 163</td>
</tr>
<tr>
<td>Dripper-rain</td>
<td>165 ± 34 ab</td>
<td>70 ± 15 c</td>
<td>1.5 ± 0.87 b</td>
<td>1.4 ± 0.23</td>
<td>518.9 ± 163</td>
</tr>
<tr>
<td>Reduced-rain</td>
<td>81 ± 34 ab</td>
<td>205 ± 34 ab</td>
<td>0.6 ± 1.05 b</td>
<td>1.3 ± 0.05</td>
<td>217.8 ± 246 b</td>
</tr>
<tr>
<td>Spring-rain</td>
<td>130 ± 29 b</td>
<td>264 ± 77 a</td>
<td>5.8 ± 1.07 a</td>
<td>2.5 ± 0.46</td>
<td>1737.9 ± 163 a</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td><strong>0.026</strong></td>
<td><strong>0.017</strong></td>
<td><strong>0.014</strong></td>
<td><strong>0.192</strong></td>
<td><strong>0.007</strong></td>
</tr>
</tbody>
</table>

The physiologically inactive ABA glucosyl ester (ABA-GE) was also higher in *spring-rain* vines. As discussed previously, this suggests that *spring-rain* vines, which were maintained without rain/irrigation during winter and early spring, have gone through a period of high ABA biosynthesis and catabolism. Hopefully, this will be revealed in the coming months when we
have the results from the roots sampled at more frequent intervals during the dormant period (one at leaf fall, two in winter, one pre-budburst and one post-budburst).

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

8.1 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 above).

8.2 Materials and methods
8.2.1 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 in 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.

8.2.2 Carbohydrates sampling and analysis

Of the six treated vines per repetition, only the two central vines were used for monitoring carbohydrate concentrations, and 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 at key phenological stages during both seasons (Table 8:1) and then frozen for later analysis of total non-structural carbohydrates (TNC).

<table>
<thead>
<tr>
<th>Phenological stage (E-L scale)</th>
<th>Season 2015/16</th>
<th>Season 2016/17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bud-break (E-L 4)</td>
<td>11 September</td>
<td>13 September</td>
</tr>
<tr>
<td>Flowering (E-L 23)</td>
<td>10 November</td>
<td>25 November</td>
</tr>
<tr>
<td>Veraison (E-L 35)</td>
<td>20 January</td>
<td>2 February</td>
</tr>
<tr>
<td>Harvest (E-L 38)</td>
<td>4 March</td>
<td>6 April</td>
</tr>
<tr>
<td>Leaf-fall (E-L 47)</td>
<td>30 May</td>
<td>23 May</td>
</tr>
</tbody>
</table>
Table 8.1 Phenological stages and sampling dates for non-structural carbohydrates on Shiraz vines during seasons 2015/16 and 2016/17.

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°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 deionised 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 deionised 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°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.

8.3 Results
8.3.1 Treatments effects on yield and its components

Yield was higher in season 2016/17 than in season 2015/16, notwithstanding treatment differences that ranged from 9% to 40% from the control (Figure 8.1). Overall, during both seasons, control vines exposed to natural winter rainfall yielded the most. Relative to these vines, neither the top-up irrigation strategies using drippers during winter nor the one that uses micro-sprinklers at budburst fully restored yield. Consistently, spring-rain decreased yield on both seasons. Only irrigation that replenished soil water content progressively during winter using micro-sprinklers restored yield to a similar level to control vines during the second season. The reduced-rain treatment significantly reduced yield during the first season (approximately by 40%), 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, when rainfall was sufficient to refill the soil profile early in spring. This highlights the importance of entering the season with soil water content that does not limit the early stages of growth and development.
Figure 8.1 Effects of winter irrigation treatments on yield of Shiraz at harvest during seasons 2015/16 and 2016/17. Means followed by different letters differ significantly at \( p < 0.05 \) by Fisher’s LSD test.

Differences in yield between treatments in the first season were mainly driven by the higher number of bunches in control vines and by the lighter bunches of reduced-rain vines (Table 8:2). Reduced-rain vines and control vines yielded similarly in the second season, which was driven by the significantly higher number of bunches in reduced-rain vines. It is likely that the microclimatic conditions in the smaller and more open canopies of the reduced-rain vines during the 2015/16 season favoured bud differentiation and fruitfulness, as verified by the higher number of bunches per shoot (Table 8:2).

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>Bunch number (vine)</th>
<th>Bunch weight (g)</th>
<th>Berry weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015/16</td>
<td>Control</td>
<td>101.6 ± 1.3 a</td>
<td>108.4 ± 6.4 a</td>
<td>0.9 ± 0.0 a</td>
</tr>
<tr>
<td></td>
<td>Sprinkler rain</td>
<td>82.3 ± 2.8 bc</td>
<td>108.8 ± 3.9 a</td>
<td>1.0 ± 0.0 a</td>
</tr>
<tr>
<td></td>
<td>Dripper rain</td>
<td>75.9 ± 3.1 c</td>
<td>109.9 ± 10.7 a</td>
<td>1.0 ± 0.0 a</td>
</tr>
<tr>
<td></td>
<td>Reduced rain</td>
<td>87.7 ± 2.7 b</td>
<td>71.0 ± 3.4 b</td>
<td>0.8 ± 0.0 b</td>
</tr>
<tr>
<td></td>
<td>Spring rain</td>
<td>84.1 ± 5.1 bc</td>
<td>105.2 ± 3.4 a</td>
<td>1.0 ± 0.0 a</td>
</tr>
<tr>
<td></td>
<td>( P ) value</td>
<td>0.001</td>
<td>0.002</td>
<td>0.011</td>
</tr>
<tr>
<td>2016/17</td>
<td>Control</td>
<td>102.5 ± 1.1 b</td>
<td>137.2 ± 1.3</td>
<td>1.1 ± 0.0 a</td>
</tr>
<tr>
<td></td>
<td>Sprinkler rain</td>
<td>94.0 ± 4.6 bc</td>
<td>138.6 ± 3.0</td>
<td>1.1 ± 0.0 a</td>
</tr>
<tr>
<td></td>
<td>Dripper rain</td>
<td>84.6 ± 2.8 cd</td>
<td>127.0 ± 6.8</td>
<td>1.1 ± 0.1 a</td>
</tr>
<tr>
<td></td>
<td>Reduced rain</td>
<td>120.3 ± 3.1 a</td>
<td>124.5 ± 2.7</td>
<td>0.9 ± 0.0 b</td>
</tr>
<tr>
<td></td>
<td>Spring rain</td>
<td>77.8 ± 3.6 d</td>
<td>124.2 ± 7.7</td>
<td>1.1 ± 0.0 a</td>
</tr>
<tr>
<td></td>
<td>( P ) value</td>
<td>&lt;0.001</td>
<td>0.159</td>
<td>0.030</td>
</tr>
</tbody>
</table>
Table 8.2: Effects of winter irrigation treatments on yield components of Shiraz at harvest during season 2015/16 and 2016/17. Means followed by different letters differ significantly at $p < 0.05$ by Fisher’s LSD test. $P$ values correspond to the one-way ANOVA.

8.3.2 Effects on vegetative growth and vine balance

A consistent number of buds was retained across treatments during the pruning in both years. However, vine vigour, estimated from pruning weight, was significantly affected by irrigation treatments (Figure 8:2). In both seasons, top-up irrigation using drippers during winter and micro-sprinklers at budburst increased pruning weight compared to the control, due to a higher weight of individual shoots in these treatments (Table 8:3). Likewise, reduced-rain during winter decreased vine vegetative growth and individual shoot weight in both seasons (Figure 8:2, Table 8:3).

![Figure 8:2](image)

The yield:pruning weight ratio was also significantly affected by the treatments. Overall, the ratio increased for all the treatments during the second season due to the higher yield. During both 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 second season, also had a higher yield:pruning weight ratio.
Table 8.3 Effects of winter irrigation treatments on vegetative growth and sink/source ratio of Shiraz during season 2015/16. 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.

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment</th>
<th>Shoot number (vine)</th>
<th>Weight per shoot (g)</th>
<th>Bunch per shoot</th>
<th>Yield/pruning wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015/16</td>
<td>Control</td>
<td>68.9 ± 3.0</td>
<td>33.1 ± 1.2</td>
<td>1.5 ± 0.1</td>
<td>5.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Sprinkler-rain</td>
<td>62.0 ± 2.1</td>
<td>35.1 ± 1.8</td>
<td>1.3 ± 0.1</td>
<td>4.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Dripper-rain</td>
<td>62.6 ± 3.7</td>
<td>43.5 ± 3.1</td>
<td>1.2 ± 0.1</td>
<td>2.7 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Reduced-rain</td>
<td>64.5 ± 1.6</td>
<td>25.7 ± 3.3</td>
<td>1.4 ± 0.1</td>
<td>3.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Spring-rain</td>
<td>68.2 ± 3.2</td>
<td>43.6 ± 1.3</td>
<td>1.3 ± 0.1</td>
<td>3.3 ± 0.3</td>
</tr>
<tr>
<td></td>
<td><em>P</em> value</td>
<td>0.346</td>
<td>&lt;0.001</td>
<td>0.050</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2016/17</td>
<td>Control</td>
<td>74.0 ± 1.8</td>
<td>36.5 ± 2.3</td>
<td>1.3 ± 0.1</td>
<td>4.6 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Sprinkler-rain</td>
<td>65.1 ± 1.3</td>
<td>41.1 ± 1.1</td>
<td>1.5 ± 0.1</td>
<td>5.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Dripper-rain</td>
<td>71.8 ± 1.0</td>
<td>42.6 ± 2.5</td>
<td>1.2 ± 0.1</td>
<td>3.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Reduced-rain</td>
<td>71.6 ± 4.9</td>
<td>32.4 ± 1.7</td>
<td>1.7 ± 0.1</td>
<td>6.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Spring-rain</td>
<td>70.3 ± 1.7</td>
<td>40.8 ± 1.7</td>
<td>1.2 ± 0.1</td>
<td>3.7 ± 0.3</td>
</tr>
<tr>
<td></td>
<td><em>P</em> value</td>
<td>0.202</td>
<td>0.011</td>
<td>0.002</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

8.3.3 Effects on reserves of total non-structural carbohydrates

The impact of the irrigation treatments 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 8.3). From veraison in the 2016/17 season, greater treatment effects were seen. The *reduced-rain* treatment, with the smallest canopy and highest yield showed a significant reduction in starch concentration (Figure 8.3) as reserves were drawn down in order to ripen the fruit.
Figure 8:3 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-L 35 - V), harvest (E-L 38 - H) and leaf fall (E-L 47 - LF). Values are averages ± one standard error of four replicates per treatment: (-●-) control, (-●-) sprinkler-rain, (-Δ-) dripper-rain, (-Δ-) reduced-rain and (-■-) spring-rain. Different letters differ significantly at $p < 0.05$ by Fisher’s LSD test.
9 EVALUATION OF WINTER RAINFALL DECLINE ON GRAPE AND WINE CHEMICAL COMPOSITION AND WINE SENSORY ATTRIBUTES

9.1 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 winters on grape and wine quality will aid the development of management practices.

9.2 Materials and method

9.2.1 Assessment of berry ripening and composition

Samples for grape composition were taken weekly from veraison to harvest and analysed using standard analytical techniques (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 five 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 °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).

9.2.2 Winemaking and wine analysis

Harvest date was defined as the point where juice TSS reached 26 °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 costs, based on the highest variability in yield within the vines of the replicate. For the sake of consistency, the same replicate was eliminated in both seasons.

After overnight storage at 0°C following harvest, the fruit was destemmed and crushed prior to transfer to 50 L plastic bins. 50 ppm SO₂ was added to the must upon crushing and correction to pH 3.6 with tartaric acid. Saccharomyces cerevisiae yeast was inoculated to conduct primary fermentation (strain Lalvin EC-1118, Lallemand Inc., Montréal, QC, Canada). The juice was fermented on skins at 18°C, with yeast assimilable nitrogen adjusted
with DAP to 200 mg/L after two days. Lactic acid bacteria (*Oenococcus oeni* Lalvin VP 41, Lallemand Inc.) were inoculated on day two of alcoholic fermentation, and wines were maintaining at 20°C until malolactic fermentation was completed. After sugar (< 2 g/L combined glucose and fructose) and malolactic fermentation (< 0.1 g/L malic acid) were completed, wine was treated with potassium metabisulphite to maintain 40 ppm of free SO₂. Cold stabilisation was induced by adding 2 g/L of KHT and placing the wine in the 0°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 with 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 the 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 software, version 1.5 (GBC Scientific Equipment Pty Ltd, Braeside, Vic., Australia). Measurements were undertaken at room temperature (21–23°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.

### 9.2.3 Wine sensory assessment

### 9.3 Results

#### 9.3.1 Berry ripening and fruit composition

At harvest, berry composition was significantly affected by the irrigation treatments (Table 9:1). Both the concentration (amount per unit of fresh weight) and content (amount per berry) of anthocyanins were affected. In relation to control, skin anthocyanin concentration was approximately 18% higher in both *dripper-rain* and *reduced-rain*, and 9% higher in *spring-rain*; however, no differences were found between control and *sprinkler-rain*. These differences were partially explained by the smaller mass of *reduced-rain* berries (Table 9:1), which increased the surface to volume ratio in smaller berries compared to larger ones, and by the higher content of anthocyanin in *dripper-rain* berries (Table 9:1).

Similar to anthocyanins, compared to control, the concentration of phenolics was higher in *dripper-rain* and *reduced-rain* treatments (by 10% and 20% respectively); whereas the phenolic substances content in each berry was higher in *reduced-rain* treatments by 20% compared to control and *sprinkler-rain*, and by 10% compared to *dripper- and spring-rain*. In
relation to the control, berry tannin concentration, expressed as milligrams of epicatechin units per gram of homogenate, was 1.9-fold higher in reduced-rain, 1.5-fold higher in dripper-rain and 1.2-fold higher in sprinkler- and spring-rain treatments. Juice TSS was lower in control and spring-rain but titratable acidity was higher in these treatments. Winter irrigation did not alter fruit pH at harvest (Table 9:1).
Table 9: One-way ANOVA of the effects of winter irrigation treatments on must composition of Shiraz at harvest in February 2016.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Control</th>
<th>Sprinkler-rain</th>
<th>Dripper-rain</th>
<th>Reduced-rain</th>
<th>Spring-rain</th>
<th>Statistical difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthocyanins (mg/g)</td>
<td>1.1 a&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.1 a</td>
<td>1.3 bc</td>
<td>1.3 c</td>
<td>1.2 ab</td>
<td>*</td>
</tr>
<tr>
<td>Anthocyanins (mg/berry)</td>
<td>1.0 a</td>
<td>1.0 a</td>
<td>1.2 b</td>
<td>1.1 a</td>
<td>1.1 ab</td>
<td>*</td>
</tr>
<tr>
<td>Tannins (mg/g homogenate)</td>
<td>1.5 a</td>
<td>1.6 a</td>
<td>2.2 b</td>
<td>2.9 c</td>
<td>1.9 ab</td>
<td>***</td>
</tr>
<tr>
<td>Tannins (mg/L)</td>
<td>139.8 a</td>
<td>155.6 a</td>
<td>214.9 b</td>
<td>276.8 c</td>
<td>178.4 ab</td>
<td>***</td>
</tr>
<tr>
<td>Phenolic substances (au/berry)</td>
<td>0.9 a</td>
<td>1.0 a</td>
<td>1.1 b</td>
<td>1.0 ab</td>
<td>1.0 ab</td>
<td>*</td>
</tr>
<tr>
<td>Phenolic substances (au/g)</td>
<td>1.0 a</td>
<td>1.0 a</td>
<td>1.1 b</td>
<td>1.2 c</td>
<td>1.1 ab</td>
<td>***</td>
</tr>
<tr>
<td>Total soluble solids (°Brix)</td>
<td>25.5 a</td>
<td>26.5 b</td>
<td>26.7 b</td>
<td>26.5 b</td>
<td>25.3 a</td>
<td>**</td>
</tr>
<tr>
<td>Titratable acidity (g/L)</td>
<td>6.4 bc</td>
<td>6.1 ab</td>
<td>6.0 ab</td>
<td>6.0 a</td>
<td>6.5 c</td>
<td>*</td>
</tr>
<tr>
<td>pH</td>
<td>3.5 bc</td>
<td>3.6 ab</td>
<td>3.6 ab</td>
<td>3.6 b</td>
<td>3.6 ab</td>
<td>ns</td>
</tr>
</tbody>
</table>

<sup>a</sup>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.

<sup>b</sup>Values are means. Within a row, values followed by the same letter are not significantly different according to Fisher’s LSD test at \( p < 0.05 \).
9.3.2 Wine composition and sensory attributes

The study included a chemical characterisation of wines immediately after pressing (Figure 9:1), at bottling (~3 months after pressing) and with the sensory analysis (planned ~7 months after pressing).

Figure 9:1 Principal component (PC) analysis of young Shiraz wine (at pressing) compositional (black font) and chromatic (blue font) data during the 2015/16 vintage.

Observed differences in grape phenolic composition between treatments were mirrored by the differences in the wines. To further explore the correlation between wine composition and irrigation treatments, data were subjected to multivariate analysis using the principal components routine (Figure 9:1). The first two principal components (PCs) with eigenvalues greater than one were originally retained, accounting for ~94% of the observed variation in wine composition and CIELab chromatic differences between treatments. The third PC explained less than ~7% of the observed variability; therefore, it was excluded from the analysis to simplify the interpretation. The PCA component loadings on the negative side of PC1 associated control and spring-rain treatments with yellow tones ($r = 0.72$), chemical age 1 and lightness ($r \geq 0.86$). PC1 segregate reduced-rain treatment on the positive side, and strongly associated this treatment ($r \geq 0.95$) with colour density, total phenolic, non-bleachable pigments, anthocyanin, tannins and with the degree of ionisation of anthocyanin. Reduced-rain wines were also associated with red tones and colour saturation but in a lesser
extend \((r \geq 0.61)\). Sprinkler- and dripper-rain treatments located at the central part of PC1, and were related with the chemical age 2.

The PCs showed a clear separation of treatments within the compositional and chromatic space. Reduced-rain, which used only one third of the water applied to the control, may have resulted in an early water deficit condition which translated to a positive effect on wine phenolic composition and colour, most likely as a result of a reduction in berry size (i.e. concentration of secondary metabolites). In contrast, wines from vines with natural winter rain (control) had a lower concentration of phenolic substances, which translated to their lighter and yellower colour. Interestingly, wines from spring-rain vines, which received only half of 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.
WINTER RAINFALL DECLINE AFFECTS THE ACCUMULATION OF SALT IN VINEYARD SOIL

10.1 Introduction

In the Barossa Valley, the cycles of vineyard irrigation and natural rainfall determine an increase of soil salinity during the dry summer 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 leached about 75% of the salt from soils under the vine contributing to maintaining soil salinity below the threshold for salinity damage to occur (Stevens et al. 2012). Insufficient winter rainfall may 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 reduced winter rainfall may prevent salt accumulation, while reduced rainfall would allow this to occur.

10.2 Material and methods

10.2.1 Soil sampling

Soil samples were collected twice during the season; the first sampling was conducted around budburst, coinciding the period when soil moisture is expected to be at its maximum, whereas the second sampling time, at veraison, is 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.

10.2.2 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°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°C.

10.2.3 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°C until it reached a constant weight.
10.3 Results

10.3.1 Seasonal variation in soil salinity

We assessed soil salinity at the end of winter and mid-summer in seasons 2015/16 and 2016/17. For all the irrigation treatments and sampling dates, soil EC1:5 was below the threshold value of 2100 µS/cm for salinity damage in own rooted vines (Figure 10:1).

![Figure 10:1](image)

**Figure 10:1** Effects of winter rainfall and supplementary irrigation on the dynamics of soil salts accumulation during 2015/16 and 2016/17. Bars are means ± one standard error. Values are averages ± one standard error of four replicates per treatment: (-●-) control, (-○-) sprinkler-rain, (-△-) dripper-rain, (-▲-) reduced-rain and (-■-) spring-rain. Different letters indicate means that differ significantly at $p < 0.05$ by Fisher’s LSD test.

The winter irrigation treatments affected soil salinity (Figure 10:1). At three of the four sampling dates, the average salinity of reduced-rain and spring-rain treatments, which simulate reduced winter rainfall, was significantly higher than the treatments that aim to fully replenish natural winter rainfall. None of the treatments led to the accumulation of salt between the two seasons that were assessed. This is due at least in part to the 2016/17 growing season (when the rain-out shelters were not in place) being significantly wetter than the 2015/16 season.
11 PRELIMINARY CONCLUSIONS AND FUTURE WORK

This study has demonstrated vine responses to reduced winter rainfall and a range of irrigation replenishment options. Top-up winter irrigation either using sprinklers or drippers, to a similar level as natural winter rain, still resulted in a reduction in yield. The causes have not been confirmed, but it is likely the pattern of wetting of the soil is influencing root growth and longevity and then vine performance in the following season. Insights into the relation of growth between roots and canopy, i.e. leaf area index (LAI), early in the growing season and hormonal signalling (i.e. ABA) will help to clarify this relationship. Reduced winter rainfall (in the lowest two deciles) improved grape and wine composition at the cost of a reduction in yield of 40%. On the other hand, irrigation to refill the profile at budburst caused excess vegetative growth, which negatively affected grape and wine composition without restoring yield.

The cumulative impact of reduced winter rainfall on vine performance and the dynamics of salt leaching and accumulation in the soil profile will take at least a further season to confirm. The rain-out shelters and the irrigation infrastructure deployed in the field for this experiment provide an ongoing opportunity to simulate reductions in winter rainfall due to climate change; and to develop management practices in order to counter them. The cause of the yield reduction and methods to prevent it occurring should remain the focus of the coming season and future work.

12 OPPORTUNITIES TO EXTEND THIS PROJECT

The methods trialled to restore winter rainfall (including the current practice of filling the profile in spring) did not maintain yield at a similar level to the control (natural rain). A key focus of future work in this area is the evaluation of alternatives to the current top-up irrigation treatments to maintain yield following dry winters. Options include either changing the soil wetting pattern using alternatives to the mini-sprinklers and drippers, such as buried mid row drippers, or modifying the time of soil drying and wetting, refilling soil profile with drippers earlier in autumn or at the beginning of spring.
13 COMMUNICATION

Presentations:


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