Climate adaptation: developing irrigation strategies to combat dry winters



FINAL REPORT TO WINE AUSTRALIA

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1 ABSTRACT

Reduced winter rainfall is expected as a consequence of climate change. Low rainfall during winter, resulting in a soil profile that is not full by spring, has been shown to reduce grapevine canopy growth and yield. Building on previous work, irrigation strategies were evaluated that modified the pattern and timing of supplementary soil wetting in winter. Multiple laterals of drippers were used, and the irrigation period extended from winter through to bud burst or fruit set. All irrigation treatments (single and multiple laterals, and application at budburst or through until fruit set) yielded significantly higher than the Control. Maintaining soil moisture during winter through irrigation or rainfall is critical, but the extension of this irrigation into spring maximised vineyard productivity.

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. Observed declines in winter rainfall and pressure on water resources for irrigation will place increasing strain on these production systems. Observations of seasonal variation and the results of a previous project (SAR 1302) have demonstrated the negative effects of dry soil in spring on vine performance, and the absence of effective irrigation strategies that fully restore yield. In the earlier project even when the soil moisture was maintained during winter using irrigation (drip or sprinkler), yield was reduced compared to the Control vines exposed to winter rainfall. Filling up an empty soil profile at budburst (as opposed to attempting to maintain it throughout winter) resulted in the lowest yield and excessive canopy growth, which impacted negatively on wine phenolic composition and sensory attributes.

This project aimed to build on the previous work and increase vineyard resilience by developing irrigation strategies to maintain vineyard productivity following dry winters. During the three seasons, from 2018 to 2021, we explored irrigation strategies that aimed to restore vine performance to a similar level to the vines exposed to long-term average patterns of winter and spring rainfall (Control); a goal not attained in the previous project. The best performing (closest yield to the Control) treatment from the previous project was irrigation with micro-sprinklers under the canopy that simulated the pattern of soil wetting of rainfall. However, the majority of Australian vineyards are irrigated using drip-based systems; therefore, one focus of this current project was to evaluate drip-irrigation methods that wet the mid-row space to supplement low winter rainfall, with the aim to maintain yield following dry winters and springs. The second focus was to extend irrigation beyond the start of spring (budburst). As in the previous project, elevated yields (similar and higher than the Control treatments) were observed when the vines received significant rainfall during spring.

An experimental trial was designed and implemented that successfully replicated winter drought conditions in a Shiraz vineyard at Nuriootpa Research Station in the Barossa Valley. Rainout shelters were deployed so that rainfall was excluded during winter, with the covers being installed in May and removed around mid-September, at the time of budburst, to avoid confounding effects associated with growing vines under the covers. Treatments were designed to replicate a winter with reduced water input due to low rainfall or irrigation, followed by additional irrigation during spring. Irrigation was applied either using a single lateral or with an altered soil wetting pattern by using multiple rows of drippers. The winter irrigation (rainfall replacement) period was extended into spring (past budburst), which was later than in the previous project. Treatments were arranged in a replicated factorial experiment combining two methods of irrigation (single and multiple laterals) and two periods of application (budburst to 10 cm shoot length or from budburst to fruit set). In each season, we measured the effect of the treatments on (i) yield, pruning mass and their components, (ii) dynamics of canopy growth, quantified as leaf area index (LAI), and root growth during the season, (iii) vine carbohydrate reserves, (iv) fruit quality parameters, and (v) wine chemical and sensory characteristics. We also assessed growing conditions as affected by the treatments on the dynamics of soil drying and wetting within the season and its implications on vine water potential.

The experiment confirmed expectations on the importance of maintaining soil moisture during winter, but it also contrasted with previous findings. Yield in the irrigated treatments, regardless of the method and timing of water application, was significantly higher than in the Control. Vines irrigated with a single lateral yielded significantly more than the Control and also more than vines irrigated with multiple laterals, indicating limited value from irrigation with multiple laterals to manage dry winters. Irrigation at budburst or from budburst to fruit set increased yield over the Control vines, with some minor differences between timing treatments. In the previous project we found that irrigation at budburst when the soil profile was empty following full exclusion of winter rainfall resulted in the lowest yield and excessive canopy growth. In this current trial we topped up the soil profile at budburst after limited irrigation had also been applied during winter, resulting in a higher yield than Control vines. These findings suggest that the timing of irrigation is less critical than previously thought, but that a minimum level of moisture is critical during winter to balance yield and canopy growth when top-up irrigation is applied from budburst.

In this trial, both Control and irrigated vines received approx. 247 mm of water from irrigation and effective rain during dormancy and until fruit set. Control vines received 90% during dormancy and 10% from budburst to fruit set, which contrasted with the irrigated vines that received 30% during dormancy and the remaining 70% (165 mm, which represents approx. half of the seasonal water requirement) from budburst to fruit set, resulting in significant (approximately 25%) yield increases compared to the Control vines in dry seasons.

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

3 BACKGROUND

Projections from climate change models (Remenyi et al. 2019) 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 150 mm 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.

In the previous project based at the same site, Bonada et al. (2020, 2021) successfully developed and implemented an experimental system designed to replicate winter drought. Shelters were erected so that rainfall was excluded during winter, with the covers being installed in May and removed in mid-September. Irrigation treatments were designed and implemented to replicate rainfall or irrigation programs, to respond to low winter rainfall. They observed that 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 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. 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 during 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 lower compared to the Control in the two dry years, but in the wetter year was similar to the Control. Although maintaining moisture in the soil profile throughout the winter did not consistently restore yield to the level of the Control, this was the most successful management option, particularly when using micro-sprinklers under the canopy.

The results and observations from the first treatment strongly informed the research targets for this current project, which are to maintain vineyard productivity despite dry winters. 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). Therefore, a key focus of the new project was the evaluation of drip irrigation-based methods to supplement low winter rainfall,

with the aim to maintain yield following dry winters. The second research question built on the observation that the vines that received irrigation equivalent to one third of the historical average rainfall during winter showed a significant increase in yield when rainfall occurred early in spring once the covers were removed. In response to this, an extended irrigation period at the beginning of spring was investigated, with the expectation that this management option would restore vine performance to a similar level to the Control treatment.

4 PROJECT AIMS

1. Improved knowledge on the influence of water availability during winter and spring on vine growth and development, including the impacts on root and canopy physiology.

2. Irrigation application systems/methods that will allow vineyard productivity to be maintained despite dry winters.

5 EXPERIMENTAL SETUP TO SIMULATE REDUCED WINTER RAINFALL.

Experimental site

The trial site was established in 2018 at the SARDI Nuriootpa research station (34 ^{o}S, 139 ^{o}E) in the Barossa Valley of SA. 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 et al. 2002). The Shiraz vines (clone 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.

Treatment details

In addition to a Control treatment, which defined the baseline for comparison with vines exposed to the long-term average (LTA) of recorded rainfall, the irrigation treatments were designed to compare alternative times and methods of irrigation following a dry winter. Treatments were arranged in a factorial design with four replicates combining two methods of irrigation (D, Drippers located on a single lateral; and, TD, drippers located on three laterals) and two times of application (Bb, budburst to 10 cm shoot growth; and, Bb_set, budburst to fruit set) (Figure 5:1). The irrigation treatments were defined as follows (Figure 5:2): 1) vines exposed to natural rainfall (*Control*) with top-up irrigation using under-canopy micro-sprinklers, if necessary, to match mean May-August LTA rainfall. This amount corresponds to 230 mm and was calculated from historical records during the period 1952-2015 for Nuriootpa. Vines with winter rainfall exclusion and reduced irrigation during winter, receiving 30% of LTA during vine dormancy and 70% after budburst with 2) a single lateral of drippers under the vines (D-Bb), or 3) with three laterals, one under the vines and one approx. 150 mm each side (TD-Bb). Vines with the same irrigation in winter (30% of LTA) but with the remaining 70% applied from budburst to fruit set with 4) a single lateral of drippers (D-Bb_set) or 5) with three laterals (TD-Bb_set).

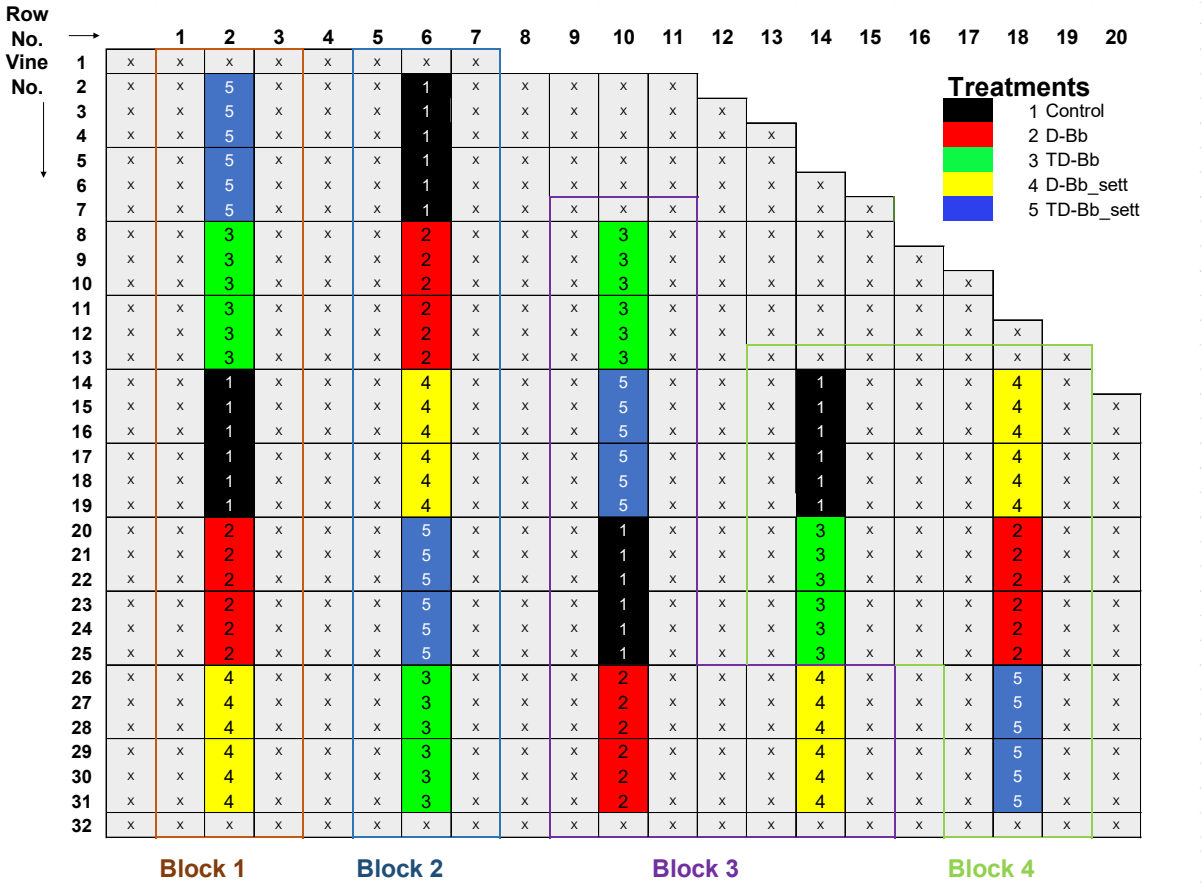


Figure 5:1 Experimental design

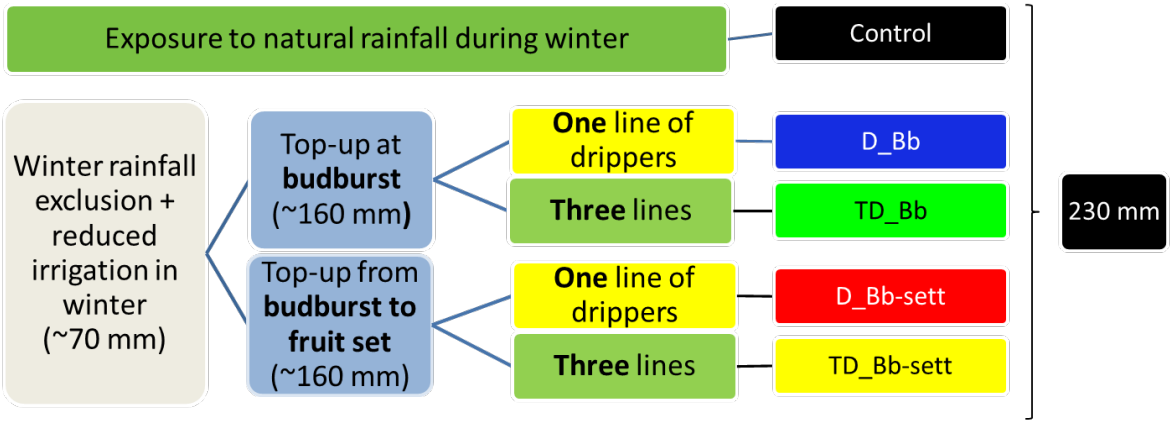


Figure 5:2 Schematic representation of the treatments.

The large-scale rainfall exclusion system

Shelters were used to exclude rainfall from May to August, as previously described in Bonada et al. (2020). Briefly, the system consists of modular roof 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. Rainwater was directed away from the vineyard using galvanised steel gutters and 100 mm PVC pipe.

Irrigation set-up

Irrigation was applied to the *Control* treatment using under-canopy micro-sprinklers to reach the May-August average (Table 5:1). 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.

Winter irrigation was applied depending on the irrigation treatment (Figure 5:2) using single or multiple irrigation laterals. For the treatments with a single lateral under the vines, a system was installed with 19 mm poly pipe equipped with 3 L/h in-line pressure-compensating drippers (PCJ, Netafim, Australia) spaced at 0.75 m. For the treatments with three laterals, irrigation was applied using dripper lines with in-line pressure-compensating drippers spaced every 0.75 cm and with a flow rate of 1 L/h (Uniram CNL 16010, Netafim, Australia). From the finalisation of the irrigation treatments, i.e. from fruit set, and during summer months, all the treatments were irrigated equally using one lateral with in-line pressure-compensating drippers spaced at 0.75 m interval. Vines were watered at a flow rate of 6.6 L/h per vine, using approximately 24 h irrigation events.

Plant water status during the season.

Two complementary approaches were used to characterise the dynamics of plant water status during the season; stem water potential (Ψ_{stem}), accounting for short-term factors affecting plant water status, and carbon isotope composition ($\delta^{13}C$), which integrates plant water stress during the entire season.

Stem water potential was assessed fortnightly starting at close to flowering and extending to harvest using a Scholander type pressure chamber (PMS Instruments, Model 1005, Albany, OR, USA) using the procedures of Hsiao (2007). For $\delta^{13}C$ analysis, juice collected at harvest was centrifuged for 4 minutes at 4500 RPM and 50 mL was sterilised using an autoclave at 120 ^{o}C for 20 minutes. Samples were stored at room temperature until isotopic analysis was performed at the Mawson Analytical Spectrometry Services (MASS) Facility, University of Adelaide. Carbon isotope composition of the grape sugars were measured on approximately 10 µL of berry juice, freeze dried in tin capsules (3 mg dried weight) using a continuous flow isotope ratio mass spectrometer (Nu Horizon IRMS with EuroVector EA, Wrexham, Wales, UK).

Growing conditions seasons 2018-2021

Evaporative demand and water applied

Seasons 2019/20 (S2) was the hottest of the three seasons, while season 2020/21 (S3) was the coolest; from budburst to harvest, season 2019/20 accumulated 106 GDD more than

season 2018/19 (S1) and 177 GDD more than season 2020/21 (Table 5:1). Reference ET (ET_o) followed the same trend between seasons, and ET_o was around 20 mm higher in S2 than in S1, and up to 45 mm higher than in the mild season S3.

Table 5:1 Rainfall, irrigation, accumulated growing degree days (GDD) and evaporative demand during seasons 2018/19, 2019/20 and 2020/21. *1 Effective rainfall is defined as rain higher than 10 mm, or higher than 4 mm when soil surface remains wet from the previous day's rain (McCarthy et al. 2004). *2 GDD base 10°C from 15 September to 31 March. *3 Summed daily reference evapotranspiration (mm) from the dates of budburst and harvest of Control vines. Data sourced from the Bureau of Meteorology for Nuriootpa, SA.

		Water received (mm)												
		Rainfall				Irrigation					Irri + effective rainfall			
Season	Treatment	Dormancy	Bb to setting	Setting to harvest	Total	Dormancy	Bb to 10 cm shoot	10 cm shoot to setting	Dormancy to setting	Setting to harvest	Bb to setting	Dormancy to setting	GDD*2 (°C)	ET_o*3 (mm)
2018/19														
	D-Bb					72	147	-	219		155	227		
	D-Bb_sett	-				70	64	74	208		146	216		
	TD-Bb		27 (8)*1	24 (0)	51	71	148	-	219	70	156	227	2149	1002
	TD-Bb_sett					72	71	67	210		146	218		
	Control	186			237	46	-	-	46		8	240		
2019/20														
	D-Bb					70	138	-	208		159	229		
	D-Bb_sett	-				70	51	89	210		161	231	2255	1021
	TD-Bb		43 (21)	44 (31)	87	71	141	-	212	78	162	233		
	TD-Bb_sett					75	54	80	209		155	230		
	Control	214			292	17	-	-	17		21	252		
2020/21														
	D-Bb					80	138	-	218		186	266		
	D-Bb_sett	-				77	60	77	214		185	262		
	TD-Bb		73 (48)	40 (13)	113	80	139	-	219	83	187	267	2078	976
	TD-Bb_sett					81	61	74	216		183	264		
	Control	275			388	23	-	-	23		48	346		

As is typical for the Mediterranean climate of this region, most of the rainfall occurred during the period when the vines were dormant (May to August). Only during S3 did winter rainfall (275 mm) exceeded the LTA (230 mm). From the LTA rainfall, winter rainfall fell short by 25 mm in S2 and by 44 mm in S1. Spring rainfall followed the same trend as winter rainfall and during the period budburst to fruit set, vines received 73 mm in S3, 43 mm in S2 and only 27 mm in S1. Summer rainfall was around 40 mm in S2 and S3, and 24 mm in S1.

Control vines exposed to natural winter rain received a total of 186 mm in S1, 214 mm in S2 and 275 mm during winter of S3 (Table 5:1, Figure 5:3). Supplementary irrigation was applied to Control vines in the dry winters of S1 (46 mm) and S2 (17 mm) to reach close to the long-term average for this site. Irrigation was also applied to Control vines in the wet S3 early in August (23 mm), to balance for the lack of rain during June and July this year (46 mm short in relation to the 114 mm expected for the intra-monthly period June/July). Rainfall during August of S3, however, exceeded the monthly LTA by approx. 26 mm, resulting in Control vines this season receiving comparatively more water from rainfall and irrigation during dormancy (298 mm) than in S1 (232 mm) and S2 (231 mm).

Irrigation was applied during winter at a similar level to the first decile (~76 mm; see treatment details) to simulate dry conditions; applications were made in three events of ~25 mm each, at monthly intervals, and starting from mid-June. Water applied was similar

between irrigation treatments; treatments received approx. 71 mm (SD = 0.95) in S1, 71 mm (SD = 2.38) in S2 and 79 mm (SD = 1.73) in S3. The remaining water to reach the LTA of this site was applied on weekly irrigation events, from the time of budburst to when the shoots reached 10 cm for Bb treatments, or from budburst to fruit set in the Bb_set treatments. Between irrigation and effective rainfall, vines received 151 mm (SD = 5.50) in S1, 159 mm (SD = 3.09) in S2, and 185 mm (SD = 1.70) in S3, in five or ten irrigation events of approximately 29 or 14 mm each, for Bb or Bb_set treatments, respectively.

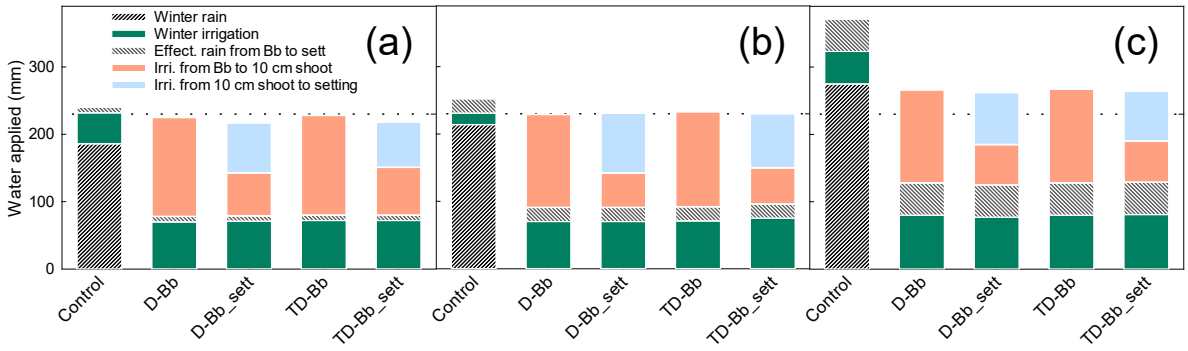


Figure 5:3 Water received by each irrigation treatment as rainfall and irrigation during dormancy, and from budburst (E-L4) to fruit set (E-L27), during seasons (a) 2018/19, (b) 2019/20, and (c) 2020/21. The lined bar corresponds to winter rain (from 1 May to the time of budburst), and to effective rain (> 10 mm or > 4 mm after successive days with rain) from budburst to fruit set. The solid bar corresponds to supplementary irrigation during the period from budburst to a shoot length of 10 cm (E-L12), and from this stage to fruit set. The horizontal dotted line indicates the average rain from May to August (230 mm) during the period 1952-2015 in Nuriootpa, SA.

From the time from fruit set to harvest during seasons 2018/19 to 2020/21 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 70 mm in season 2018/19, 109 mm in season 2019/20, and 96 mm in season 2020/21 (Table 5:1).

Characterisation of vine water status

The mid-day stem water potential reflected the patterns of soil drying and wetting during the growing season (Figure 5:4). In a similar pattern across the seasons S1, S2 and S3, the maximum Ψ_{stem} occurred early in the season, around the time of budburst, and decreased progressively as the soil dried and summer progressed. Water potentials between -1.1 and -1.3 MPa were reached before veraison during the drier seasons S1 and S2, or close after veraison during the wetter S3. Following common practices for this region, supplementary irrigation was applied from 11/01/2019 in S1, 18/12/2020 in S2, and 21/12/2021 in S3 to maintain stem water potentials during fruit ripening between -1.1 and -1.3 MPa.

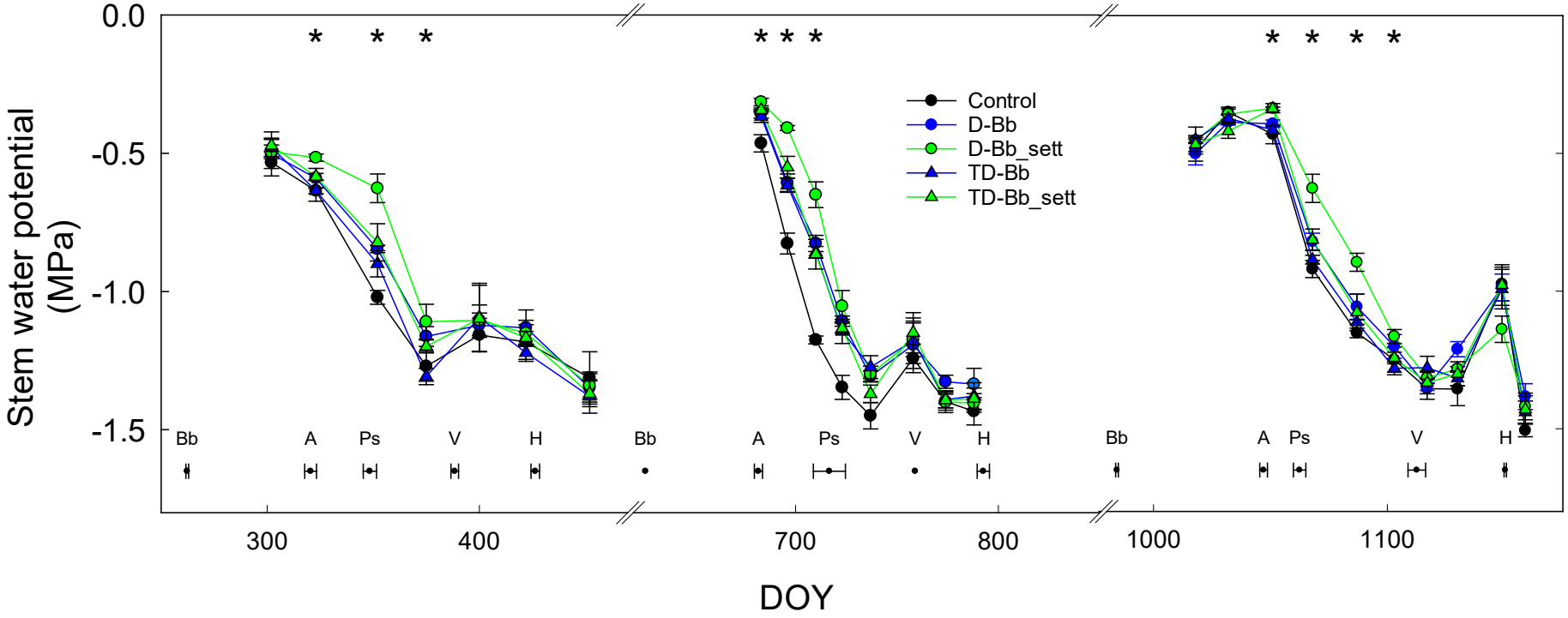


Figure 5:4 Dynamics of mid-day stem water potential of Shiraz vines subject to a range of irrigation treatments in chronological time (DOY, days of the year from 01/01/2018). Data are mean from four field replicates. Black circles indicate key phenology stages (mean ± SD): budburst (Bb), anthesis (A), berry pea size (PS), veraison (V) and harvest (H). (*) indicates significant difference between irrigation treatments from the two-way ANOVA at a $P < 0.05$ significant level for the effect of the method (D, Dripper in a single lateral; and, TD, in multiple laterals), the time (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set), or the method x time interaction.

We measured the effect of the treatments and their interaction on Ψ_{stem} across the entire growing season and at each measured date using a repeated measure ANOVA (Table 5:2). The ANOVA showed no significant effect on the time, method of irrigation, and time x method interaction on Ψ_{stem} for any of the seasons, but a significant interaction between the time and the date of measurement on S2 and S3. Some of the differences between treatments were reflected by the comparison between means; significant differences in Ψ_{stem} between treatments were only detected early in the season, around the period between flowering and berry pea-size.

Table 5:2 *P* value from the repeated measure ANOVA showing the effect of the Method and Time of irrigation, and their interaction, on stem water potential, for the entire season or between factors effect at each measured time.

Source of variation	Season		
	2018/19	2019/20	2020/21
Method (M)	0.063	0.107	0.114
Time (T)	0.070	0.332	0.214
M x T	0.863	0.371	0.264
Date (D)	< 0.0001	< 0.0001	< 0.0001
M x D	0.285	0.219	0.162
T x D	0.390	0.024	0.007
M x T x D	0.838	0.113	0.077

We extended the analysis and compared Ψ_{stem} during the period between flowering and fruit set, between irrigation treatments and the unsheltered Control vines (Figure 5:5a and b). Control vines were more water stressed than the treated vines regardless of the treatment. The two-way ANOVA on the residuals from the 1=1 line on Ψ_{stem} from the Control vines indicated a significant effect of the method (*P* = 0.033) and the time (*P* = 0.020) of irrigation, but no effect on the interaction (*P* = 0.347). Vines irrigated with a single line of emitters under the vines had higher Ψ_{stem} than their counterpart irrigated with multiple laterals (Figure 5:5a). Similarly, prolonged irrigation during the period between budburst to fruit set was more effective in maintaining higher Ψ_{stem} than irrigation at budburst (Figure 5:5b).

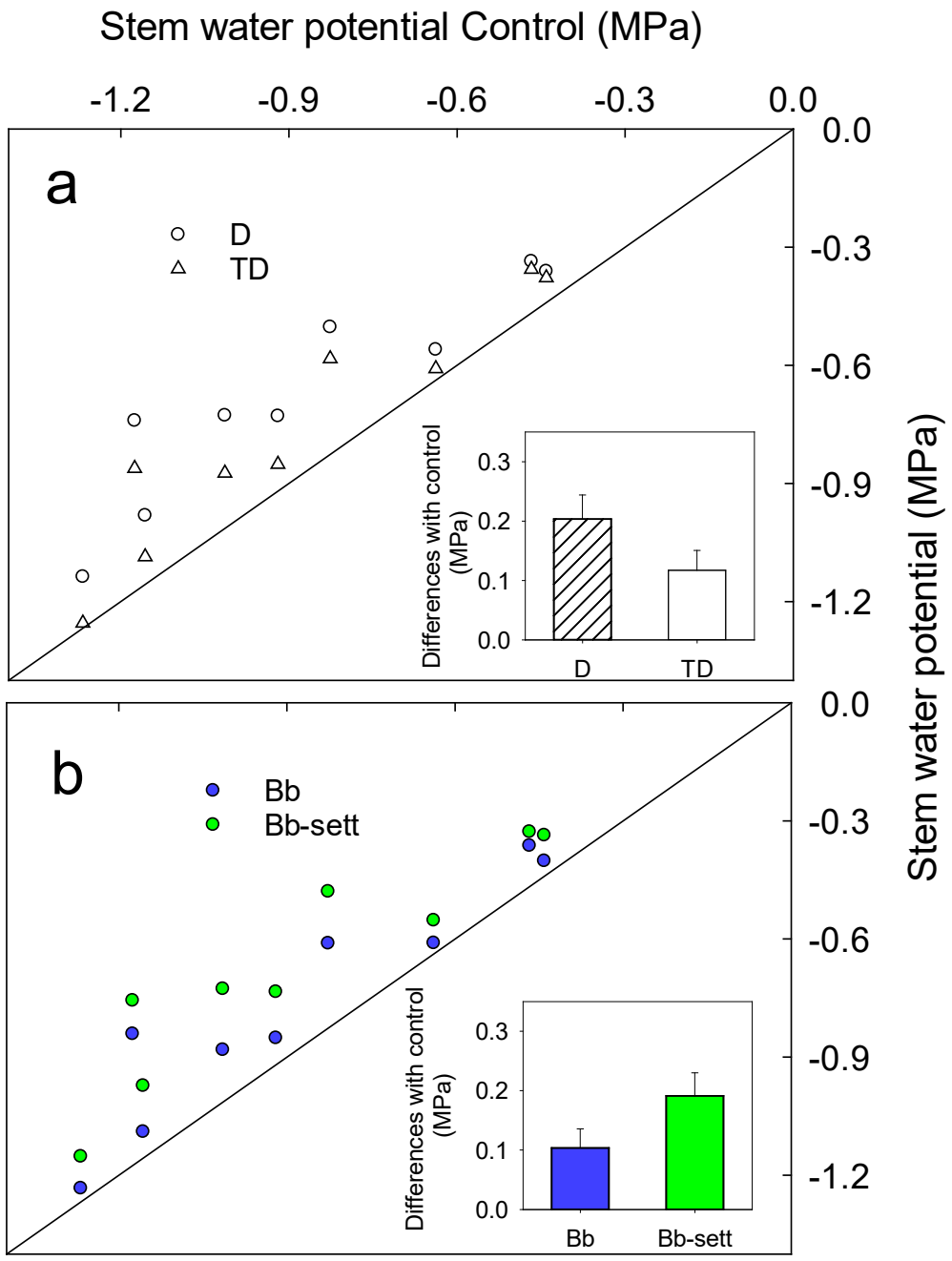


Figure 5:5 Relationships between stem water potential of Control vines exposed to natural rainfall and stem water potential of vines exposed to (a) two methods of irrigation (D, dripper in a single lateral; and, TD, in multiple laterals) and (b) two times of irrigation (Bb, budburst to 10 cm long shoot; and, Bb_set, budburst to fruit set). Values are means of four replicates per treatment, with three vines measured in each repetition, during seasons 2018/19 to 2020/21. Lines shows the 1=1 between x and y. Insets on a and b shows residuals with the 1=1 line.

The stable carbon isotope composition in grape juice has been shown to be a robust physiological indicator of vine water status during ripening (Gaudillère et al. 2002, van Leeuwen et al. 2009, Spangenberg and Zufferey 2018). This analysis measures the relative concentration of ^{13}C and ^{12}C on berry sugars produced during the photosynthesis and is primarily defined by the contribution of CO_2 from the atmosphere (mainly ^{12}C) and the intracellular CO_2 (^{13}C). When the stomata close due to water stress, there is an increase in the proportion of CO_2 cycled within the intracellular space inside the leaf, therefore increasing the relative proportion of ^{13}C contained in berry sugars. This means that the $\delta^{13}C$ provides a fingerprint the berry sugars that can be traced back the level of water stress that the vine has experienced during the growing season. $\delta^{13}C$ can integrate the effects of the management practices (especially irrigation), the site (soil physico-chemical properties, topology, and climate) and plant material (variety, clone and combination of rootstock/scion) that modulated soil water availability and vine water uptake during the season.

We measured $\delta^{13}C$ at harvest during the three vintages. In agreement with the analysis of stem water potential during the season (Figure 5:5) we found that $\delta^{13}C$ was higher in Control vines, indicating that vines under this treatment suffered a higher level of water stress (Figure 5:6). No differences were found, however, for the single and combined effect of the method and time of irrigation. This highlights some possible limitations of $\delta^{13}C$ measured in the must in detecting water stress in the period prior to the onset of accumulation of sugars in the berry. In this experiment water stress was transient and restricted to the period between approximately flowering to berry pea-size (Figure 5:4), which preceded the period of rapid accumulation of sugars in the fruit.

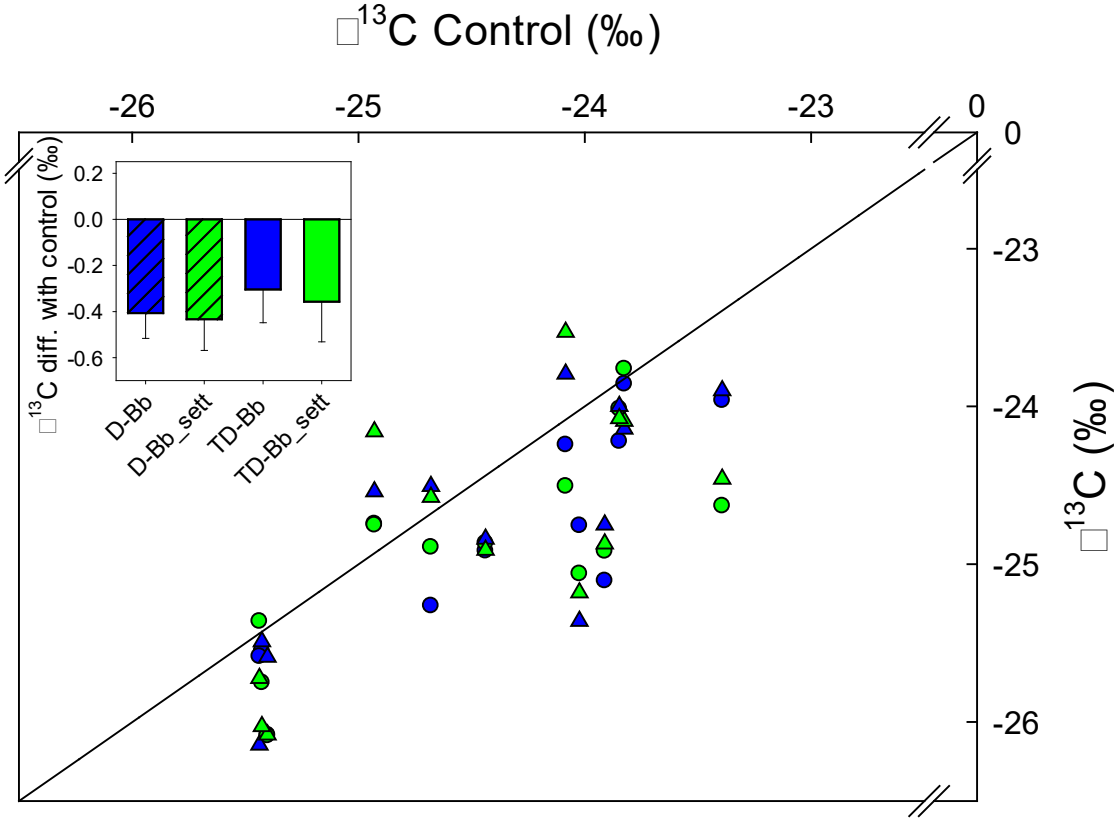


Figure 5:6 Relationships between $\delta^{13}C$ measured in the must at harvest of Control vines exposed to natural rainfall and $\delta^{13}C$ of vines exposed to two methods of irrigation (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set) in a factorial experiment. Values are means of four replicates per treatment during three seasons (2018/19, 2019/20 and 2020/21). The line shows the 1=1 between x and y. Inset shows residuals with the 1=1 line.

Soil moisture monitoring

Soil moisture status was monitored approximately every ten days using a capacitance moisture sensor (Diviner 2000, Sentek, Magill, South Australia). Access tubes were located adjacent to the vine, at approx. 15 cm apart from the vine trunk, at 75 cm from the vine trunk, and at the mid-row space at 150 cm from the trunk (Figure 5:7). At each position and sampling time, soil moisture was measure at 10 cm intervals from the ground level up to 110 cm.



Figure 5:7 Location of access tubes in the trial. Three tubes per repetition were installed in winter 2018; adjacent to the vine, at approx. 15 cm from the vine trunk, 75 cm from the vine trunk and in the mid row space, 150 cm from the vine trunk.

The calibration of the probe for the local soil type was completed using existing calibration curves from the probe's manufacturer. To match the calibration with the texture at each soil depth (every 10 cm), intact cores were taken from three locations of the trial up to 100 cm depth in PVC clear sleeves using a Geoprobe Macro-Core® soil sampling system (Geoprobe, Salina, Kansas, USA). An initial visual inspection was done on the intact soil cores to identify variations in colour that indicate possible change in texture that denote each soil horizon, followed by the determination of the texture at each horizon using the 'field textural analysis' (Figure 5:8). Plant available water capacity (PAWC) of the soil up to one metre depth was estimated based on water content-pressure head from fixed pressures at 33 kPa (field capacity, FC) and 1500 kPa (crop lower limit, CLL) from previous measurements of similar soil types in the Barossa (McCarthy, person communication) and published values for the Northern Adelaide Plain (NAP) soils (Mallants et al. 2019). Daily plant available water (PAW) was estimated as the difference between the CLL and the volumetric soil water content from the soil as measured by the capacitance probes.



Figure 5:8 (a) Soil sampling of intact cores up to 100 cm for textural analysis. Samples were collected using (b) PVC clear sleeves and processed in the laboratory following the 'field textural analysis' protocol. (c) The hydraulic hammer-driven system used for sampling is mounted in a trailer with a telescopic arm that allows for lateral adjustments.

The dynamics of PAW reflected the patterns of soil water depletion and replenishment across the irrigation treatments and during the seasons (Figure 5:9). Irrespective of the treatments, PAW reached a maximum each year at around the time of budburst and progressively dried from there during the summer months until it reached a minimum around harvest. The Control treatment showed comparatively higher PAW during the wet months (winter) but a lower PAW from approximately budburst to the time of harvest. The opposite pattern was observed on the remaining treatments, which were subjected to rainfall exclusion during winter and supplementary irrigation in winter but mainly during spring. These treatments had lower PAW than Control during winter but a higher PAW after irrigation treatments started from budburst. These differences were maintained for most of the growing season - until harvest.

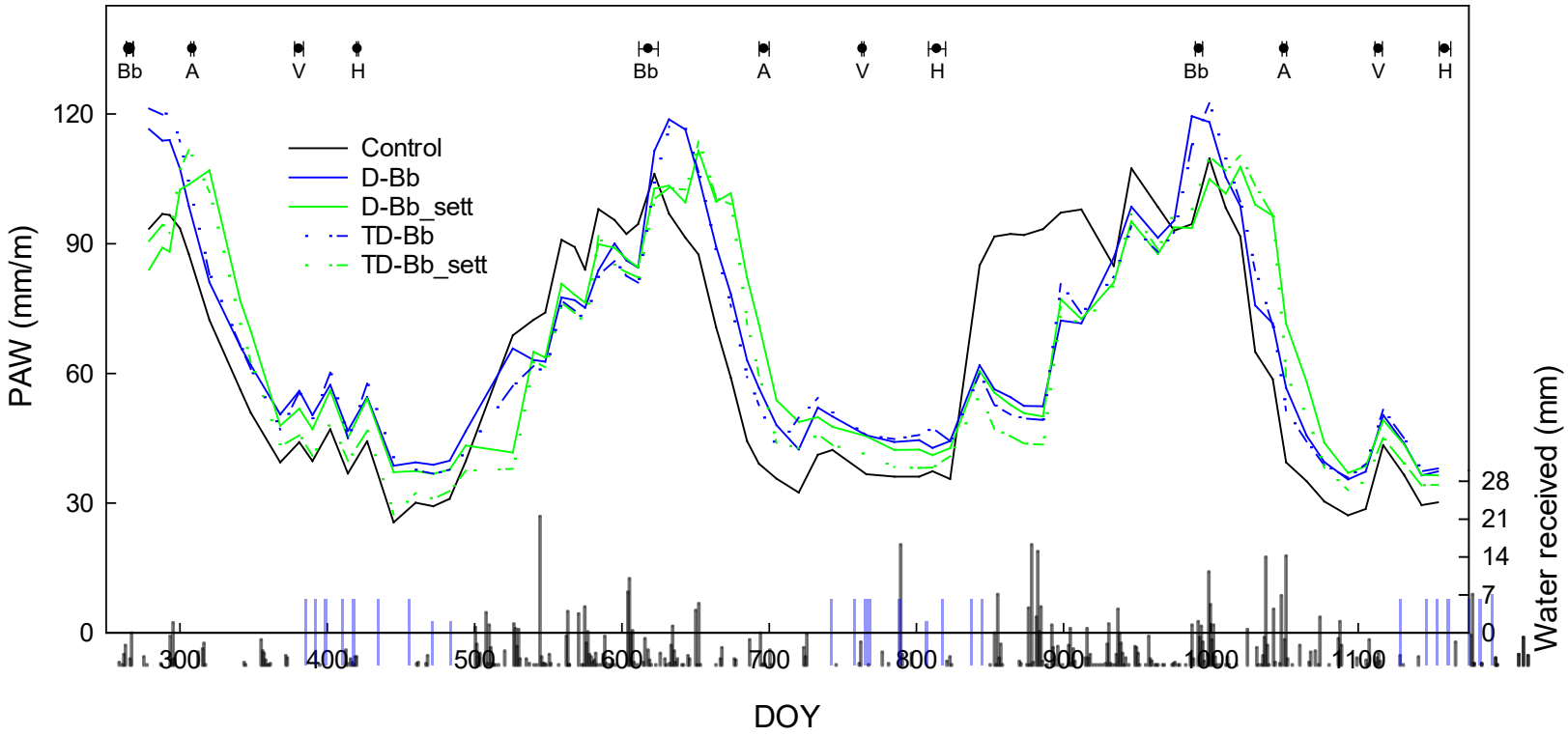


Figure 5:9 The dynamics of soil total available water during seasons 2018 to 2021 [days of the year from 01/01/2018 (DOY)] up to 1 m below ground level for a factorial experiment combining two methods (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). Bars indicate water received during the growing season from irrigation ( ) and rainfall ( ). Key phenostages (mean ± SD) are indicated: budburst (Bb), E-L4; anthesis (A), E-L23; veraison (V), E-L35 and harvest (H).

The differences in soil water content between treatments at key phenological stages were evaluated by expressing the soil water deficit (SWD) as the difference between PAWC and PAW. The impact of the method and time of irrigation at different phenological stages and soil moisture measurement locations in the inter-row space (Figure 5:10) were compared.

Regardless of the treatment, there was a clear increment in soil water deficit as the growing season progressed from budburst to veraison. However, except at veraison, where SWD was similar between Control and treated vines, there was an interaction between method or time of irrigation with the positions, which started at budburst and lasted until fruit set.

At budburst, after both the Bb and Bb-set treatments had received some irrigation (Table 5:1 & Figure 5:3), SWD increased toward the mid-row space under D but not under the TD or Control treatments (Figure 5:10a). This may have been the result of a more uniform pattern of soil wetting under Control vines exposed to winter rainfall and on TD vines with extra laterals in the mid-row space. This same pattern was maintained between D and TD at the time of fruit set in the 75 cm and 150 cm positions (Figure 5:10c), but not in the 15 cm position close to the root ball, where soil moisture depletion was higher and SWD increased for all the treatments. By fruit set, Control plots had a substantial higher SWD irrespective of the sampling position. At veraison, well after irrigation treatments had finished, the extra lateral in the mid-row space of the TD treatment was unable to account for vine water use and extra soil evaporation from the more exposed inter-row space and, therefore, SWD increased more under this combination of treatment and position (Figure 5:10e).

Irrigation at Bb increased soil water availability over Bb_set and Control treatments at budburst, as indicated by the lower SWD at the three locations under this treatment (Figure 5:10b). This effect, however, was reversed at fruit set (Figure 5:10d), when Bb irrigated vines had a SWD similar to the Control vines, and a significantly higher SWD than the Bb_set irrigated vines. At veraison, when most of the soil moisture had been used to sustain growth, and limited summer supplementary irrigation has been applied, all the plots irrespective of the time of irrigation and position were experiencing a similar level of SWD (Figure 5:10f).

Overall, this indicated that differences between position, methods and times of irrigation were transient during early stages of development between budburst and fruit set. For all the positions and times of sampling Control vines where exposed to a higher SWD than treated vines. TD generates a uniform wetting of the soil, as reflected by the even SWD for the three soil moisture measurement locations from budburst to fruit set. Likewise, Bb_set irrigation favoured soil water availability from budburst to fruit set for the three sampling locations.

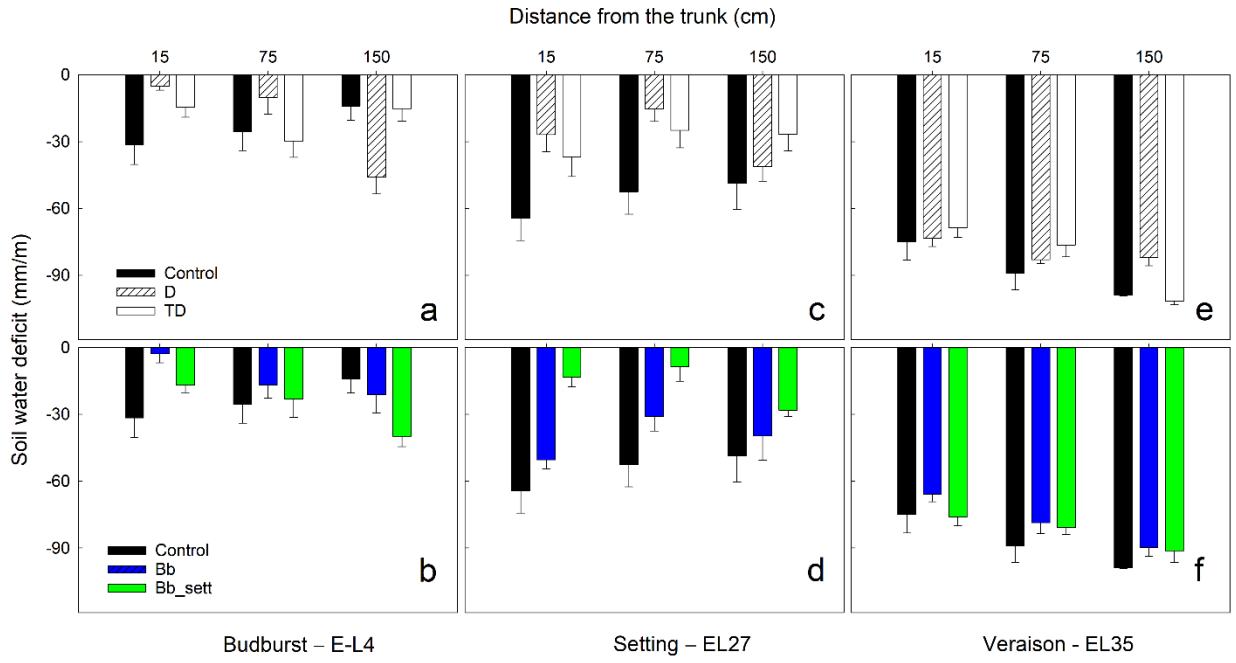


Figure 5:10 Soil water deficit in the three locations (15 cm, 75 cm and 150 cm from the vine trunk) and at different phenological stages on Shiraz vines exposed to (a, c and e) two methods (D, dripper in a single lateral; and, TD, in multiple laterals) and (b, d and f) two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). Water deficit was estimated as the difference between the plant available water capacity (PAWC) and the daily total available water (PAW) of the soil in three positions (15, 75 and 150 cm apart from the trunk towards the mid-row space) and at three phenological stages: (a, b) budburst, (c, d) fruit set, and (e, f) veraison. Bars are means ± SE of four replicates per treatment from data pooled across seasons 2018 to 2021.

6 EFFECT OF WINTER RAINFALL EXCLUSION AND SUPPLEMENTARY IRRIGATION IN WINTER AND SPRING ON VINE GROWTH AND DEVELOPMENT

Introduction

Experimental data suggested that dry soil at the end of winter delays budburst and limited canopy growth during the season. In a previous study we showed that a reduction in soil water content by 10% (volumetric water content) corresponded to a delay in the time of budburst of around 13 days (Bonada et al. 2020). Similarly, reduced rainfall in winter limited canopy growth during the season, resulting in smaller canopies, which also limited vine capacity to produce fruit. On the other hand, irrigation at the time of budburst to refill the soil profile following a winter with no rainfall stimulated vegetative over reproductive growth, i.e. increased pruning-wt:yield and root-wt:yield ratios, and decreased fruit and wine composition. In this section we covered the impacts that the methods and times of irrigation trialled in this project have on vine development (phenology), canopy growth (leaf are index, LAI) and root growth to confirm this relationship.

Materials and methods

Phenology

Phenology was assessed weekly from budburst until harvest. Growth stages were estimated visually using the E-L scale (Coombe 1995). The effect of the method and time of irrigation on the timing of key phenology stages was determined as the difference in days that vines of each treatment reached the phenostage stage relative to Control vines.

Leaf area index

Canopy size was indirectly assessed as leaf area index (LAI) using digital photography and gap fraction analysis. Upward looking digital images were taken from canopies approximately every two 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 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 on each side of the image. Images were taken avoiding direct sunshine (during the evening, early morning or in overcast conditions), which interferes 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 in Spring.

Results

Treatments effects on grapevine phenology

Neither the method nor the time of irrigation had a consistent effect across the seasons on the timing of key phenostages (Figure 6:2). In relation to the Control, both the time and method of irrigation advanced budburst by approximately one day in seasons S1 and S3 but had no effect relative to the Control during this period in S2. Stage EL-31 (pea size) showed a larger difference between treatments in S2 and S3. The advancement observed on the timing of EL-31 in treated vines in S2 and S3, coincided with larger differences in berry mass between treated and Control vines in these seasons (section 8). It is likely the observed differences in phenology at EL-31 are the results of the effects of growth, i.e. increase in mass, as opposed to changes in the timing of phenostages.

Effect of treatments on LAI

Leaf area index assessed during the season reflected differences in canopy size between treatments (Figure 6:3). Control vines showed lower LAI than the remaining treatments during seasons S1 and S2 starting from the very early stages of canopy growth and extending until leaf fall. In season S3, LAI of Control vines diverged from the other treatments during the period between veraison to leaf fall. Overall, regardless of the timing of irrigation, irrigation with a single lateral under the row increased LAI from approx. pea size to harvest in S1, and from approx. anthesis to harvest in S2. Differences in LAI between single lateral and multilateral treatments were only transient during season S3 and confined to the period before veraison.

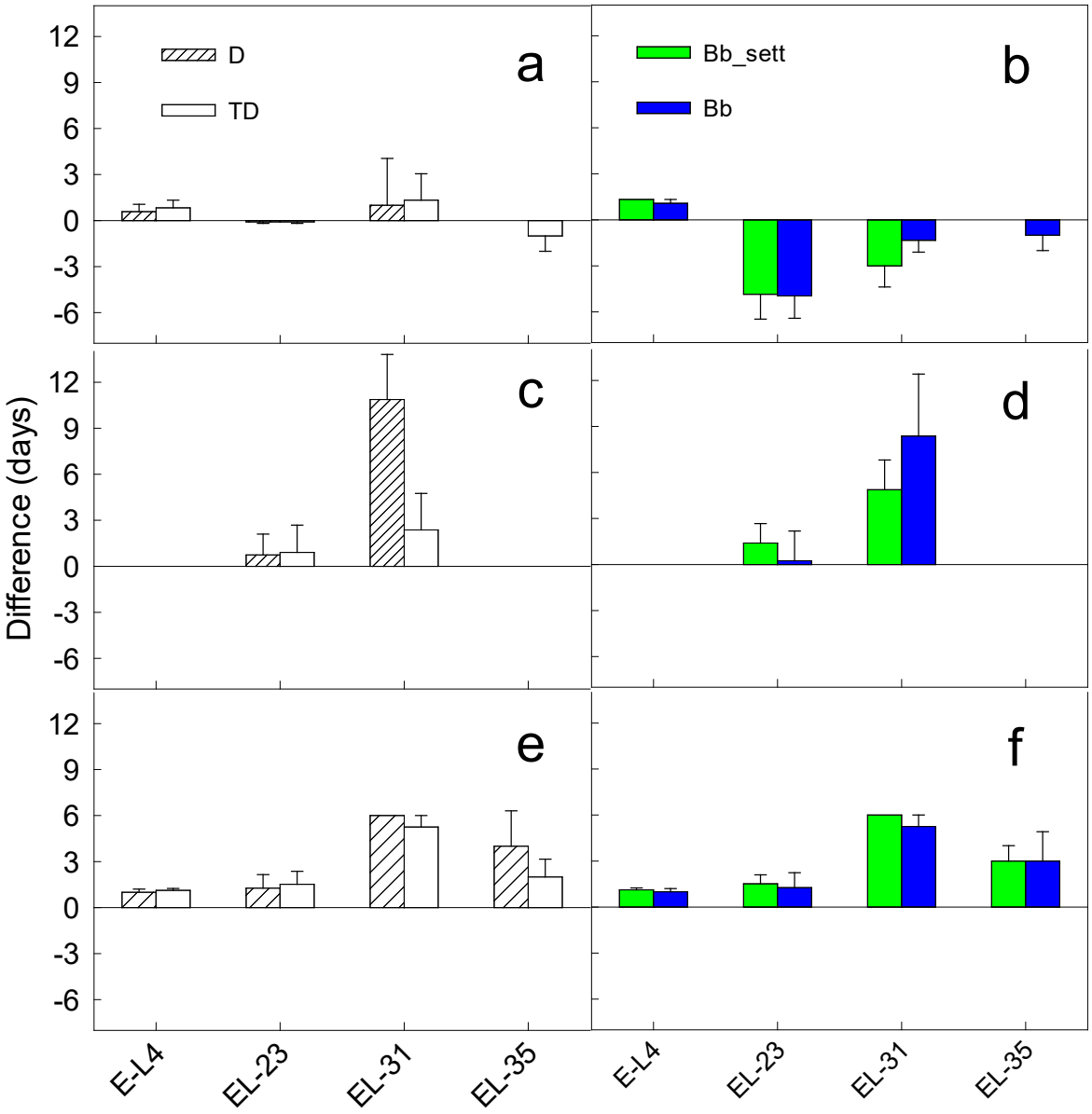


Figure 6:2 Effects of (a, c and e) two methods (D, Dripper in a single lateral; and, TD, in multiple laterals), and (b, d and f) two times (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set) of irrigation on phenology during seasons (a and b) 2018/19, (c and d) 2019/20 and (e and f) 2020/21. Irrigation effects correspond to the difference in days at which treatments reached key phenological stages in relation to Control vines: budburst (E-L4), full bloom (E-L23), berry pea size (E-L31) and veraison (E-L35). Values are means ± SE of four replicates per treatment.

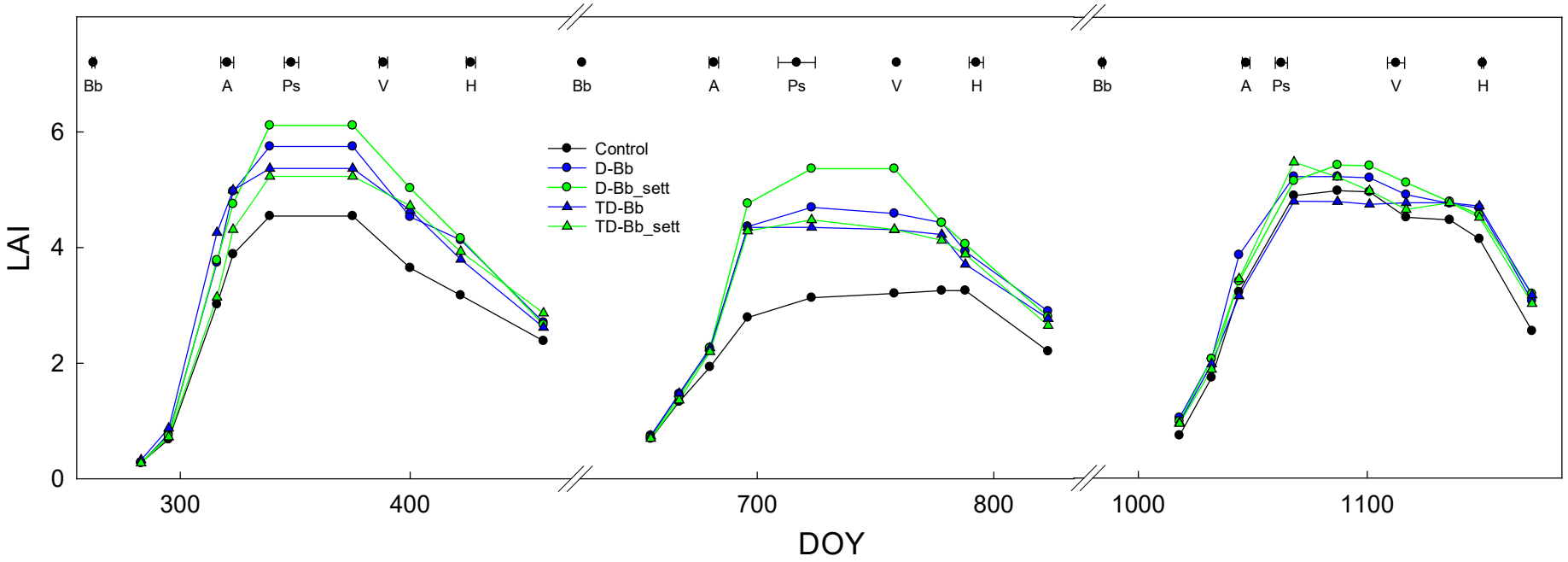


Figure 6:3 Seasonal patterns of Leaf Area Index (LAI) for three years (2018/19, 2019/20 and 2020/21) on a factorial experiment combining two methods (D, Dripper in a single lateral; and, TD, in multiple laterals), and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). Control vines exposed to natural rainfall were included for comparison. A continuous time scale where day of year (DOY) starts on 01/01/2018 was used. Values are running average of four replicates per treatment. Black circles indicate key phenological stages (mean ± SD): budburst (Bb), flowering (A), berry pea size (PS), veraison (V) and harvest (H).

To account for interactions between treatments, growth stages and seasons that may be obscuring treatments effects on LAI, we calculated the reaction norms for the LAI (Trentacoste et al. 2011, Sadras et al. 2013, Bonada et al. 2020). We calculated the mean LAI, referred to as the 'environmental mean', across the two times and two methods of irrigation each season, including the Control, and correlated it against the actual value of LAI for each treatment. The deviations (residuals) from the x=y line were then taken as a measure of the treatment effect and analysed using an AVOVA (Figure 6:4a).

The two-way ANOVA between the method and time of irrigation on the residuals from the x=y line, showed a significant effect of the method of irrigation (Figure 6:4b). Dripper irrigated vines with a single lateral had a higher LAI than vines irrigated with multiple laterals, and then the Control vines that received natural winter and spring rainfall. The effect of the time of irrigation was not detected as significant by the two-way ANOVA. There was also an interaction between the time and method of irrigation on LAI, which has practical implications on the management of irrigation following budburst (Figure 6:4c). Irrigation from budburst to set increased LAI more than its counterpart irrigated at budburst when irrigation was applied with a single lateral, but this effect on LAI was reversed when the same amount of water was applied with multiple laterals. This indicates that the potential benefit of wetting a higher proportion of the vineyard floor by extra laterals in the mid-row space will not be captured by the vines if this practice is not accompanied by an increment in the volume of water applied to compensate for the extra evaporation in the more exposed mid-row space.

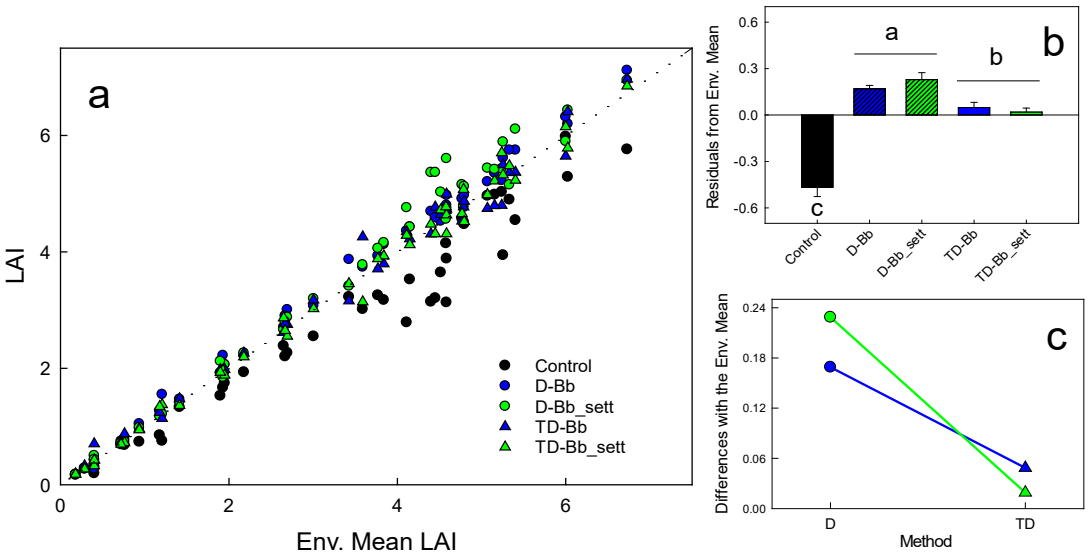


Figure 6:4 Relationship between LAI in a three-year factorial experiment combining two methods (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set), including a Control treatment exposed to natural rainfall, and the environmental mean of LAI across treatments. The dashed line in (a) indicates the reference line y = x. (b) shows residuals with the 1=1 line; bars followed by different letters differs significantly at $P < 0.05$ by Fisher's LSD test. (c) interaction between method and time of irrigation on the residuals between LAI and the environmental mean.

7 EFFECT OF WINTER RAINFALL EXCLUSION AND SUPPLEMENTARY IRRIGATION ON ROOT DISTRIBUTION

Introduction

Root distribution depends largely on soil physical properties, chiefly size and the arrangement of particles and pores. Beyond chemical constraints that may deter root growth, soil may bound root growth by imposing physical barriers or by limiting available oxygen necessary for root growth, elongation and nutrient uptake. While the genotype shapes root growth and bound its response to the surrounding environment. Trade-offs on the partitioning of growth between the canopy and root system, and between the formation and maintenance of new root tissues, define the capacity of the plant to response to the environment. Plant organs can adapt to the environment by changing function and/or by changing morphology. Root plasticity, for example, is an evolutionary response that allows species to adapt to periods of water stress by investing resources to grow lateral roots.

Materials and methods

Soil sampling, root processing and scanning

Soil samples were collected up to 100 cm depth using a 5 cm internal diameter hydraulic hammer-driven probe as previously described in Bonada et al. (2020). Samples were collected from the central vines at each replicate, mirroring the distribution of the soil moisture access tubes, i.e. adjacent to the vine trunk, and at 75 cm and 150 cm from the trunk towards the mid-row space. Samples were collected at budburst (E-L 4), flowering (E-L 23), veraison (E-L 35), harvest (E-L 38) and leaf fall (E-L 47) during seasons 2018/19 and 2019/20; and at budburst, flowering, and harvest in season 2020/21. 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. Root morphological traits were measured using a root analysis software package (WinRHIZO, Regent Instrument Inc., Quebec, Canada) as previously described (Bouma et al. 2001). After scanning, roots were dried in paper bags at 70 °C to a constant mass, and results expressed in dry matter (DM, g). Root length density and surface area density were calculated as the ratio of the root length or surface per volume of soil, and expressed in km/m^3 and m^2/m^3. Average root diameter was expressed in mm. Specific root length (SRL) and specific root area (SRA) were calculated as the ratio of root length or root area to root dry mass, and expressed as m/g or m^2/g.

Results

We ran a multi-factor ANOVA to explore variations in fine root traits as impacted by the season, phenological stage, irrigation treatments, sampling position (depth and distance from the trunk) and their interactions (Table 7:1). The four traits assessed responded to the effect of the season ($P \leq 0.003$). As indicated by root dry mass, there was more root growth in the

wet season S3 than in the dry seasons S1 and S2 (Figure 7:1a). This was reflected in the RLD (Figure 7:1b), which ranked S3 (2.6 Km/m^3) > S2 (1.6 Km/m^3) > S1 (1 Km/m^3). SRL and root diameter showed the opposite trend than root dry mass and RLD (Figure 7:1c and d); during the wet season S3 SRL was around 37% lower and the diameter slightly thinner than in the dry season S1, suggesting a higher efficiency of nutrient acquisition versus utilisation to grow longer and thicker roots in years with higher water (and potentially nutrient) availability (Reingwirtz et al. 2021). There were minor differences in root dry mass and SRL between budburst, flowering and harvest (data not shown). RLD, however, increased from budburst and peaked around the time of harvest; except for S3 when RLD peaked at the time of flowering, coinciding with the wet spring. Most of the changes in RLD occurred in the sampling position adjacent to the trunk.

Table 7:1 *P* values from the ANOVA on the effect of the season, phenological stage, method and time of irrigation, sampling position and depth, and their interactions for fine root traits. Values in bold are lower than 0.1.

Source	Fine root dry mass (g/m^3)	Specific root lenght (m/g)	Root density (Km/m^3)	Diameter (mm)
Season (S)	**<0.0001**	**0.003**	**<0.0001**	**<0.0001**
Phenological stage (E-L)	0.204	0.397	**<0.0001**	**<0.0001**
Method (M)	**0.002**	0.485	**<0.0001**	0.315
Time (T)	**0.047**	**0.061**	**0.040**	**0.089**
Depth (D)	**<0.0001**	**0.004**	**<0.0001**	**<0.0001**
Position (P)	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
S x E-L	**0.013**	**0.015**	**<0.0001**	**<0.0001**
S x M	0.195	0.127	**0.002**	0.594
S x T	0.866	0.351	0.779	**0.028**
S x D	**<0.0001**	0.475	**<0.0001**	0.202
S x P	**<0.0001**	**0.063**	**<0.0001**	0.114
E-L x M	0.902	0.626	0.553	0.150
E-L x T	0.815	**0.063**	0.327	0.877
E-L x D	0.512	0.839	0.490	0.435
E-L x P	**0.012**	0.136	**<0.0001**	0.512
M x T	0.375	**0.035**	**0.086**	0.128
M x D	0.242	0.528	0.223	0.538
M x P	**<0.0001**	0.698	**<0.0001**	0.222
T x D	0.879	0.472	**0.055**	0.747
T x P	0.171	0.472	0.243	0.815
D x P	**<0.0001**	0.261	**<0.0001**	**<0.0001**

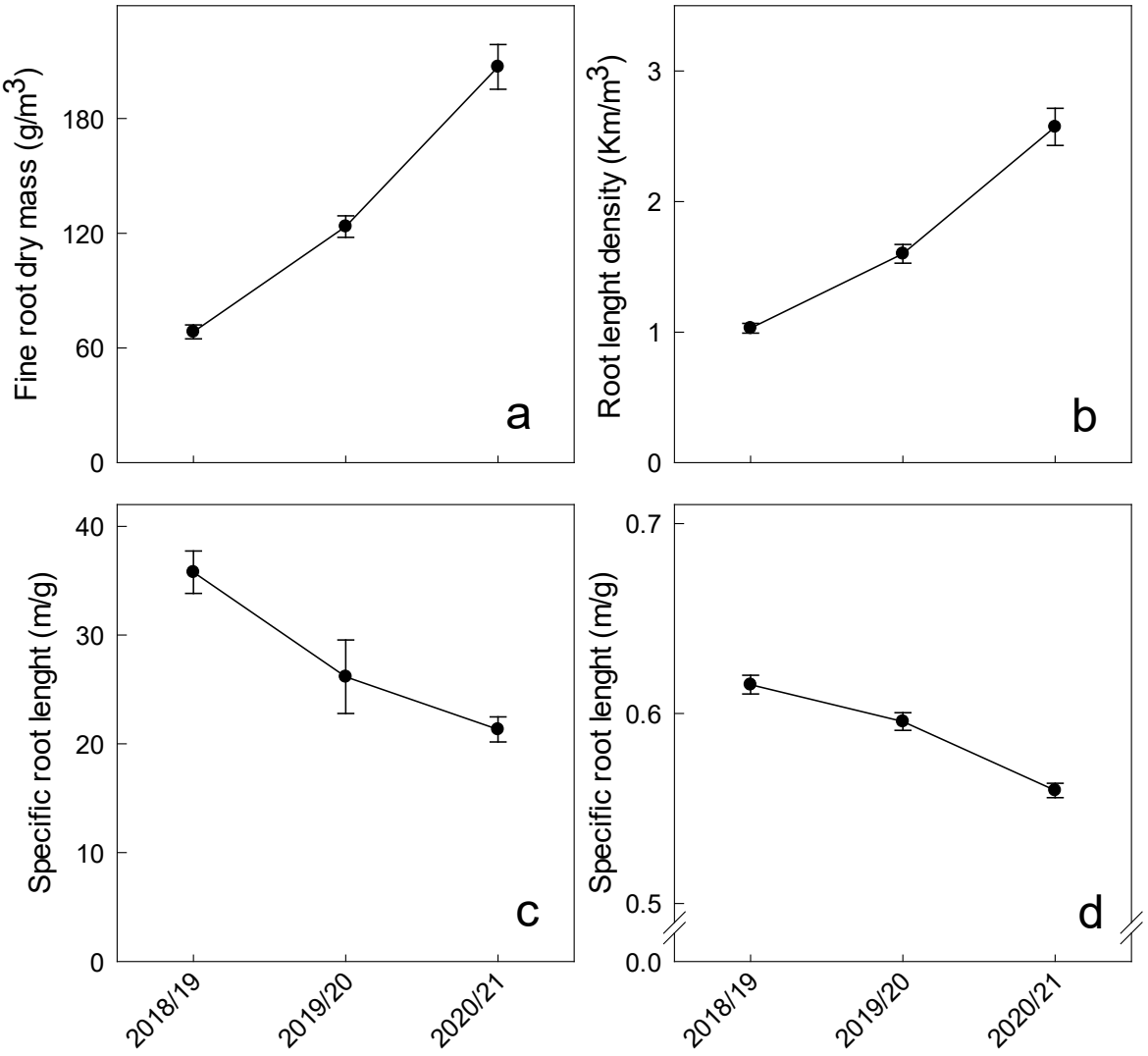


Figure 7:1 Root traits measured across three seasons (2018-2021). Points are means ± SE for data pooled between treatments and between sampling times and positions.

There was an additive effect of the method and the time of irrigation on root dry mass and root length density. Irrigation with multiple laterals and irrigation from budburst to fruit set both increased root dry mass and root length density (Figure 7:2a and b). As reflected by the interaction between the method and sampling position ($P < 0.0001$), the extra growth with multiple laterals was mainly confined to the position adjacent to the trunk, challenging the hypothesis that, under the conditions of this experiment, the extra lateral of irrigation in the mid-row space may favour root growth in this area. Specific root length responded to the interaction between the method and time of irrigation. The timing of irrigation did not impact on the specific root length when irrigation was applied with multiple laterals but extended irrigation from budburst to fruit set, as opposed to irrigation applied at budburst, decreased specific root length when applied with a single lateral (Figure 7:2c). This suggests that the vines responded to the higher availability of water under extended irrigation with a single lateral, which concentrated water within a smaller fraction of the soil (Figure 5:10), by growing shorter and thicker roots (Figure 7:2d).

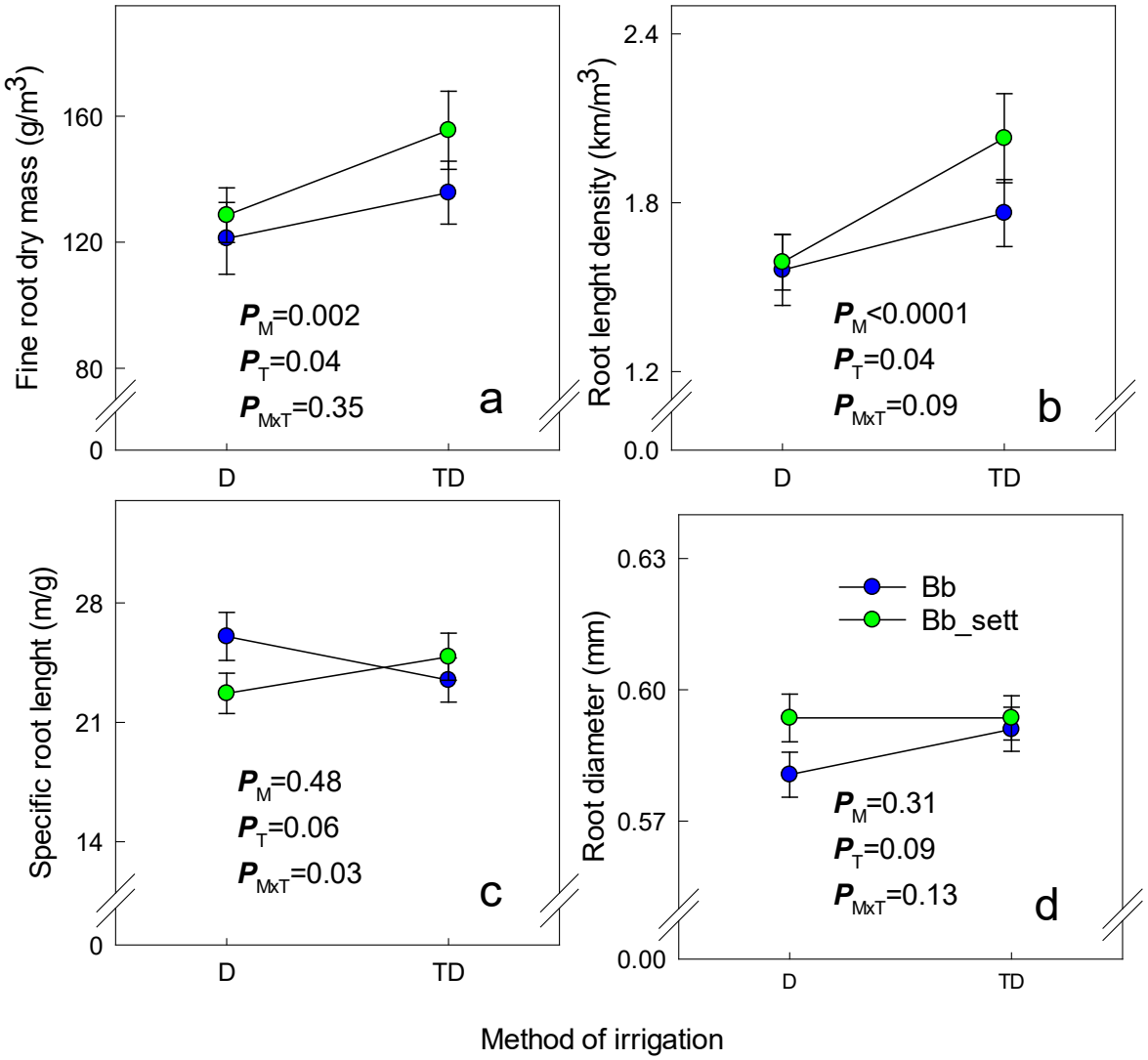


Figure 7:2 Root traits from a factorial experiment combining two methods (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). Data are from three seasons (2018-2021) and values are mean ± SE from four field repetitions. *P* values are from the ANOVA for the single and combined effect of the method (M) and time of irrigation (T).

Root length density decreased by approx. 55% (from 2.8 to 1.3 km/m^3) between 30 and 60 cm depth, with minor differences at depths between 60 and 90 cm (from 1.3 to 1.1 km/m^3). Irrigation with multiple laterals slightly increased root length density at each depth (Figure 7:3a), whereas irrigation from Bb to fruit set promoted root growth over the Bb irrigated counterpart mainly in the first 30 cm (Figure 7:3b). Specific root length, however, contrasted between irrigation treatment and depth. Both irrigation at budburst or from budburst to fruit set slightly (approx. 7%) increased specific root length between 30 and 60 cm, but, more markedly (approx. 32%) between 60 and 90 cm (Figure 7:3d). Whereas irrigation with multiple laterals increased specific root length progressively with depth, single lateral irrigation only increased specific root length in the deeper soil layer beyond 66 cm (Figure 7:3b). This is consistent with the pattern of wetting under each treatment; single-lateral irrigation

concentrated water in a smaller area under the vines and wets the soil more evenly up to 60 cm in comparison with multiple lateral irrigation, which applies the same amount of water over a larger area, generating a gradient of moisture with depth. This suggest that the method, more than the time of irrigation, changed both root biomass accumulation and modified the root morphology in response.

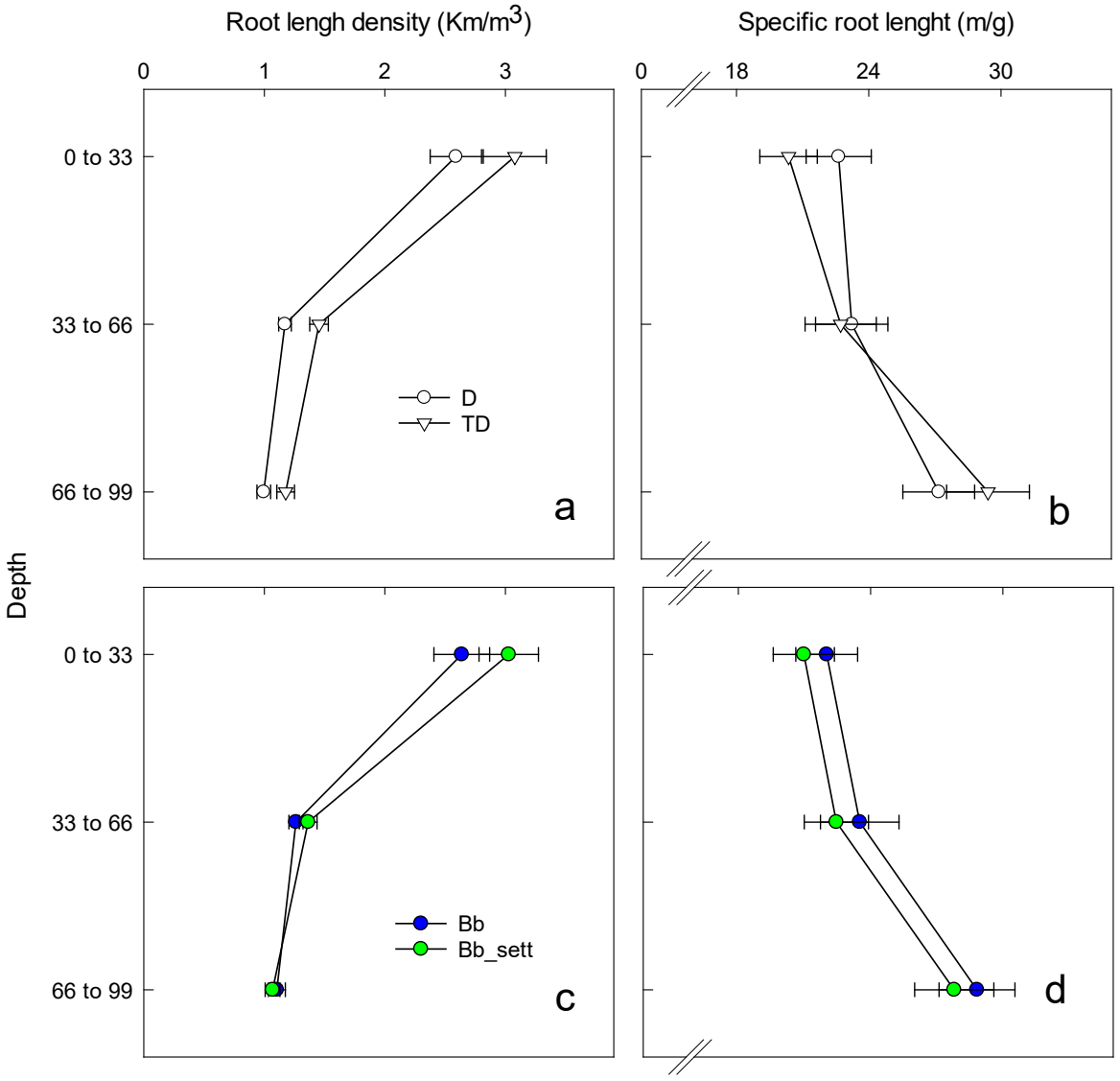


Figure 7:3 Root traits at different sampling depths from a factorial experiment combining two methods (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). Data are from three seasons (2018-2021) and values are mean ± SE from four field repetitions.

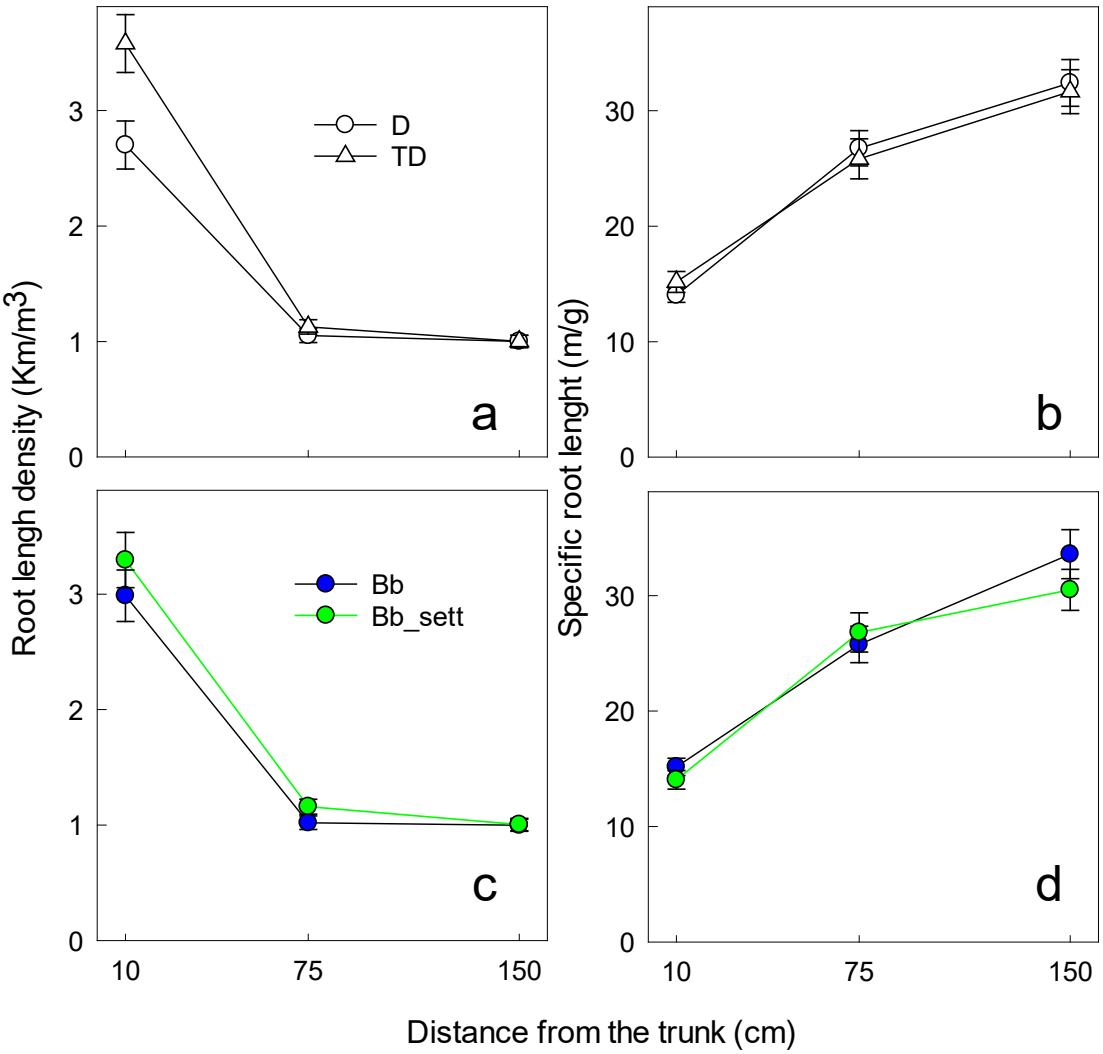


Figure 7:4 Root traits at three sampling positions in the mid-row space (10, 75 and 150 cm from the vine trunk) from a factorial experiment combining two methods (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). Data are from three seasons (2018-2021) and values are mean ± SE from four field repetitions.

8 EFFECTS OF WINTER RAINFALL DECLINE AND SUPPLEMENTARY IRRIGATION IN SPRING ON YIELD, AND ITS COMPONENTS, AND PLANT RESERVES

Introduction

In a previous experiment we found that a reduction in rain during winter to approximately one third of the historical average reduced yield (by 24–42%) and canopy size (by 16–31%). Reduced soil moisture prior to spring affected yield components by increasing the number of bunches per shoot but reducing yield due to smaller berries and lighter bunches. Reduced canopy size under water stress also had a detrimental effect on the accumulation of total carbohydrates reserves in the trunk during the current season which limited yield in the following season. Natural rain (Control) or equivalent sprinkler irrigation, providing water during winter, resulted in a higher yield:pruning mass ratio, but reduction in yield was still observed when drip irrigation was used to replace winter rainfall. Refilling the soil profile in spring after dry winters favoured growth partitioning toward canopy and roots, increased carbohydrate reserves in the trunk, but resulted in a large yield penalty (-10 to -32%).

In this section we explored alternative irrigation management practices with the aim to fully restore yield to similar levels to the Control vines.

Materials and methods

Yield, pruning weight and their components

At harvest we assessed fruit yield, the number of bunches per vine and the average berry weight, and calculated 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.

Vine sampling and determination of reserves

From the six treated vines in each replicate, only the three central vines were used for monitoring carbohydrate concentration, whereas the remaining vines acted as buffers. One vine was marked in each replicate and season when the first sample was collected during winter (or at budburst in 2020/21), and all the subsequent samples during that season were taken from the same vine. The initial sample was taken at the base of the trunk, approximately 15 cm from the ground level, followed by samples at approximately 10 cm intervals towards the cordon. Samples were collected with a 4.8 mm drill bit to a depth visually estimated as the centre of the trunk at key phenological stages each season (Table 8:1) and then frozen for later analysis.

Table 8:1 Phenological stages and sampling dates for non-structural carbohydrates during season 2018-20.

Phenological stage (E-L scale)	Season 2018/19	Season 2019/20	Season 2020/21
Winter	13 August	12 August	-
Bud-break (E-L 4)	26 September	23 September	9 September
Flowering (E-L 23)	19 November	21 November	24 November
Veraison (E-L 35)	30 January	28 January	-
Harvest (E-L 38)	14 March	19 March	4 March
Leaf-fall (E-L 47)	14 June	11 June	-

Sample were dried at 60° C for 48 hours and ground to a fine powder (~ 50 µm) with a Rocklabs Benchtop Ring Mill (Sietronics, Canning Vale, WA, Australia). The determination of vine reserves, i.e. nitrogen, starch and soluble sugars, was done by ATR–FT-IR spectroscopy using the method previously described by Schmidtke et al. (2012). Briefly, infrared spectra of samples were collected using an Alpha Fourier transform spectrophotometers (Bruker) configured for attenuated total reflectance (ATR) at ambient temperature using the OPUS software version 6.5. Each measurement consisted of 64 scans at 1.4 cm^{-1} resolution over the region 374–7496 cm^{-1}, with a background measurement against air conducted every 10 samples. The concentration of starch, soluble sugars, and nitrogen on the samples was estimated using a predictive model previously tested and calibrated at Charles Stuart University (Schmidtke et al. 2012) and results were expressed as percentage of sample dry weight (%DW).

Results

Comparison of yield across experiments

Figure 8:1 compares yield across two related experiments where rainfall was artificially excluded during winter and top-up irrigation was applied at different times, levels, and using different methods of irrigations. Exp. 1 ran from 2015 to 2018 (Wine Australia project SAR 1301) and exp. 2 from 2018 to 2021 (Wine Australia project SAR 1701).

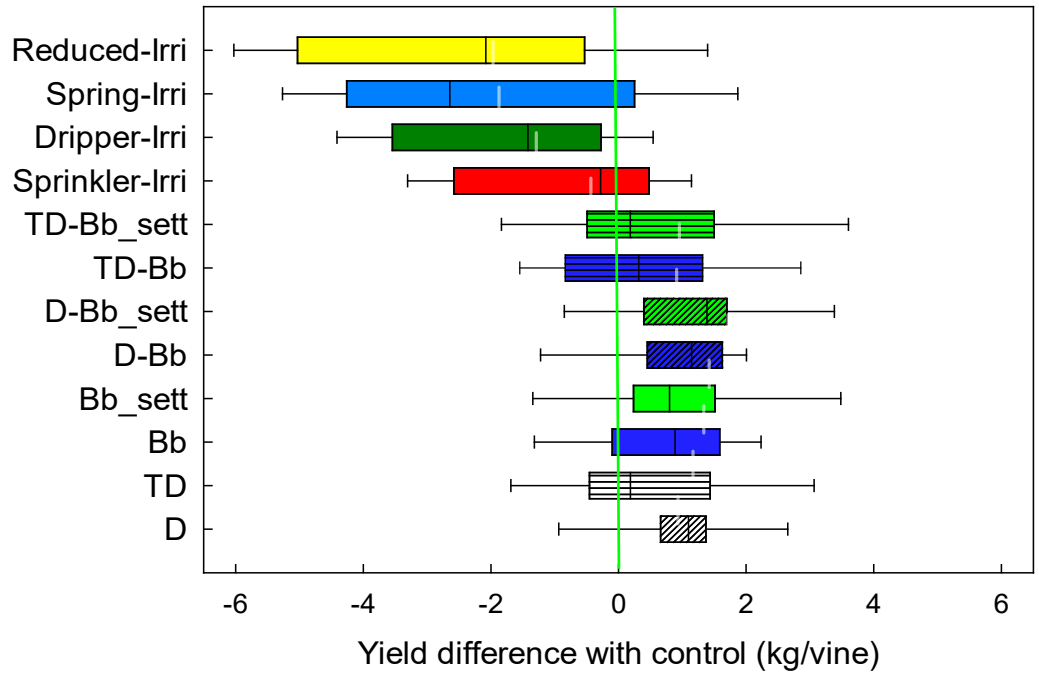


Figure 8:1 Difference in yield between irrigated and Control treatments in experiments where rainfall was excluded during winter and top-up irrigation was applied during winter (exp. 1; 2015-18) or spring (exp. 2; 2018-21). In exp. 1 irrigation was applied at the same level of LTA (230 mm) using sprinklers to irrigate the whole vineyard floor (Sprinkler-irri) or under the vine using drippers (Dripper-Irri); at a fraction of the LTA using sprinklers (Reduced-Irri; 70 mm); or applied at budburst to refill the soil profile (Spring-Irri; 150mm). In exp. 2, two methods of irrigation (D, dripper in a single lateral; TD, in multiple laterals) were combined with two times of irrigation (Bb, budburst to 10 cm shoot; Bb-set, budburst to fruit set). Data in each box are differences in yield with the corresponding Control over three seasons (n = 12). The lower value of the box indicates the 25th percentile, the grey line indicates the mean, the black line the median, and the higher bar value of the box indicates the 75th percentile. Whiskers indicate the 5th and 95th percentiles. For exp. 1 data were extracted from (Bonada et al. 2020).

In exp.1 we established the baseline for a comparison with future climate scenarios by analysing the rainfall distributions from historical data from Nuriootpa SA and calculating the long-term average between May to August (Control, 230 mm). We then simulated future climate scenarios with reduced rainfall in winter, similar to the lowest decile of the distribution (Reduced-Irri, 70 mm). This allowed us to explore potential adaptations strategies that replenished soil moisture at budburst following an extremely dry winter with limited rainfall (Spring-Irri, 150 mm); or that replenished soil moisture progressively during winter at the same level of Control vines but wetting a small fraction of soil under the vines using drippers (Dripper-Irri) or the whole vineyard floor using micro-sprinkler (Sprinkler-Irri).

In this experiment we found that reduced winter rainfall (in the lowest decile) had a major impact, reducing yield by up to 4.6 kg/vine (42%). Top-up winter irrigation treatments using either sprinklers or drippers, which restored water to a level similar to that of natural winter

rain (230 mm), still resulted in a reduction in yield (Figure 8:1). Across three seasons, from 2015 to 2018, sprinkler irrigated vines yielded approximately 0.8 kg/vine and dripper irrigated vines 1.9 kg/vine less than the Control vines. Similarly, irrigation that refilled the profile at budburst decreased yield by approximately 2.4 kg/vine.

The challenge for exp. 2 was to identify irrigation treatments that could maintain yield during dry years. We explored four alternative irrigation practices beyond the ones already tested in exp. 1. In two steps, we simulated a common dry winter across the treatments, where the vines received only a fraction of the LTA winter rainfall (similar to the lowest decile, ~70 mm); and then applied the remaining fraction of the LTA winter rainfall (~160 mm) factorially combining two method (D; TD) with two times (Bb; Bb_set) of irrigation (See section 5 for more details).

We found that irrigation during spring following a dry winter was much more effective in restoring yield to a similar level as the Control vines exposed to natural winter rainfall than winter irrigation (exp. 1, Figure 8:1). For the combination of methods and times of irrigation, and across the three experimental seasons, the difference in yield from the Control ranged from +58% to -14% (Figure 8:1, Table 8:2). The three-way ANOVA on the data pooled across the three seasons indicates that there was an effect of the method of irrigation (P = 0.012), but not effect of the time (P = 0.383) or interaction between method x time (P = 0.507) of irrigation. Regardless the time of irrigation, vines irrigated with a single lateral yielded approximately 1 kg/vine (from 0.2 to 1.5 kg/vine) more than the Control and 0.6 kg/vine (from 0.1 to 1.1 kg/vine) more than vines irrigated with multiple laterals. Vines irrigated at budburst yielded approximately 0.7 kg/vine (from -0.5 to 1.5 kg/vine) more than the Control but yielded marginally (and not significantly) less (0.1 kg/vine; from -0.4 to +0.3 kg/vine) than vines irrigated from budburst to fruit set.

Effect of method and time of irrigation on yield

To disentangle the seasonal effect on yield, we analysed the relationship between yield and the environmental mean of yield using pooled data across seasons following the same methodology as described in section 6 (Figures Figure 8:2 and Figure 8:3). In relation to Control vines, the effect of the method of irrigation on yield was different between low or high yielding conditions. In more restrictive yielding conditions, namely yield lower than 6 kg/vine, both single- and multiple-lateral treatments increased yield over the Control; single-lateral irrigated vines, however, had a higher yield than their multiple-lateral irrigated counterparts (Figure 8:2). When growing conditions were more conducive to higher yield, e.g. yield > 6 kg/vine, single-lateral irrigated vines had a similar yield to the Control vines but markedly more than vines irrigated with multiple laterals. Similarly, irrigation at budburst or from budburst to fruit set increased yield over Control vines during low yielding conditions but did not differ from Control vines under high yielding conditions (Figure 8:3).

Irrespective of the timing of the irrigation, application using a single lateral was more effective in maintaining or increasing yield compared to multiple laterals. The multiple laterals

increased the proportion of the soil surface that was wetted, while the amount of water applied was consistent across treatments. There is a lower density of vine roots in the mid-row (see section 7) and applying the water across the soil surface with the triple dripper may have reduced the ability of the vines to access the irrigation. The more exposed moist soil surface in the mid-row under multiple-lateral irrigation could also have contributed to increased soil evaporation and, therefore, to reduced water availability. These effects were captured by the Ψstem, which was slightly higher in single-lateral than multiple-lateral during spring months (Figure 5:5). Irrespective of the causes, the differences observed in yield between methods of irrigation support the use of dripper irrigation with a single lateral over the use of multiple laterals.

The steeper slope of the Control in relation to single- and multiple-lateral treatments (Figure 8:2) may also indicate a higher sensitivity of this treatment to the rainfall during spring. In contrast to single- and multiple-lateral irrigation treatments that were irrigated during spring, irrigation in the Control vines ceased at budburst. The higher rainfall received during spring of season 2020/21 may have contributed to the higher yield in relation to the 2018/19 and 2019/20 seasons (Table 8:2), which would have had a greater impact on the unirrigated Control than the treatments that received irrigation. Low temperatures (near frost) were also recorded during the spring of both dry seasons 2018/19 and 2019/20, the impact of any damage is difficult to assess, as it would have affected all of the treatments evenly.

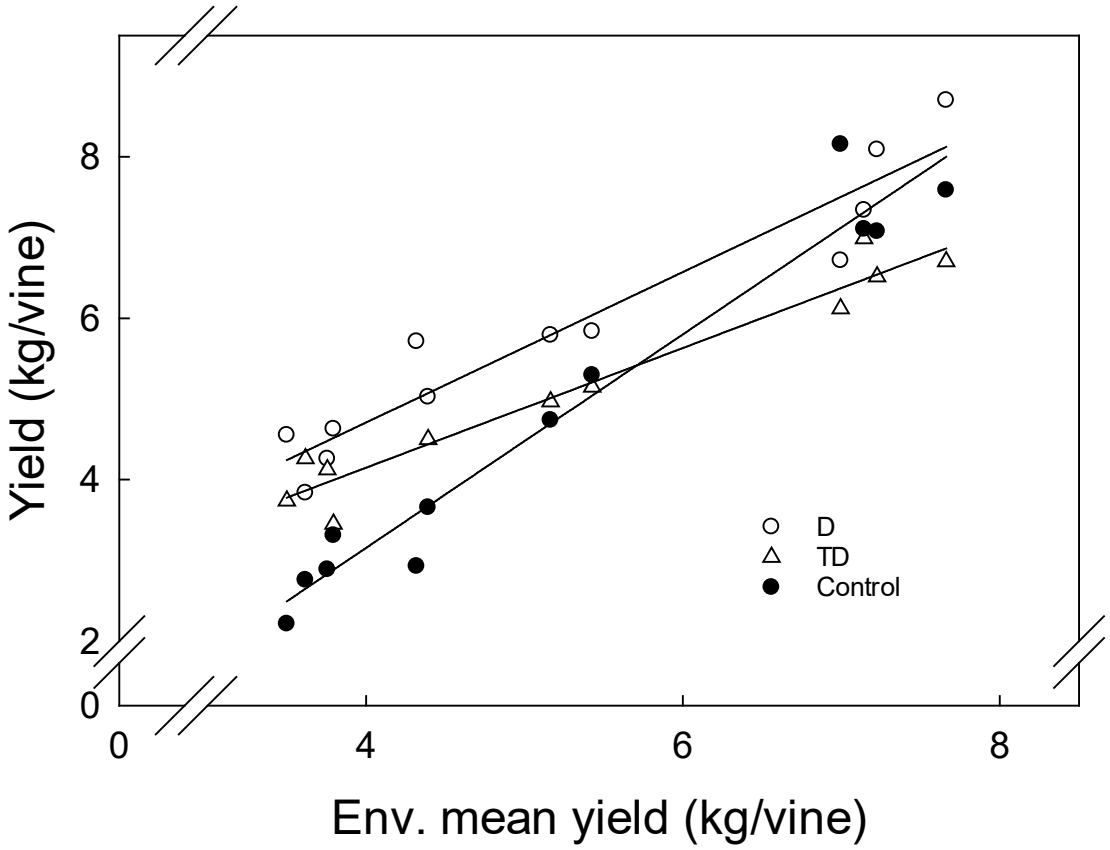


Figure 8:2 Relationships between yield and the environmental mean of yield between two methods of irrigation (D, dripper in a single lateral; and, TD, in multiple laterals) and Control vines exposed to natural rainfall. Values are means of four replicates per treatment during seasons 2018/19, 2019/20 and 2020/21. Lines are fitted regressions for each data set. Slopes and standard errors of the fitted regressions are: 0.93 ± 0.08, dripper; 0.74 ± 0.05, triple dripper; and 1.3 ± 0.08, Control.

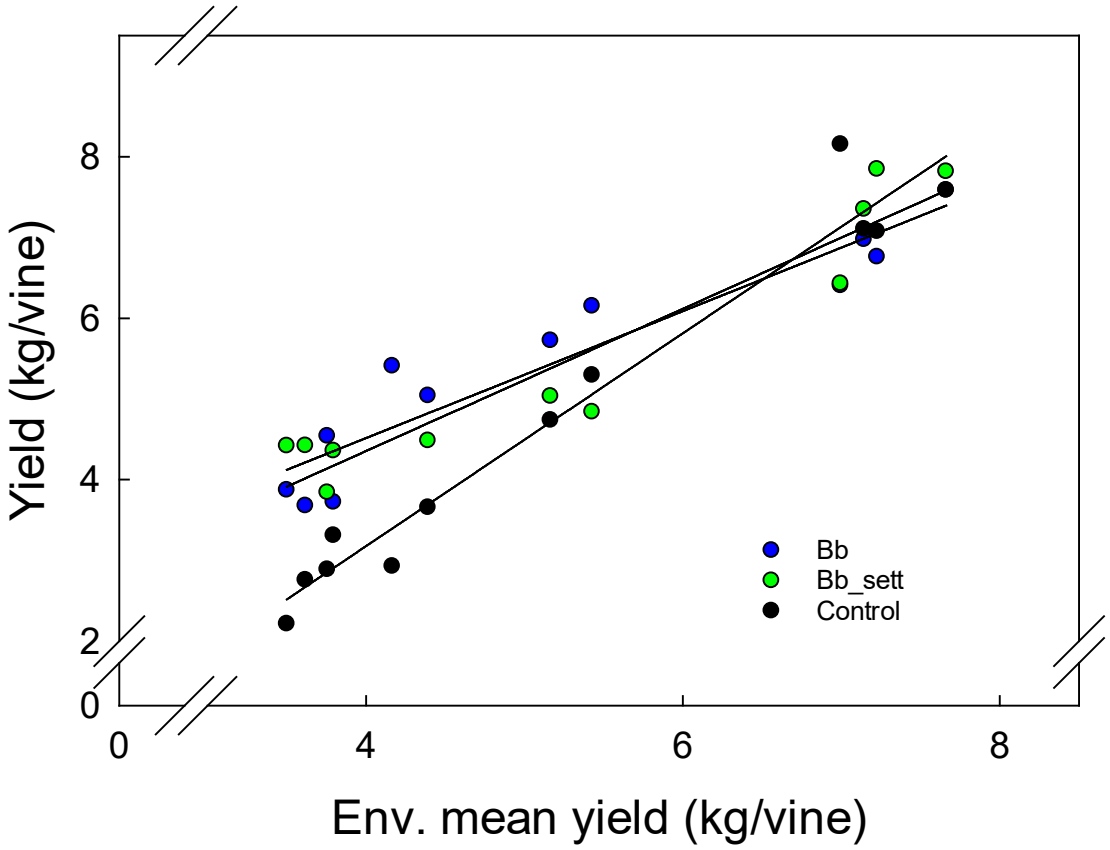


Figure 8:3 Relationships between yield and the environmental mean of yield between two times of irrigation (Bb, budburst to 10 cm shoot; and Bb_set, budburst to fruit set) and Control vines exposed to natural rainfall. Values are means of four replicates per treatment during seasons 2018/19, 2019/20 and 2020/21. Lines are fitted regressions for each data set. Slopes and standard errors of the fitted regressions are: 0.79 ± 0.08, Bb; 0.88 ± 0.09, Bb_set; and 1.32 ± 0.08, Control.

Treatment effects on yield and its components

Yield was higher in season 2020/21 than in seasons 2018/19 and 2019/20, notwithstanding treatment differences that ranged from +42% to -4% from the Control (Table 8:2). Average yield across treatments was approximately 5 kg/vine in season 2018/19, 4 kg/vine in season 2019/20 and 7 kg/vine in 2020/21. Overall, during the three seasons, Control vines exposed to natural winter rainfall yielded less than the other treatments, regardless of the combination of the methods and the times of irrigation. Yield on Control vines fell short by 25% (1.3 kg/vine) in S1, 30% in S2, and was marginally higher by 5 % (0.3 kg/vine) than the other treatments in S3.

Table 8:2 Effects of irrigation on yield components of Shiraz at harvest during seasons 2018/19, 2019/20 and 2020/21. Values are means ± SE from four replicates, each including four vines. *P* values correspond to the two-way ANOVA for the effect of the method (dripper and triple dripper), timing (Bb, Budburst; Bb-set, budburst to fruit set) and method x timing interaction. Means followed by different letters differ significantly at $P < 0.05$ by Fisher's LSD test.

Season	Method	Timing	Yield (kg/vine)	Bunch no./vine	Bunch mass (g)	Berry no./bunch	Berry mass (g)	Pruning mass (Kg/vine)	Shoot no/vine	Shoot mass (g)	Bunch no./shoot	Yield/prunning mass
2018/19	Dripper	Bb	5.4 ± 0.66	56 ± 5.09	97.4 ± 4.66	95 ± 4.90	1.0 ± 0.02 bc	3.2 ± 0.27 ab	61 ± 3.97	53.1 ± 3.53 b	0.9 ± 0.08	1.8 ± 0.34
		Bb-Sett	5.4 ± 0.44	52 ± 4.70	102.4 ± 4.88	94 ± 3.45	1.1 ± 0.02 ab	3.8 ± 0.22 a	58 ± 3.55	65.3 ± 0.99 a	0.9 ± 0.07	1.4 ± 0.07
	Triple dripper	Bb	5.5 ± 0.23	60 ± 0.82	91.2 ± 2.55	96 ± 4.20	1.0 ± 0.04 c	3.0 ± 0.18 b	58 ± 2.37	50.7 ± 2.92 b	1.0 ± 0.05	1.9 ± 0.14
		Bb-Sett	5.0 ± 0.87	52 ± 6.14	93.8 ± 5.78	84 ± 5.49	1.1 ± 0.03 a	2.8 ± 0.22 b	54 ± 3.75	46.9 ± 4.59 b	1.0 ± 0.07	1.8 ± 0.20
	Control		4.0 ± 0.62	51 ± 4.76	77.1 ± 4.85	75 ± 5.06	1.0 ± 0.01	2.4 ± 0.09	58 ± 0.73	40.9 ± 1.09	0.9 ± 0.09	1.7 ± 0.31
	P-Method (M)		0.773	0.686	0.135	0.330	0.495	**0.014**	0.326	**0.008**	0.236	0.301
	P-Timing (T)		0.639	0.249	0.430	0.175	**0.001**	0.476	0.277	0.223	0.575	0.337
	P-M x T		0.748	0.654	0.798	0.224	**0.064**	0.123	0.909	**0.030**	0.639	0.565
2019/20	Dripper	Bb	4.3 ± 0.34	72 ± 2.67	59.2 ± 2.73	62 ± 1.87	1.0 ± 0.02 b	3.1 ± 0.23	59 ± 0.64	52.8 ± 4.02	1.2 ± 0.04	1.4 ± 0.06
		Bb-Sett	4.7 ± 0.16	70 ± 3.43	67.6 ± 3.11	63 ± 3.91	1.1 ± 0.02 a	3.3 ± 0.12	60 ± 1.64	55.6 ± 1.26	1.2 ± 0.03	1.4 ± 0.06
	Triple dripper	Bb	3.8 ± 0.43	65 ± 4.82	58.9 ± 3.24	61 ± 3.40	1.0 ± 0.01 b	3.0 ± 0.18	61 ± 1.21	49.1 ± 3.29	1.1 ± 0.09	1.3 ± 0.20
		Bb-Sett	4.1 ± 0.16	69 ± 1.60	60.2 ± 3.59	61 ± 3.08	1.0 ± 0.04 b	2.8 ± 0.29	59 ± 3.45	47.8 ± 2.49	1.2 ± 0.09	1.5 ± 0.17
	Control		3.0 ± 0.32	72 ± 2.42	41.2 ± 3.92	52 ± 3.47	0.8 ± 0.03	2.3 ± 0.17	64 ± 1.18	36.0 ± 2.76	1.1 ± 0.04	1.3 ± 0.06
	P-Method (M)		0.103	0.241	0.250	0.682	0.141	0.161	0.837	0.074	0.335	0.943
	P-Timing (T)		0.270	0.884	0.156	0.778	**0.026**	0.853	0.860	0.794	0.779	0.438
	P-M x T		0.886	0.387	0.287	0.880	**0.074**	0.458	0.600	0.497	0.271	0.578
2020/21	Dripper	Bb	7.4 ± 0.49 ab	64 ± 3.58	115.6 ± 1.67 b	104 ± 2.02 a	1.1 ± 0.04 ab	3.6 ± 0.29	44 ± 1.67	82.8 ± 3.74 b	1.5 ± 0.05	2.1 ± 0.16
		Bb-Sett	8.0 ± 0.42 a	64 ± 2.86	125.2 ± 2.96 a	104 ± 3.56 a	1.2 ± 0.04 a	4.3 ± 0.13	42 ± 2.02	101.4 ± 5.00 a	1.5 ± 0.02	1.9 ± 0.11
	Triple dripper	Bb	6.4 ± 0.14 b	63 ± 3.14	99.0 ± 1.21 d	93 ± 1.74 b	1.1 ± 0.01 b	3.8 ± 0.28	46 ± 0.80	81.5 ± 4.85 b	1.4 ± 0.08	1.7 ± 0.14
		Bb-Sett	6.7 ± 0.32 b	63 ± 3.88	106.3 ± 1.84 c	92 ± 1.67 b	1.2 ± 0.02 a	3.6 ± 0.29	44 ± 0.77	82.2 ± 5.11 b	1.4 ± 0.10	1.9 ± 0.20
	Control		7.5 ± 0.25	68 ± 1.17	109.4 ± 3.09	105 ± 2.05	1.0 ± 0.03	3.4 ± 0.12	48 ± 0.90	71.2 ± 1.41	1.4 ± 0.05	2.2 ± 0.08
	P-Method (M)		**0.010**	0.777	**< 0.0001**	**< 0.0001**	0.110	0.357	0.194	**0.050**	0.279	0.333
	P-Timing (T)		0.263	0.976	**0.001**	0.797	**0.009**	0.323	0.300	**0.062**	0.471	0.889
	P-M x T		0.743	0.847	0.572	0.665	0.873	0.159	0.797	0.081	0.740	0.270

There were no differences in bunch number per vine for the single and combined effects of the method and time of irrigation. Across treatments the number of bunches per vine ranged from 51 to 60 in S1, from 65 to 72 in S2, and from 63 to 68 bunches per vine in S3. Multiple-lateral irrigation reduced bunch mass around 7% in S1, 6% in S2 and 15% in S3. Irrigation from budburst to fruit set increased bunch mass by around 4% in S1, and by 8% in both S2 and S3. However, these differences were detected as significant by the ANOVA for the effect of time and method only on S3. In comparison with the remaining treatments, bunches of Control vines were lighter by approximately 20% in S1, by 33% in S2 and by 2% in S3. There were minor differences in berry number per bunch between method and time of irrigation between seasons; but the number of berries per bunch was strongly affected on Control vines. Regardless of the combination of method and time of irrigation, bunches of Control vines had around 18 fewer berries in S1 (-19%) and around 10 fewer berries in S2 (-16%). In S3 the number of berries per bunch was higher in Control vines (6 berries, +7%). Berry mass responded to the effect of the time of irrigation in the three seasons; irrigation from budburst to fruit set increased berry mass between 7 to 12%. There were no significant differences in fruitfulness (defined as the number of bunches per shoot) between irrigation treatments and with the Control vines.

We assessed the contribution of each yield component to the total yield by normalising data as 100 x (T – C)/C, where T is the trait in the treated vine (method x time of irrigation) and C is the trait in the Control vine (Sadras et al. 2013). Across three seasons, yield response to irrigation varied from -14 to +58 %. Yield response was only marginally related to the effect of irrigation on bunch number (P = 0.10) but strongly related to the number of berries per bunch (r^2 = 0.86, P < 0.0001) (Figure 8:4a and b). Berry weight accounted for a significant part of the residual variation in yield after accounting for the number of berries per bunch (r^2 = 0.73, P = 0.0003) (Figure 8:4c).

Yield is defined by the effects of management and environmental factors on bunch number per shoot, number of berries per bunch and the mass of each individual berry. In this study we found that water stress in the early stages of development (Figure 5:4) defines a hierarchy on the contribution of these components to yield given by berries per bunch > berry mass > bunch number. Irrigation during the period between budburst and fruit set following a dry winter increased the number of berries per bunch and this was the main contributor to the difference in yield between the irrigated treatments and the unirrigated Control. A comprehensive work recently conducted across 15 grape cultivars exploring the contribution of yield components to yield on vines irrigated at a range of rates and developmental stages, concluded that berries per cluster was a 'genetically fixed' trait that is mainly unresponsive to water stress in the period before veraison (Levin et al. 2020). This is in direct contrast with the results of this current study. In the study of Levin et al. (2020), however, the pre-veraison water deficit treatment started after fruit set, well after the branching of the primordia that defines the number of flowers and potential number of berries per bunch has cessed, and lasted until veraison, which coincides with the period when bud fruitfulness (or maximum number of bunches per shoot) for the following season is defined (Keller 2020). The water stress between fruit set and veraison likely impacted on bunch initiation and resulted in the number of bunches being the main contributor to the reduction in yield observed in this

research. In our study water stress in the Control vines was imposed much earlier in the season, more likely, coincidently with the period when branching and flower differentiation in the inflorescence are expected to occur. We are cautious about the conclusion that the number of berries per bunches is a genetically fixed trait unresponsive to water stress prior to veraison and agree with the view that the impact of water deficit pre-veraison on yield components is highly specific of the trait, the period and the level of water stress.

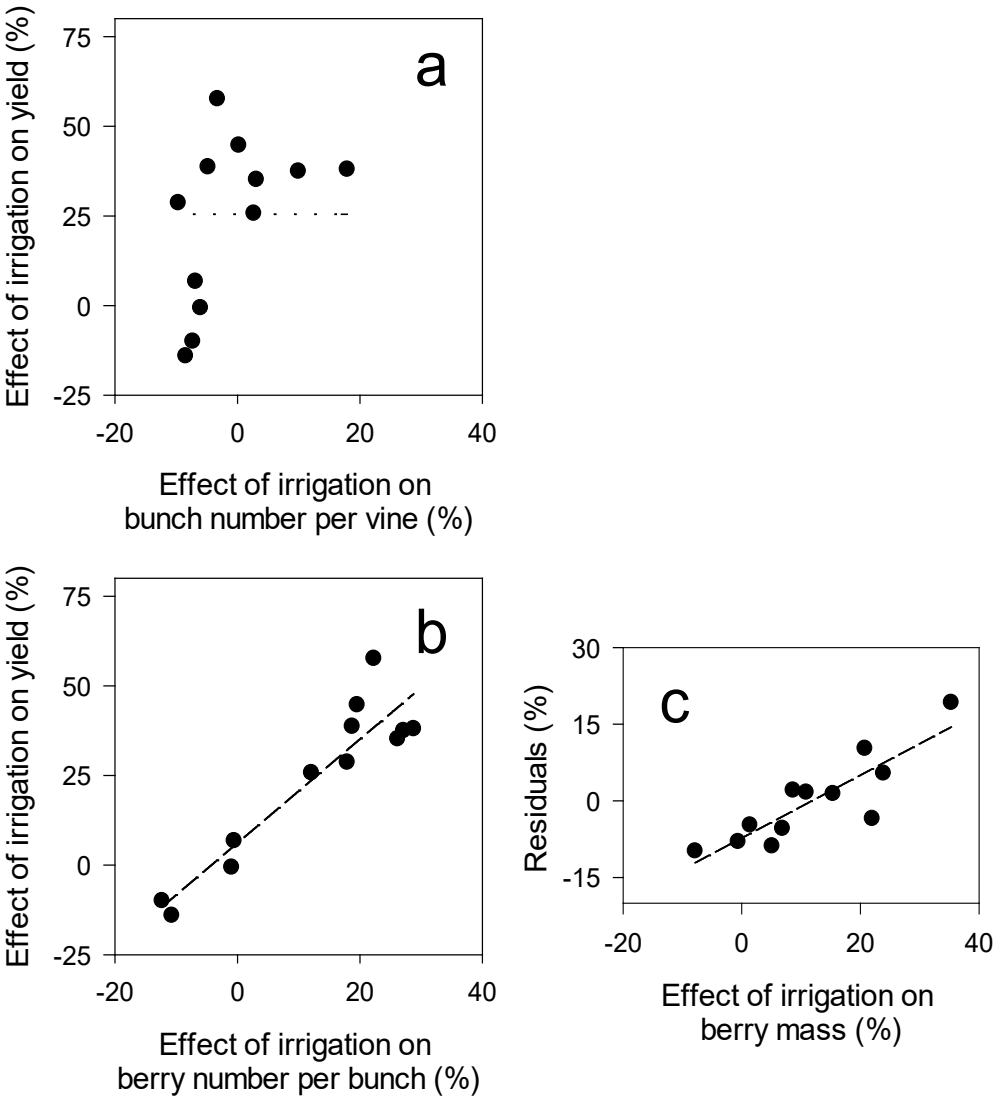


Figure 8:4 The partitioning of yield to its yield components over three years for a factorial (2 x 2) trial combining two method (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). The effect of irrigation was estimated as 100 × (T − C)/C, where T is the irrigated treatment, and C is the Control vines exposed to natural rainfall. Relationship between a) irrigation effect on yield and bunch number per vine, or b) irrigation effect on yield and berry number per bunch. (c) Residuals of the regression in (b) as a function of irrigation effect on berry mass. The dashed lines are fitted regressions for each data set. Values are means of four replicates per treatment during seasons 2018/19, 2019/20 and 2020/21

Treatment effects on pruning mass and its components

A consistent number of buds were retained across the treatments at winter pruning each year. This reflected on the number of shoots per vine counted at the time of pruning the following year, which was similar between treatments (Table 8:2). Shoot number per vine ranged from 54 to 61 in S1, from 59 to 64 in S2, and from 42 to 48 in S3, and did not vary between the treated and Control vines. The multiple-lateral irrigation reduced shoot mass by around 18% in S1, and by around 11% in S2 and S3. On the contrary, irrigation from budburst to fruit set increased shoot mass by approximately 8% in S1, by only 2% in S2 and by 12% in S3. Besides the consistent differences in shoot mass between seasons, the ANOVA only found significant differences for the effect of the interaction between method x time (or irrigation) in S1, and on the single effects of the method and time in S3. Shoot mass of Control vines was significantly lower across the three years (from 18 to 30 %) than the remaining treatments, irrespective of the combination of method and time of irrigation. The two-way ANOVA for the effects of the method and time of irrigation on pruning mass did not show significant differences between treatments. There was, however, a consistent interaction between method and time of irrigation on pruning mass over the three seasons; irrespective of the time of irrigation, multiple-lateral irrigation decreased pruning mass, but the reduction was more noticeable when irrigation was extended from budburst to fruit set. This agrees with the effect observed on LAI, where the reduction on LAI was also higher when multiple-lateral irrigation was combined with irrigation from budburst to fruit set (Figure 6:4c).

Across the three seasons, pruning mass per vine increased under irrigation from 7 to 59%. This response was mainly explained by the mass of each individual shoot (r^2 = 0.84, P < 0.0001), which increased between 14 to 60% under irrigation (Figure 8:5a). Shoot number accounted for a significant part of the residual variation in pruning mass (r^2 = 0.80, P < 0.0001; Figure 8:5b) but had a lower impact on total pruning mass per vine (r^2 = 0.18, P = 0.16; not shown).

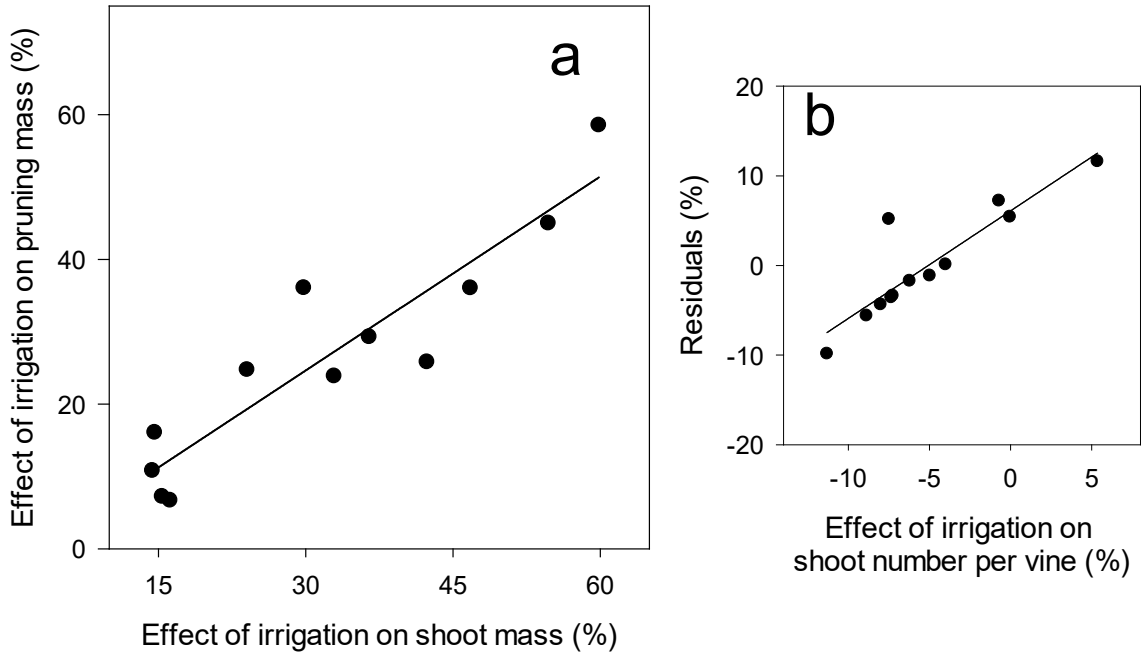


Figure 8:5 The contribution of individual shoot mass and number of shoots per vine to total vine pruning mass over three years for a factorial (2 x 2) trial combining two methods (D, Dripper in a single lateral; and, TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; and, Bb_set, budburst to fruit set). The effect of irrigation was estimated as 100 × (T − C)/C, where T is the irrigated treatment, and C is the Control vines exposed to natural rainfall. Relationship between a) irrigation effect on pruning mass and individual shoot mass, and b) residuals of the regression in (a) as a function of irrigation effect on shoot number per vine. The solid lines are fitted regressions for each data set. Values are means of four replicates per treatment during seasons 2018/19, 2019/20 and 2020/21

Effects of irrigation treatments on vine reserves

We analysed the concentration of starch, soluble sugars and nitrogen in the trunk at five phenological stages in season 2018/19 and 2019/20, and three stages in season 2020/21 (Table 8:3). Results from the four-way ANOVA (Table 8:3) indicate differences in reserves that changed between seasons, phenological stage, time of irrigation, and for the interactions between phenological stage x season (starch, soluble sugars and nitrogen), and time of irrigation x season (starch).

Table 8:3 *P* values from the four-way ANOVA showing the effect of the season, time of sampling (E-L stage), method and time of irrigation, and their interactions, on the content of reserves in the trunk.

Source of variation	Starch (%DW)	Soluble sugars (%DW)	Nitrogen (%DW)
Season (S)	< 0.0001	0.605	< 0.0001
Phenological stage (E-L)	0.006	< 0.0001	< 0.0001
Method (M)	0.477	0.817	0.806
Time (T)	0.039	0.011	0.321
S x M	0.711	0.860	0.464
S x T	0.022	0.643	0.566
S x E-L	< 0.0001	< 0.0001	< 0.0001
M x T	0.290	0.956	0.166
M x E-L	0.139	0.984	0.486
T x E-L	0.995	0.912	0.301

To separate the effects of the season and sampling time from the effect of the time of irrigation, and to compare with the Control vines, we plotted each trait against the environmental mean of the trait. Fifteen environments were defined from the combination of the phenological stages in each season. Residuals from the environmental means were used to quantify differences between treatments and with the Control.

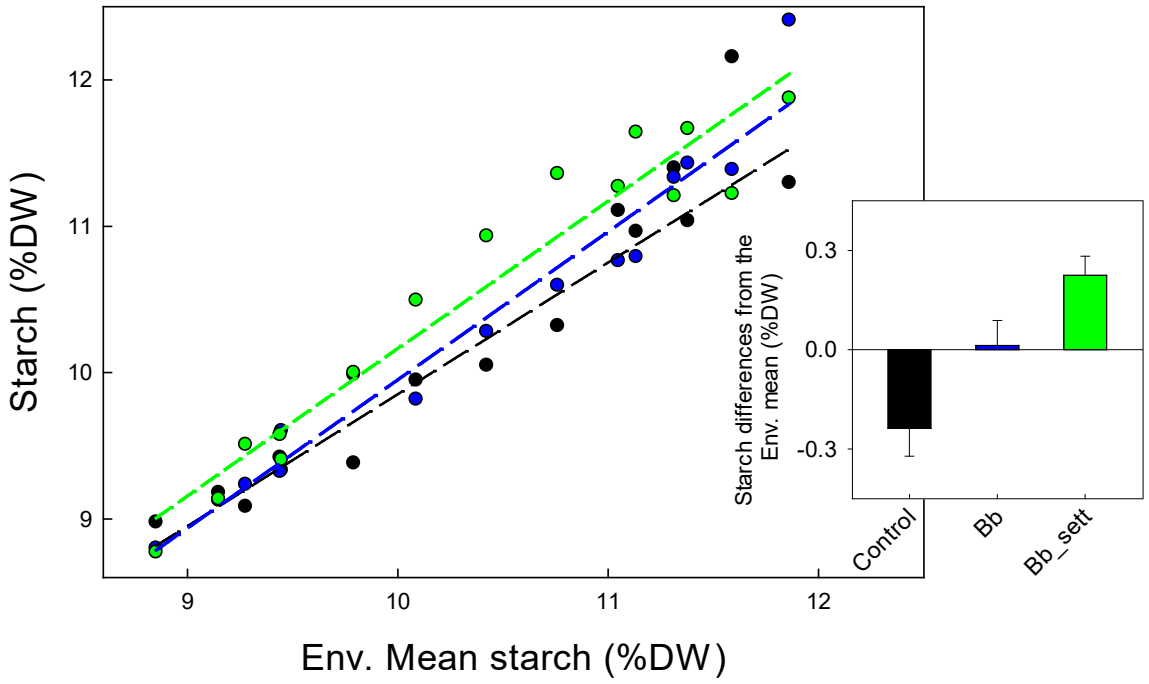


Figure 8:6 Relationships between starch and the environmental mean of starch between the two irrigation times (Bb, budburst to 10 cm shoot; and Bb_set, budburst to fruit set) and

Control vines exposed to natural rainfall. Values are means of four replicates per treatment at five phenological stages in season 2018/19 and 2019/20, and three stages in season 2020/21. Lines are fitted regressions for each data set. Slopes and standard errors of the fitted regressions are: 1.01 ± 0.06, Bb; 1.01 ± 0.07, Bb_set; and 0.9 ± 0.05, Control. Inset shows differences between treatments with the environmental mean and bars are means ± SE.

Irrigation from budburst to fruit set increased the concentration of starch in the trunk compared to the vines irrigated at budburst, which in turn had a higher starch concentration compared to the Control vines (Figure 8:6). The higher starch concentrations observed in both of the irrigated treatments is likely to have supported them to sustain a higher yield. When growing conditions were more conducive to higher yield, such as the substantial rainfall after budburst (Table 5:1) during the 2020/21 season (Table 8:2), the difference in trunk starch concentrations between the irrigated and Control vines was smaller, which also aligned with smaller differences in water potential (Figure 5:4) and canopy growth (Figure 6:3) between the Control and irrigated treatments.

The impact of reserves on yield and yield components

We quantified variation in yield and yield components between Control and irrigated treatments due to variation in reserves at different phenological stages. We used a similar approach to the one used in the section on 'Treatments effects on yield and its components'. The effect of irrigation was estimated as 100 × (T − C)/C, where T is the irrigated treatment, and C is the Control vines exposed to natural rainfall. A Pearson correlation test on the normalised traits was later conducted to explore the relationship between traits.

Table 8:4 P values from the Pearson correlation test between normalised yield components and trunk reserves (starch, soluble sugars and nitrogen, DW%) at different phenological stages during the current season: flowering (Fl), veraison (V), harvest (H); and the year before: at flowering (Fl yb), leaf fall (Lf yb), and winter (W yb). Normalisation was done as 100 × (T − C)/C, where T is the irrigated treatment, and C is the Control vines exposed to natural rainfall. Values in bold are different from 0 with a significance level as indicated in the coloured *P* scale.

Variables	Yield	Bunch no./vine	Bunch mass	Berry mass	Berry no./bunch	Prunning mass	Shoot no.	Shoot mass	Ravaz index	Fruitfulness (bunch no./shoot)
Starch Fl	-0.32	-0.34	-0.22	0.22	-0.50	-0.41	**-0.61**	-0.16	-0.13	0.00
Soluble sugars Fl	0.37	**0.89**	0.01	**-0.62**	**0.59**	0.39	**0.76**	0.11	0.15	**0.61**
Nitrogen Fl	0.38	0.48	0.24	-0.27	**0.61**	0.24	0.47	0.12	0.42	0.32
Starch Fl yb	-0.33	-0.44	-0.24	-0.12	-0.28	-0.25	**-0.76**	-0.07	-0.30	0.09
Soluble sugars Fl yb	**0.74**	0.31	**0.77**	0.65	**0.82**	**0.78**	0.15	**0.75**	0.58	0.13
Nitrogen Fl yb	-0.09	-0.27	-0.06	-0.09	-0.06	-0.05	**0.78**	-0.22	-0.14	-0.66
Starch H	0.50	**0.70**	0.22	-0.29	0.57	0.20	0.47	-0.10	0.49	0.59
Soluble sugars H	-0.07	0.01	-0.10	-0.28	0.11	0.04	0.09	0.02	-0.11	-0.05
Nitrogen H	**-0.82**	-0.18	**-0.86**	-0.53	**-0.72**	**-0.68**	-0.30	**-0.60**	-0.57	0.00
Starch Lf yb	-0.20	0.14	-0.24	-0.10	-0.32	-0.15	-0.43	-0.06	-0.18	0.38
Soluble sugars Lf yb	0.00	-0.19	0.03	-0.21	0.21	-0.04	0.39	-0.11	0.05	-0.36
Nitrogen Lf yb	-0.16	0.37	-0.26	-0.44	-0.11	-0.16	-0.12	-0.13	-0.12	0.36
Nitrogen Fl	**-0.71**	0.31	-0.69	-0.52	-0.22	-0.52	0.00	-0.61	-0.14	0.38
Starch V	-0.03	-0.48	0.36	0.41	-0.24	-0.31	-0.42	-0.07	0.47	-0.27
Soluble sugars V	-0.26	**0.91**	**-0.83**	**-0.92**	0.53	0.01	**0.77**	-0.36	-0.30	0.62
Starch Wyb	0.02	-0.59	0.43	0.58	-0.61	-0.12	-0.38	-0.05	0.10	-0.54
Soluble sugars Wyb	0.27	0.24	0.02	-0.13	0.46	0.06	0.05	0.19	0.24	0.34
Nitrogen Wyb	0.08	0.22	-0.14	-0.18	0.16	-0.04	0.32	-0.09	0.16	0.08
P scale	<0.0001	0.001	0.01	0.05	0.10	0.20	0.40	0.50	0.60	1.00
Starch Fl	0.316	0.281	0.501	0.497	0.094	0.188	0.037	0.619	0.690	0.993
Soluble sugars Fl	0.233	0.000	0.975	0.032	0.046	0.213	0.004	0.739	0.652	0.037
Nitrogen Fl	0.224	0.115	0.445	0.405	0.036	0.443	0.121	0.715	0.174	0.307
Starch Fl yb	0.431	0.279	0.561	0.775	0.510	0.554	0.029	0.872	0.475	0.827
Soluble sugars Fl yb	0.034	0.462	0.025	0.080	0.012	0.022	0.720	0.031	0.130	0.763
Nitrogen Fl yb	0.836	0.525	0.884	0.828	0.881	0.903	0.024	0.595	0.740	0.076
Starch H	0.115	0.016	0.511	0.382	0.069	0.547	0.149	0.778	0.122	0.056
Soluble sugars H	0.835	0.972	0.764	0.372	0.738	0.899	0.772	0.962	0.723	0.872
Nitrogen H	0.001	0.581	0.000	0.079	0.008	0.015	0.339	0.040	0.053	0.998
Starch Lf yb	0.639	0.749	0.561	0.822	0.437	0.722	0.289	0.893	0.671	0.353
Soluble sugars Lf yb	0.998	0.654	0.944	0.614	0.623	0.933	0.337	0.799	0.903	0.375
Nitrogen Lf yb	0.713	0.363	0.533	0.270	0.802	0.699	0.786	0.758	0.782	0.386
Nitrogen Fl	0.048	0.459	0.059	0.182	0.609	0.183	0.994	0.108	0.748	0.355
Starch V	0.947	0.229	0.388	0.313	0.569	0.454	0.296	0.878	0.242	0.513
Soluble sugars V	0.526	0.002	0.011	0.001	0.177	0.984	0.024	0.383	0.470	0.101
Starch W yb	0.960	0.123	0.285	0.131	0.110	0.769	0.349	0.900	0.820	0.167
Soluble sugars W yb	0.524	0.562	0.969	0.765	0.255	0.891	0.911	0.652	0.573	0.415
Nitrogen W yb	0.844	0.598	0.738	0.671	0.708	0.918	0.445	0.827	0.710	0.859

Irrigation during spring and until fruit set increased yield over the unirrigated Control, and these differences in yield were mainly explained by bunch mass and the number and mass of individual berries (Figure 8:4). Previous research has shown that carbohydrate availability is strongly linked to vine reproductive performance (Bennett et al. 2005, Smith and Holzapfel 2009). We observed a positive correlation between the number of berries per bunch and the concentration of soluble sugars at flowering the same year (r = 0.59, P = 0.046) but also a stronger correlation with the concentration of soluble sugars at flowering during the previous season (r = 0.82, *P* = 0.012). Soluble sugars at flowering were also correlated with the number of bunches per vine (r = 0.89, *P* < 0.0001) and per shoot (r = 0.61, *P* = 0.037). This suggests that increased carbohydrate availability during yield formation favours inflorescence initiation as the shoots develop in the season before harvest and inflorescence differentiation after bud break in the harvest season (Lebon et al. 2008). Sucrose, glucose and fructose are the main sugars available to support the developing inflorescences and these are particularly critical during the period of flowering when vegetative and reproductive growth compete for resources. These sugars are the product of mobilisation of reserves from the perennial organs and from photosynthesis by the leaves. We did not observe a relationship between starch concentration and yield that indicate mobilisation of sugars from the trunk, but we cannot rule out mobilisation from the roots as we did not measured reserves in the roots in the current experiment.

We found that variation in yield between the irrigation treatments and the Control were negatively correlated with nitrogen reserves in the trunk at veraison (r = -0.71, *P* = 0.048) and harvest (r = -0.82, *P* = 0.001, Table 8:4). When the irrigated vines yielded less than the Control (such as in season 2020/21; Table 8:2), these vines had relatively more nitrogen (Figure 8:7a). This was reversed when irrigated vines carried a greater yield than the Control and once the yield of these vines exceeded the Control by approximately 24%, the concentration of nitrogen was lower than in the Control vines. This suggest that (1) nitrogen may be limiting productivity, and (2) that vines may be buffering the increased demands at higher yields by drawing nitrogen from the pool of reserves of the trunk and, more likely, from the roots (Zufferey et al. 2015). The negative relationship between the difference in pruning mass and nitrogen reserves at harvest (Table 8:4) also supports the conclusion that the vines are drawing nitrogen reserves from the trunk to sustain the growth of bigger canopies under spring irrigation. Pruning mass was always higher in the irrigated vines compared to the Control (Table 8:2; Figure 8:7b); when canopies of irrigated vines were more than 26% larger than the Control vines, nitrogen concentration in the trunk of irrigated vines decreased below the Control vines (Figure 8:7b).

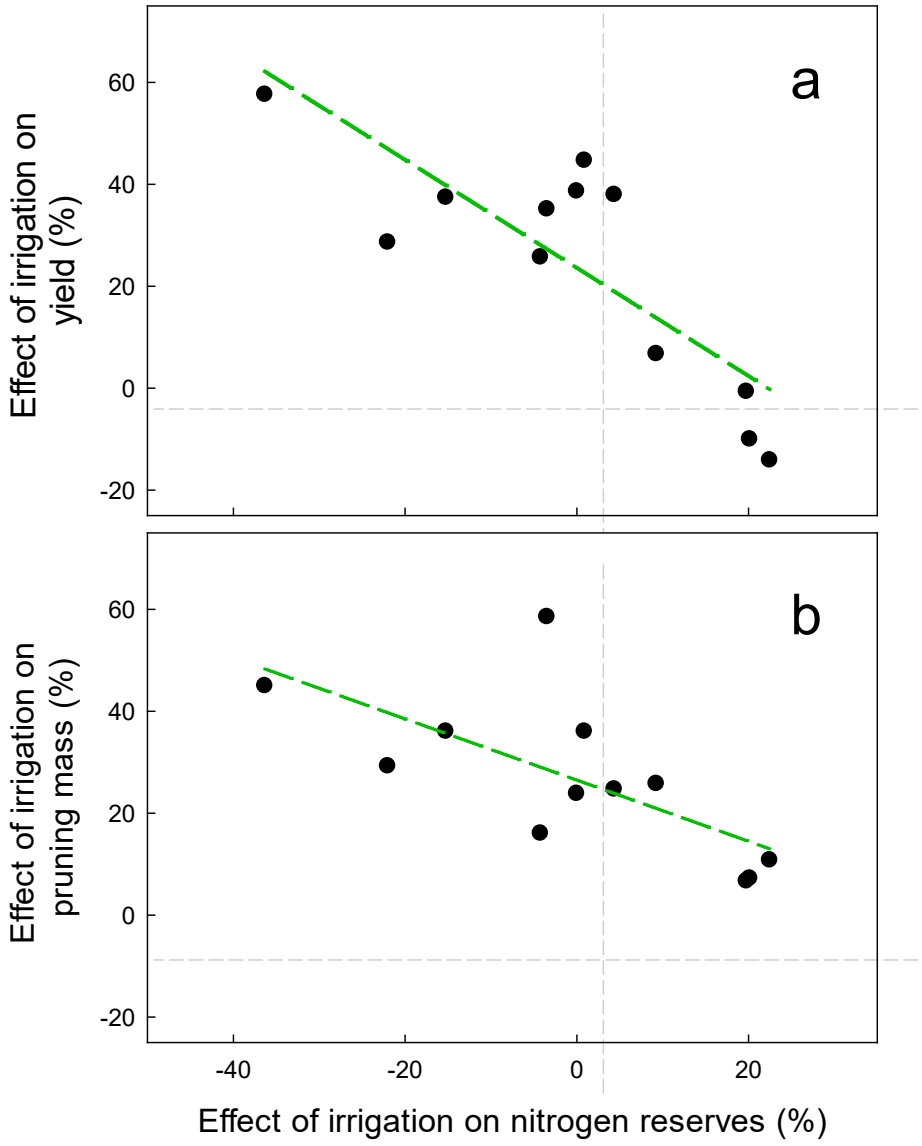


Figure 8:7 Relationship between the difference in nitrogen with (a) yield and (b) pruning mass between Control vines exposed to rainfall during winter and vines with reduced rainfall in winter and supplementary irrigation during spring. The effect of irrigation was estimated as 100 × (T − C)/C, where T is the trait in the irrigated treatment, and C is the Control. Values are means of four replicates per treatment during seasons 2018/19, 2019/20 and 2020/21. The dashed line are the fitted regressions: (a) y = 23.6 - 1.06 x; (b) y = 26.5 - 0.6 x.

9 EFFECT OF IRRIGATION TREATMENTS ON FRUIT AND WINE COMPOSITION

Introduction

Reduced rainfall or irrigation during winter or in spring following a dry winter impact the partitioning of vine growth (Bonada et al. 2020) which has implications on fruit and wine composition (Bonada et al. 2021). With a focus on Shiraz under conditions in the Barossa Valley, in a previous project we explored some irrigation practices that influenced wine style. The result from the previous experiment indicated that reduced rainfall during vine dormancy and into spring led to a shortage of water during the early stages of vine development, resulting in a lower yield, but more open canopies. Higher canopy porosity around flowering favoured the concentration of phenolic substances in the fruit and in the wine, and contributed to the development of colour, flavour and aroma intensity and body in the wine. In contrast, when moisture was restored in spring to an empty soil profile by natural rainfall or supplementary irrigation, yield was reduced, and vines developed denser canopies. Lower canopy porosity under this treatment contributed to a lower concentration of phenolic substances in the fruit and in the wines and promoted the development of some negative attributes in the wines. When soil moisture was restored during winter using drippers or micro-sprinklers under the canopy, vines had an improved balance between canopy and yield, and the wines preserved some of the attributes typical of Barossa Valley Shiraz. Here we assessed the impact on fruit and wine composition from a new set of irrigation treatments that aimed to fully restore yield to a similar level to the vines exposed to average winter rainfall.

Materials and methods

Assessment of berry ripening and composition

Samples for grape composition were taken weekly from veraison to harvest and analysed using standard techniques (Iland et al. 2004). Samples of 120 berries were taken 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).

Winemaking and wine analysis

Harvest date was defined as the point where juice TSS reached 26 ^{o}Brix. Small-scale standardised winemaking was completed and the identity of the field replicates was maintained. Each year, 15 wines from fruit from three field replicates was made by WIC Winemaking Services. Two field replicates were combined due to their low yield and to maintain a consistent size of the ferments between treatments and years at 25 kg of fruit. For the sake of consistency, the same replicates (3 and 4) were combined each year before winemaking.

After overnight storage at 0 ^{o}C following harvest, the fruit was destemmed and crushed prior to transfer to 50 L plastic bins. 50 ppm SO_2 were added to the must upon crushing and corrected to pH 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 (< 0.1 g/L malic acid) fermentations were completed, the wine was treated with potassium metabisulfite to maintain 40 mg/L of free SO_2. Cold stabilisation was induced by adding 2 g/L of KHT and holding the wine at 0 ^{o}C 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 eight-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 ^{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.

Wine sensory assessment

Training for sensory descriptive analysis

A panel of twelve (2018/19), ten (2019/20) and eleven (2020/21) assessors with an average age of 52 years was convened to evaluate the wines on the three seasons. All panellists were part of the external AWRI trained descriptive analysis panel and had extensive experience in wine sensory descriptive analysis.

Every year, 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 first 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 second 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 that needed adjustment were discussed and the final list of terms and standards was determined. For the formal sessions this list was refined to include two appearance terms in 2018/19 and 2019/20 and one appearance term in 2020/21; 13 aroma terms in 2018/19, 12 in 2019/20 and 10 in 2020/21; and 12 flavour terms in 2018/19 and 11 in each of 2019/20 and 2020/21. Viscosity was included as an 'other' term in all three seasons. The final list of attributes, definitions/synonyms and reference standards for both years is shown in Table 9:1.

Table 9:1 Attributes, definitions and reference standards evaluated by panellists in formal sessions for the wines during descriptive analysis in 2018/19, 2019/20 and 2020/21.

Attribute	Definition/Synonyms	Standard†	Year		
			2019	2020	2021
Appearance					
Purple	The degree of purple colour intensity in the sample	—¥	X‡	X	-§
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	160 µL of 1 g/L dimethyl sulfide and 19 mL blackcurrant syrup (Ribena®)	X	X	X
Chocolate	Intensity of the aroma of chocolate and coffee beans	4 dark chocolate chips (Absolute Organic) and 1 roasted coffee bean	X	X	-
Confection	Intensity of the aroma of confection and red lollies	1 red lolly and ¼ musk lolly, not in wine	X	-	-
Dark fruit	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
Cooked vegetables	Intensity of the aroma of dirty drains (natural gas), reminiscent of cooked vegetables, green beans, asparagus, 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	X
Earthy	Intensity of the aroma of earth, beetroot, leather and mushroom	5 g dry soil, not in wine	X	X	X
Floral	Intensity of the aroma of flowers: roses, violets and honeysuckle	0.5 mL rose water and 0.25 mL orange blossom water (Maharajah)	X	-	-
Herb	Intensity of the aromas of various herbs, dried and fresh: mint, eucalypt, oregano, nutmeg and menthol	50 µL of 0.98 g/L 1,8-cineole and 50 µL of Menta syrup (Fabbri)	X	X	X
Jammy	Intensity of the aroma of blackberry jam and dried fruits.	2 teaspoons of blackberry jam in 1 mL water (Beerenberg). Not in wine.	-	X	X
Pungent	Intensity of the aroma and effect of alcohol	4 mL of 95% food grade ethanol (Tarac Technologies)	X	X	X
Red fruit	Intensity of the aroma of red fruits and berries: raspberries, strawberries, cranberries and red cherries	3 frozen raspberries (Sara Lee brand) and 1 frozen strawberry (Welch's brand)	X	X	X
Savoury	Intensity of the aroma of meat broth and olives	3 kalamata olives (Always Fresh). 20 mL chicken stock mixture (Massel). Both not in wine	X	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	5 µL of 53.82 mg/L of isopropyl methoxypyrazine	X	X	X
Vanilla	Intensity of the aroma of vanilla	0.1 g whole vanilla bean (Taylor and Colledge brand) not in wine	X	X	-
Flavour					
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	X	X
Chocolate	Intensity of the aroma of chocolate	—	X	-	-
Dark fruit	Intensity of the flavour of various dark fruits: blackberries, currants and plums	—	X	X	X
Earthy	Intensity of the flavour of earth and beetroot	—	X	X	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
Jammy	Intensity of the flavour of blackberry jam	—	-	-	X
Red fruit	Intensity of the flavour of red fruits and berries: raspberries, strawberries, cherries and cranberries	—	X	X	X
Savoury	Intensity of the flavour of meat broth and olives	—	X	X	-
Stalky	Intensity of the flavour of green stalks, rhubarb stalks, fresh tomato leaf and stalk	—	X	X	X
Sweetness	Intensity of the sweet taste of the sample	8 g/L table sugar (Woolworths essentials) in water	X	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 Yalumba Classic Dry Red unless otherwise noted.
‡Attribute assessed in a particular year.
§Attribute no assessed in a particular year.
¥Attribute which did not require standard.

Evaluation of the wines

All samples were presented to panellists in 30 mL aliquots, in three-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. 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. Sensory trial design, including presentation order and data acquisition was completed using Compusense Cloud sensory evaluation software (Compusense Inc., Guelph, Canada).

Panel performance was assessed using Compusense software and R with the SensomineR (sensominer.free.fr/) and FactomineR (factominer.free.fr/) packages. The performance assessment included analysis of variance for the effect of judge, wine and presentation replicate and their interactions, degree of agreement with the panel mean, degree of discrimination across samples and the residual standard deviation of each judge by attribute. All judges were found to be performing to an acceptable standard.

Analysis of variance (ANOVA) was carried out using Minitab 18 (Minitab Inc., Sydney, NSW). The effects of the treatment, judge, judge by treatment, field replicate nested into treatment, judge by field replicate nested into treatment, and presentation replicate nested into treatment and field replicate were assessed, treating judge as a random effect. Following ANOVA, Fisher's least significant difference (LSD) value was calculated (P = 0.05) for the treatment effect using the judge*treatment mean square error term. Principal component analysis (PCA) was conducted for the means of the treatments of the significant ($P < 0.05$) and close to significant ($P < 0.10$) attributes of each of the irrigation treatments using the correlation matrix (XLSTAT 2017, Paris, France).

Effect of method and time of irrigation on wine sensory profile

We quantified the effects of the treatments in the sensory profile of the wines in three steps. First, we normalised the effect of the irrigation treatments for each sensory attribute in relation to the Control. Normalisation was done as 100 x (T – C)/C, where T is the score of the sensory attribute in the treated wine (method or time of irrigation), and C is the score of the same attribute in the Control wines. Before the normalisation, scores for each attribute were averaged from data pooled across the three wine replicates within each of the three seasons. Secondly, we plotted the relationships between the normalised scores of the attributes between the irrigation treatments. This relationship is defined within four quadrants (Figure

9:1a); when the result is within quadrant I or III it indicates that the treatments either increased (I) or decreased (III) the score of the attribute in a similar manner to their relationship with the Control. Results in quadrants II and IV indicated discrepancies between treatment and the score of the same attribute. With quadrant II indicating that the treatment on the x-axis decreases the score of the attribute whereas the treatment on the y-axis increased the score and the opposite occurring for a result in quadrant IV. Third, the relationship between the normalised scores of the attributes of the irrigation treatments were defined relative to the y = x baseline for comparison between treatments (Figure 9:1b). The null hypothesis is that there is no difference among treatments on the score, so attributes are close to the x = y line. Departures from the baseline, measured as the residuals from the x = y line, indicates the magnitude of the treatment effect (Jones et al. 2022).

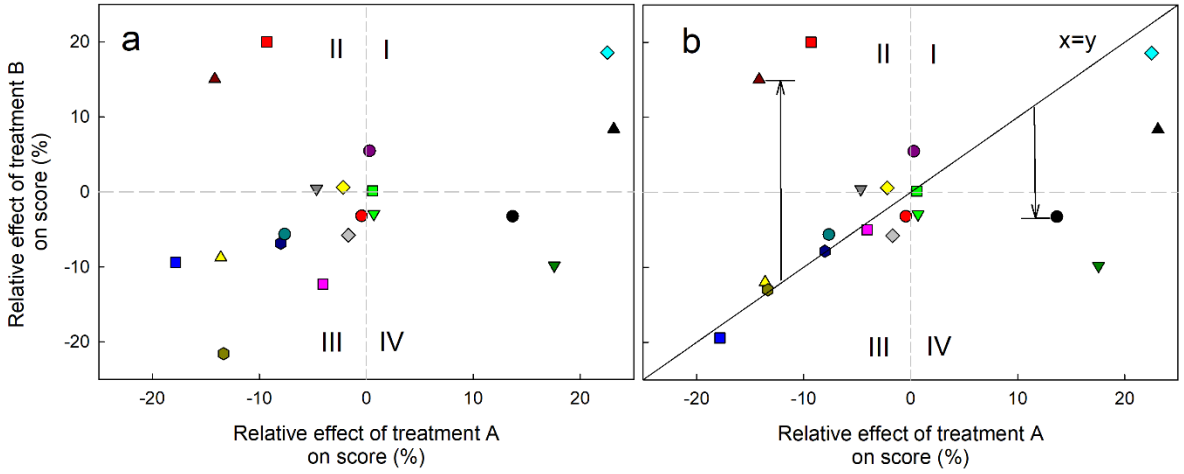


Figure 9:1 The conceptual representation of the model used to measure the effect of the treatments on wine sensory attributes. a) Dashed lines delimit four quadrants according to the hypothetical response between treatments on x and y. b) Baseline where y = x indicates no difference in the score between treatments. Residuals from the y = x indicates differences in the score between treatments.

Results

Fruit composition at harvest

We analysed the effect of the season (S), method (M) and time (T) of irrigation, and their interactions, on fruit composition at harvest for each season (Table 9:2). The three-way ANOVA revealed that 10 out of 11 traits responded to the effect of season, which comprises the interactive effect of the weather and management practices each year. One trait responded to the effect of the M, four traits responded to the effect of the T, two traits responded to the interaction between S x M, and only one trait to the interaction between S x T or M x T.

To disentangle the interactions between method and time with the season, we conducted a two-way ANOVA analysis between method and time of irrigation for each season separately (Table 9:2). Eight traits changed between irrigation treatments (M, T and/or M x T) and season. TSS at harvest was higher in S1 (average 28 ^{o}Brix) than in S2 (average 26.7 ^{o}Brix) and S3 (average 25.9 ^{o}Brix). We managed to harvest treatments at a similar stage of maturity in S1 but there were some minor, although significant, differences between treatments in season S2 and S3. TSS across irrigation treatments ranged from 26.4 to 26.9 ^{o}Brix in S1, and from 25.4 to 26.4 ^{o}Brix in S3. The timing of irrigation (T) impacted on the TSS at harvest. Compared to irrigation at budburst, irrigation from budburst to fruit set delayed the accumulation of sugar in the berry by 0.3 ^{o}Brix in S2 and by 0.6 ^{o}Brix in season S3. The TA was slightly higher (between 0.12 to 0.23 g/L) in the single-lateral compared to the multiple-lateral irrigated vines, but these differences were only detected as significant by the ANOVA in S2. Berry juice pH was low in S3 (3.67), compared to S1 (4.32) and S2 (4.66). The pH responded to the effect of the method of irrigation (M) in S1 and in S3, and to the effect of timing (T) and M x T in S1, but these differences were small and would have minor implications for winemaking. There were some treatment effects on the nitrogen concentration in the fruit. In S1 and S2 multiple-lateral irrigation decreased YAN (around 4 to 6%) and NH_3 (around 10 to 20%) in comparison to the single-lateral irrigated treatment. These effects were reversed in S3 when the multiple-lateral irrigation increased YAN (approx. 9%) and NH_3 (approx. 4%) in relation to single-lateral irrigation. Irrigation from budburst to fruit set increased YAN (around 5 to 13%) and NH_3 (around 5 to 24%) over irrigation at budburst in S1 and S3 but had no impact on any of these traits in S2.

Anthocyanin concentration (per gram of berry), a trait that correlates positively with wine quality, only responded to the effect of the T of irrigation in S3. Irrigation from budburst to fruit set reduced the concentration of anthocyanins in relation to the budburst irrigated counterpart by 14% (from 1.73 to 1.48 mg/g). Multiple-lateral irrigation slightly increased anthocyanin concentration (between 5 to 11%) over single-lateral irrigation across the three seasons but was not detected by the ANOVA at $P < 0.05$. Tannin concentration (per gram of berry) responded to the effect of method of irrigation (M) in S1 and S2, and to the effect of the timing of irrigation (T) only in S1. In relation to single-lateral, multiple-lateral irrigation increased tannin concentration by ~ 9% (from 4.37 to 4.78 mg/g) in S1 and by ~13% (from 4.82 to 5.43 mg/g) in S2. Irrigation from budburst to fruit set decreased tannin concentration by ~ 14% in season S1 (from 4.91 to 4.24 mg/g) and by ~5% in S2 (from 5.25 to 5 mg/g) in relation to its counterpart that was only irrigated at budburst. A similar trend was observed with the concentration of total phenolics which was increased slightly by multiple-lateral irrigation (from 3 to 6%) in S1 and S2 and decreased under budburst to fruit set irrigation in S1 and S3.

Table 9:2 Two- and three-way ANOVA for the effect of the method (D, dripper, and TD, triple dripper) and time of irrigation (Bb, Budburst; Bb-set, budburst to fruit set) on fruit composition at harvest during seasons 2018/19, 2019/20 and 2020/21. Values are the means from four replicates. Within the column, means followed by different letters differ significantly at $P < 0.05$ by Fisher's LSD test. Mean from Control treatments have been included as a reference and are not included in the ANOVA or Fisher's LSD tests.

Season	Method	Time	TSS (°Brix)	TA (g/l)	pH	Malic acid (g/L)	YAN (mg N/L)	NH3 (mg N/L)	Anthocyanins (mg/g)	Anthocyanins (mg/berry)	Tannins (mg/g homogenate)	Phenolic substances (au/g)	Phenolic substances (au/berry)
2018/19	D	Bb	28.20	4.37	4.37 a	2.41	259.00	56.00	1.44	1.47	4.76 ab	1.29	1.32
		Bb_Sett	28.25	4.70	4.46 a	2.72	319.67	75.67	1.39	1.51	3.98 c	1.18	1.28
	TD	Bb	28.55	4.03	4.33 a	2.30	272.33	55.00	1.49	1.42	5.06 a	1.34	1.27
		Bb_Sett	27.28	4.67	4.10 b	2.51	282.33	63.00	1.48	1.65	4.50 b	1.28	1.43
	Control		27.79	4.66	4.15	2.58	247.66	48.66	1.53	1.58	4.84	1.33	1.37
	P-Method (M)		0.927	0.613	**0.002**	0.333	0.705	0.504	0.321	0.347	**0.048**	0.112	0.152
	P-Time (T)		0.739	0.203	**0.037**	0.139	0.282	0.194	0.994	0.082	**0.007**	0.178	0.208
	P-M x T		0.524	0.679	**0.001**	0.766	0.432	0.566	0.525	0.204	**0.004**	0.268	0.053
2019/20	D	Bb	26.89 a	4.77 a	4.77	2.67	284.50	94.67	1.61	1.54 b	4.99 ab	1.38 b	1.32 b
		Bb_Sett	26.62 ab	4.67 ab	4.67	2.50	275.00	99.33	1.60	1.68 ab	4.65 b	1.44 ab	1.52 a
	TD	Bb	26.77 ab	4.53 ab	4.53	2.59	259.50	78.33	1.80	1.74 a	5.52 ab	1.46 a	1.42 ab
		Bb_Sett	26.44 a	4.67 b	4.67	2.39	264.50	76.67	1.75	1.70 ab	5.35 a	1.46 ab	1.43 ab
	Control		26.76	5.16	3.58	2.56	223.00	76.33	1.91	1.52	6.50	1.47	1.17
	P-Method (M)		0.290	**0.003**	0.816	0.690	0.746	0.301	0.156	0.077	**0.002**	**0.032**	0.975
	P-Time (T)		**0.045**	0.906	0.457	0.455	0.967	0.934	0.797	0.383	0.136	0.209	**0.020**
	P-M x T		0.836	0.417	0.714	0.956	0.894	0.862	0.891	0.165	0.613	0.151	**0.044**
2020/21	D	Bb	26.02 ab	4.77	3.60 b	2.82	246.00	73.0	1.71 ab	1.90 ab	4.16	0.78	0.87 ab
		Bb_Sett	25.41 b	4.70	3.67 ab	3.10	301.33	86.7	1.46 c	1.76 b	4.20	0.75	0.91 a
	TD	Bb	26.39 a	4.60	3.72 a	3.04	311.67	85.3	1.83 a	1.94 a	4.17	0.79	0.83 b
		Bb_Sett	25.84 ab	4.40	3.69 ab	2.83	286.67	80.0	1.54 bc	1.78 b	3.95	0.73	0.85 ab
	Control		25.60	4.96	3.58	2.94	241.00	68.00	1.86	1.94	4.13	0.78	0.82
	P-Method (M)		0.151	0.096	**0.043**	0.893	0.451	0.755	0.203	0.556	0.608	0.805	0.058
	P-Time (T)		**0.045**	0.312	0.530	0.845	0.650	0.648	**0.003**	**0.009**	0.701	0.076	0.210
	P-M x T		0.923	0.604	0.140	0.156	0.147	0.310	0.776	0.894	0.593	0.570	0.663
Source of variation													
	Season (S)		**< 0.0001**	**< 0.0000**	**< 0.0001**	**0.003**	0.836	**0.028**	0.002	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
	Method (M)		0.923	0.006	0.564	0.333	0.947	0.235	0.065	0.131	0.062	0.080	0.563
	Time (T)		0.019	0.548	**0.022**	0.902	0.453	0.197	**0.043**	0.639	0.063	0.301	**< 0.001**
	S x M		0.341	0.179	**0.008**	0.806	0.650	0.398	0.998	0.739	0.238	0.208	**0.036**
	S x T		0.794	0.597	0.057	0.071	0.777	0.839	0.226	**0.032**	0.105	0.224	0.110
	M x T		0.280	0.382	**0.012**	0.567	0.367	0.447	0.540	0.582	0.199	0.482	0.819

We further explored the impact of the combined effects of the method and time of irrigation on fruit composition using Principal Component Analysis (PCA), by pooling data together between seasons. We included the Control treatment in the PCA as a supplementary variable to benchmark the effect of the irrigation treatments against vines receiving natural average rainfall during winter and spring (Figure 9:2). The individual irrigation methods (D, dripper, and TD, triple dripper) and time of irrigation (Bb, Budburst; Bb-set, budburst to fruit set) also imposed as supplementary variables in the PCA to allow the effects of the single treatments to be compared.

The first two principal components (PCs), with eigenvalues greater than two were retained, accounting together for ~83% of the observed variation in fruit composition. PC1 accounted for approx. 59% of the variation and was mainly explained by differences in the concentration of tannins, anthocyanins and total phenolics, and by the content of ammonium (NH_3) and juice titratable acidity (TA). Part of the remaining variation was explained by PC2, which accounted for 24% of the difference in composition at harvest. PC2 was mainly explained by juice pH, TSS and by the concentration of malic acid.

The component loadings strongly associated ($r > 0.96$) with the positive side of PC1 were the concentration of tannins, anthocyanins and total phenolics. The negative side of PC1 was associated with TA and NH_3 ($r > 0.87$) and, to a lesser extent, with the content of total phenolics ($r = 0.71$), and malic acid and YAN ($r > 0.5$). Component loadings associated pH ($r = 0.90$) and TSS and malic acid ($r > 0.72$) on the positive side of PC2, and anthocyanins and total phenolic content on its negative side ($r > 0.42$).

Factor loadings segregate TD-Bb on the positive side of PC1 indicating a higher concentration of tannins, anthocyanins and total phenolics on the fruit from vines that received this treatment. D-Bb_set located on the opposite site of PC1 suggesting a relatively lower concentration of phenolic compounds (anthocyanins, tannins and total phenolics), higher acidity and a higher concentration of nitrogen-rich compounds (NH_3 and YAN). TD-Bb_set and D-Bb were located approximately in the centre of PC1, indicating similarities between these treatments on the components strongly associated to PC1, i.e. concentration of tannins, anthocyanins and total phenolics. However, D-Bb was also located on the centre of PC2, whereas TD-Bb_set was segregated on the negative site of PC2, suggesting a higher content of total phenolics and anthocyanins under this treatment but lower pH and TSS.

The distribution of the single factors, i.e. D, TD and Bb, Bb_set, on the orthogonal compositional space shows some similarities but also some differences between these treatments, and the Control. D irrigation, that concentrated water application close to the trunk, or irrigation from Bb to set (Bb_set), that extended the period of irrigation until fruit set, both located on the negative site of PC1. This suggests a detrimental effect of these treatments on the accumulation of phenolics in the fruit but an increase in TA and nitrogen rich compounds. The opposite effect was observed, on TD irrigation with multiple laterals, which increased the fraction of wetted soil, or irrigation only applied close to budburst (Bb), likewise in Control vines exposed to natural winter rainfall. These treatments, located on the positive site of PC1, suggesting an enhancement in the accumulation of phenolics in the fruit at harvest. TD, Bb and Control had relatively smaller canopies (Table 8:2) due to the higher

water stress in the early stages of growth (Figure 5:4 and Figure 5:5), with also smaller bunches and lower yield (Table 8:2). All these conditions may have affected fruit composition by 1) increasing the concentration of phenolics per gram of berry, and 2) by favouring the accumulation of phenolics under better microclimatic conditions in more open canopies.

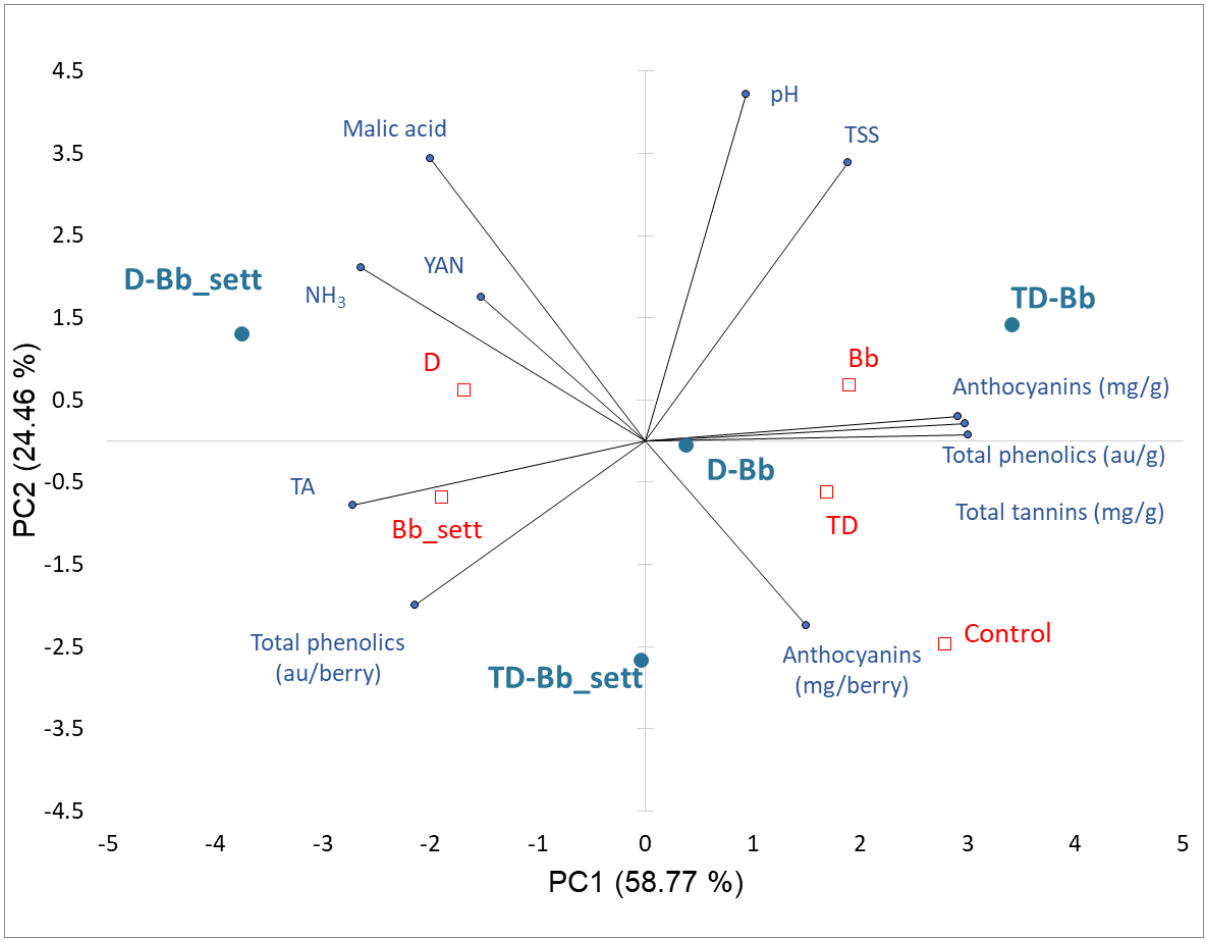


Figure 9:2 Principal component analysis of Shiraz fruit composition at the time of harvest from a factorial experiment combining two methods of irrigation (D, dripper in a single lateral; TD, in multiple laterals) and two times of irrigation (Bb, budburst to 10 cm shoot; Bb-set, budburst to fruit set). Data pooled together from seasons 2018/19, 2019/2020 and 2020/21. Coordinates in the orthogonal compositional space were calculated from the combination of Methods and Times of irrigation (blue). Supplementary variables (red) were also included for the purpose to understand the single effects of the treatments and to compare with the effect of the Control vines.

Wine sensory composition

Season 2018/19

From the nested ANOVA the attributes 'opacity' and 'purple' rated by the panel as significantly different between the treatments at a $P \leq 0.05$. Five additional attributes differed significantly at a $P \leq 0.10$: 'savoury_A', 'cooked vegetable_A', 'pungency_A', 'acidity' and 'red fruit_F'. A PCA that included each of the wine replicates (Figure 9:3) was created using the seven attributes with $P \leq 0.1$. PC1 explained 55.1% of the variation in the data and PC2

explained 24.7% of the variance. PC1 had highly positive factor loading for attributes 'purple', 'acidity' and 'opacity', and negative factor loading on the 'cooked vegetable _A'. Control wines on the far right of the PC1 were rated highly in the attributes 'purple', 'acidity' and 'opacity', whereas D-Bb_set on the opposite side of PC1 were rated low these attributes but high on 'cooked vegetable _A'. The attribute 'red fruit_F' was negatively loaded on PC2 and 'savoury_A' and 'pungency_A' were loaded positively. These attributes contributed the most to the vertical axis separation of the treatments. The treatment TD-Bb_set loaded on the negative side of PC2 and was associated to 'red fruit_A'. The treatment D-Bb clustered on the positive side of PC2 and was defined by 'savoury' and 'pungent' aromas.

The ellipses indicate that there were no significant differences between Control and TD-Bb treatments but differences between Control and D-Bb, D-Bb_set and TD-Bb_set. Similarly, there were no differences between D treatments regardless of the time of irrigation but some differences between TD treatments when irrigated around Bb or between Bb and set.

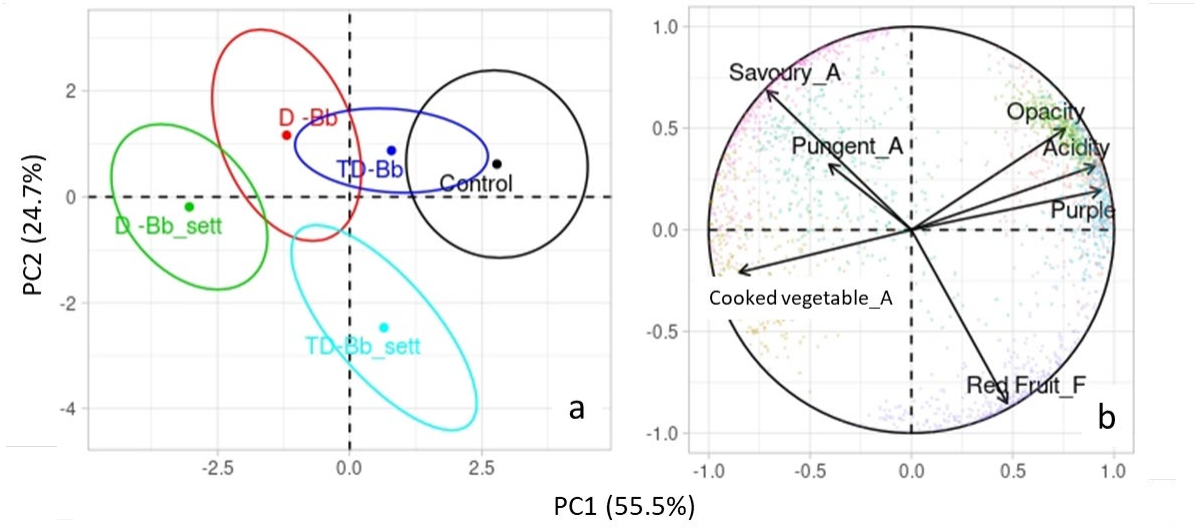


Figure 9:3 Principal component analysis of the descriptive sensory data of Shiraz wines during season 2018/19. (a) wine factor maps with 95% confidence ellipses (showing the relative positioning of the treatment means in two-dimensional space) based on multivariate distribution of Hotelling's test (P < 0.05). (b) loadings for significant (*P* < 0.1) appearance, aroma (_A) and flavour (_F) sensory attributes.

Season 2019/20

From the nested ANOVA, one attribute, 'blackcurrant_A', differed significantly at a $P \leq 0.05$ among the treatments, and four attributes: 'purple', 'chocolate_A', 'savoury_A' and 'savoury_F' differed significantly at a $P \leq 0.10$. There were also significant ($P < 0.05$) field replicates nested in treatment effects for 'opacity', 'purple', 'blackcurrant_A', 'cooked vegetable_A', 'blackcurrant_F' and 'savoury_F', and ($P < 0.10$) for 'chocolate_A' and 'pungency_A'; this is expected when field replicates are kept separate in viticultural trials.

The PCA from the attributes that were significantly affected by the treatments (Figure 9:4) showed that PC1 and PC2 explained 70.7% and 16.9% of the variation in the data respectively. Beyond the PC2, eigenvalues were below 1 and explained little variability in the data.

PC1 had highly positive loadings for the attributes 'chocolate_A' and 'savoury' aroma and flavour. TD-Bb_set on the far right of the PC1 and was rated highly in these attributes. Conversely, 'blackcurrant_A' was highly negatively loaded along PC1 and associated with TD-Bb and Control. The vertical separation of the treatments was determined by the intensity of attribute 'purple', this attribute was most positively loaded on PC2 and separated the Control from D-Bb treatments. Notwithstanding the large amount of intra-treatment variation, as indicated by the size of the ellipses, there were some clear differences between treatments. In a similar manner to the 2018/19 season, there were differences between wines from the Control and the TD-Bb_set and D-Bb treatments; and between wines from the TD treatments irrigated at Bb or Bb_set. As in season 2018/19, no differences were found in 2019/20 between Control and TD-Bb; however, in 2019/20 the D-Bb_set wines did not differ from any of the other treatments.

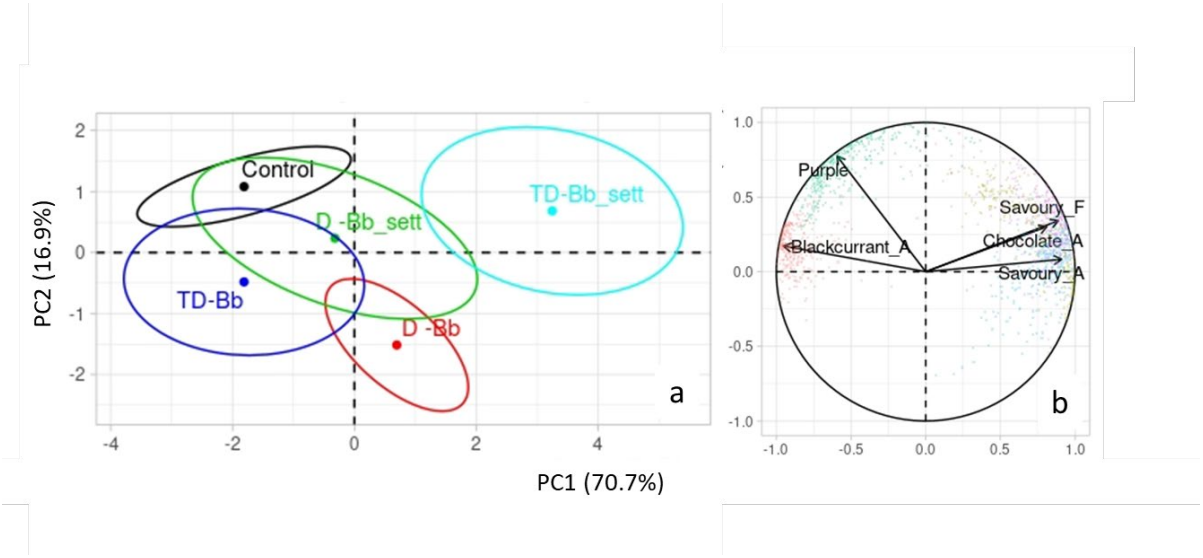


Figure 9:4 Principal component analysis of descriptive sensory data of Shiraz wines from the season 2019/20. (a) wine factor maps with 95% confidence ellipses (showing the relative positioning of the treatment means in two-dimensional space) based on multivariate distribution of Hotelling's test ($P < 0.05$). (b) loadings for significant ($P < 0.1$) appearance, aroma (_A) and flavour (_F) sensory attributes.

Season 2020/21

Results from the ANOVA showed evidence that the attributes 'opacity', 'astringency', 'blackcurrant_F', 'jammy_F' and 'dark fruit_F' differed among the treatments at a $P < 0.1$. The influence on wine colour ('opacity') was the largest treatment effect in this season. There were a number of field replicates nested into treatment effects for the attributes that were also significantly affected by the treatments, these were: 'opacity', 'dark fruit_A', 'spice_A', 'herb_A', 'cooked vegetable_A', 'astringency', 'sweetness', 'blackcurrant_F', 'jammy_F' and 'earthy_F'.

The PCA for each of the field replicate wines (Figure 9:5) was created using the attributes with P ≤ 0.1. PC1 explained 55.2% of the variation in the data and PC2 explained 34.1% of the variance. PC1 had highly positive factor loading for the attributes 'opacity' and 'dark fruit_F', and negative factor loading on the attribute 'blackcurrant_F'. Control wines on the far right of the PC1 were rated highly in the attributes opacity' and 'dark fruit_F'. Conversely, the wines of D-Bb_set were negatively loaded along PC1 and were rated highly in the attribute 'blaclcurrant_F'. The attribute 'astringency' was negatively loaded on PC2 while 'jammy_A' was loaded positively and these attributes contributed the most to the vertical axis separation. The treatment TD-Bb_set loaded on the positive side of PC2 and was associated to 'jammy_F'. Conversely, the treatment D-Bb segregated on the negative side of PC2 and was defined by a higher 'astringency'. Like the previous two seasons, Control wines clustered near TD-Bb and separated from the D-Bb and TD-Bb_set. In as similar manner to the 2018/19 season, maximum separation on PC1 was found between Control and D-Bb_set.

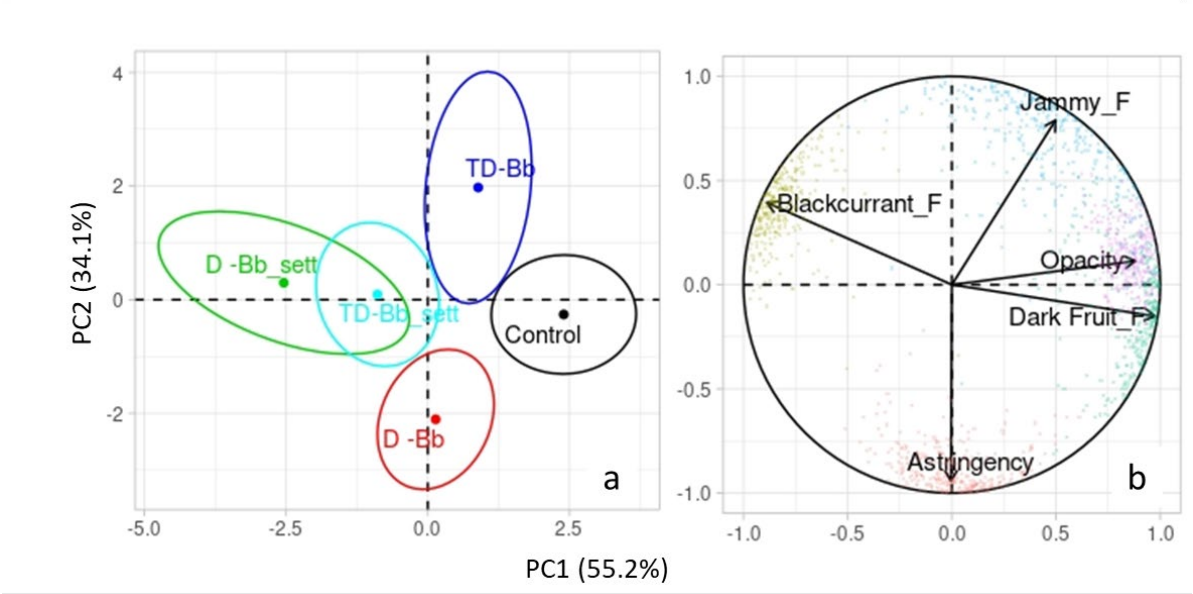


Figure 9:5 Principal component analysis of descriptive sensory data of Shiraz wines during season 2020/21. (a) wine factor maps with 95% confidence ellipses (showing the relative positioning of the treatment means in a two-dimensional space) based on multivariate distribution of Hotelling's test ($P < 0.05$). (b) loadings for significant ($P < 0.1$) appearance and flavour (_F) sensory attributes.

Effect of the treatments on wine attributes

A major potential constraint of descriptive sensory analysis in multi-seasonal studies is that the annual panel results confine their interpretation to a single season. This makes the interactions between treatments and season on wine sensory attributes difficult to investigate and could prevent conclusions being drawn on variation in treatments responses over time. To account for this, we analysed the effect of the treatments on sensory attributes by pooling sensory scores across the three experimental seasons. We analysed the effect of the irrigation treatments on individual sensory attributes by comparing the score of each attribute with the Control and between the irrigation treatments (Figure 9:6). There are two

aspects to this analysis: the position of the attribute in each quadrant and the offset from the x=y baseline (Figure 9:1). The quadrant indicates whether the treatment increased or decreased the perception of a sensory attribute in the wine in relation to the Control. The residuals from the x=y line indicates the magnitude of the offset attributable to each irrigation treatment.

For the appearance attributes, both 'opacity' and 'purple' located on quadrant III (Figure 9:6 a and d), and the offset ranged from -1.9 to 2% (Figure 9:7 a and b); indicating that both attributes were rated lower than in Control wines; but with undetectable differences between irrigation treatments.

Two aroma attributes ('cooked vegetables' and 'savoury') were located in quadrant I, indicating that consistently from season-to-season, the irrigation method and timing increased the score of these attributes in relation to the Control (Figure 9:6 b and e, and Figure 9:7). The wines from these treated vines were scored ~20% higher than Control for the attribute 'cooked vegetables' regardless of the combination of timing or method of irrigation. The attribute 'savoury' was perceived ~15% higher in D than in TD wines, and ~10% higher in Bb_set than in Bb wines. The attributes 'chocolate', 'confection', 'jammy', 'spice' and 'herb' were located in quadrant III, suggesting that the irrigation treatments decreased the perception of these attributes in relation to the Control wines. Residuals for the attributes 'chocolate', 'confection', 'jammy' and 'spice' ranged between -1 to 6%, indicating similar responses in these attributes between methods and timing of irrigation. The attribute 'herb' was located close to the x=y line on the relationship between D and TD, but it was perceived 14% higher in the Bb_set than in the Bb wines. Only the attribute 'floral' located in quadrant II in the relationship between D and TD (Figure 9:6b), indicating that, in relation to the Control, this attribute was perceived higher under TD (~ 5%) but lower under D (~ -14%). There were no differences between Bb and Bb_set in the attribute 'floral' but the attributed was enhanced under TD by ~ 19% (Figure 9:7b). The remaining aroma attributes ('blackcurrant', 'dark fruit', 'cooked vegetable', 'earthy', 'pungent', 'red fruit', 'stalky' and 'vanilla') located close to zero on both axes and near the x=y line for the relation between Method (-4 to 5%) and Timing (-6 to 7%) of irrigation, suggesting no differences with the Control and between treatments.

For flavours, the attributes 'savoury', 'blackcurrant' and 'sweetness' were located in quadrant I; indicating that they were perceived higher for the irrigated treatments than in the Control (Figure 9:6 c and f). The attributes 'chocolate' and 'jammy' located in quadrant III, indicating the opposite effect. The attributes 'savoury' and 'blackcurrant' were perceived in a similar manner in the wines from the D and TD treatments, but up to 11% higher in Bb_set than in Bb wines. The attribute 'sweetness' was slightly higher in the D (7%) than in the TD, and in Bb_set (5%) than in Bb. There were no differences in 'chocolate' between methods or times of irrigations, but 'jammy' was marginally higher (6%) in the Bb_set wines. There were no differences with the Control or between the treatments for the attributes 'acidity', 'astringency', 'bitterness', 'dark fruit', 'earthy', 'hotness', 'red fruit', 'stalky' and 'viscosity'.

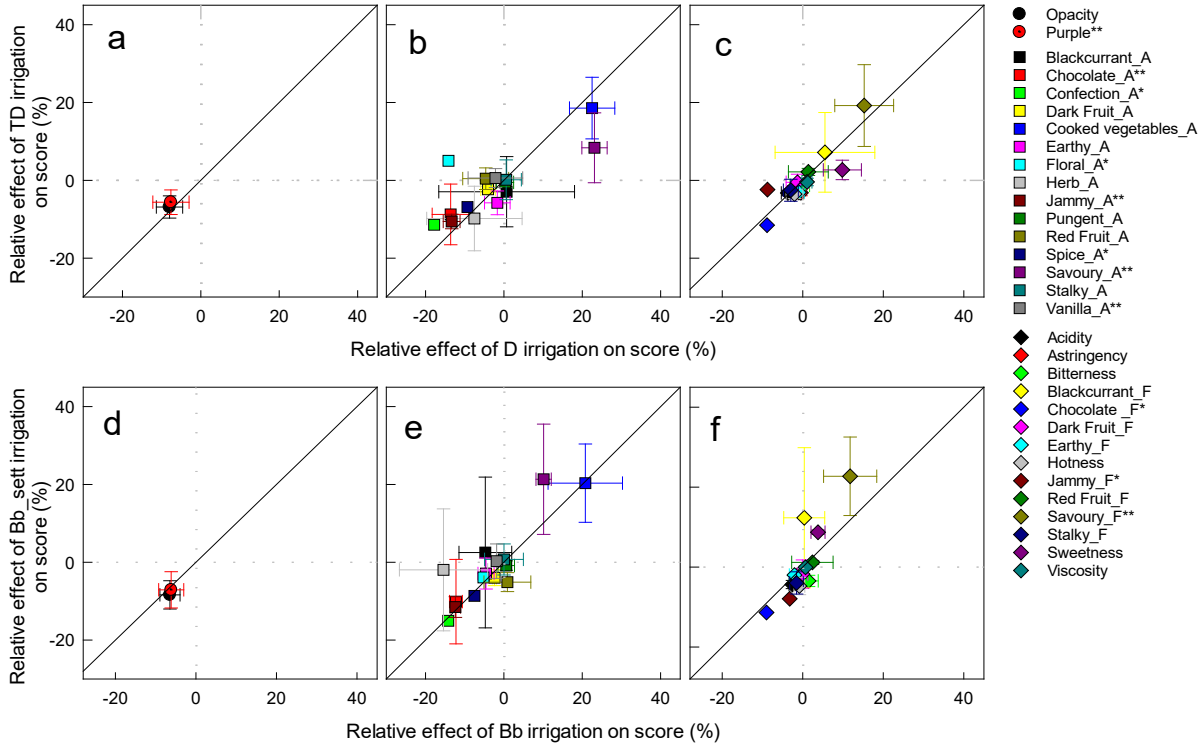


Figure 9:6 Relationship between the normalised scores between (a, b and c) the two irrigation methods (D, dripper in a single lateral; TD, in multiple laterals) and (d, e and f) the two times of irrigation (Bb, budburst to 10 cm shoot; Bb-set, budburst to fruit set) for (●, a and d) appearance, (■, b and e) aroma and (♦, c and f) flavour attributes. Each point is the mean ± standard error from three wine replicates pooled across three seasons (2018-21). Dashed lines delimit four quadrants according to the hypothetical response between treatments on x and y. The solid lines are y = x. In the legend, attribute names are followed for '_A' for aromas and '_F' for flavours. Asterisk in the legend indicates presence of the attribute one (*), two (**) or three seasons (absence of *).

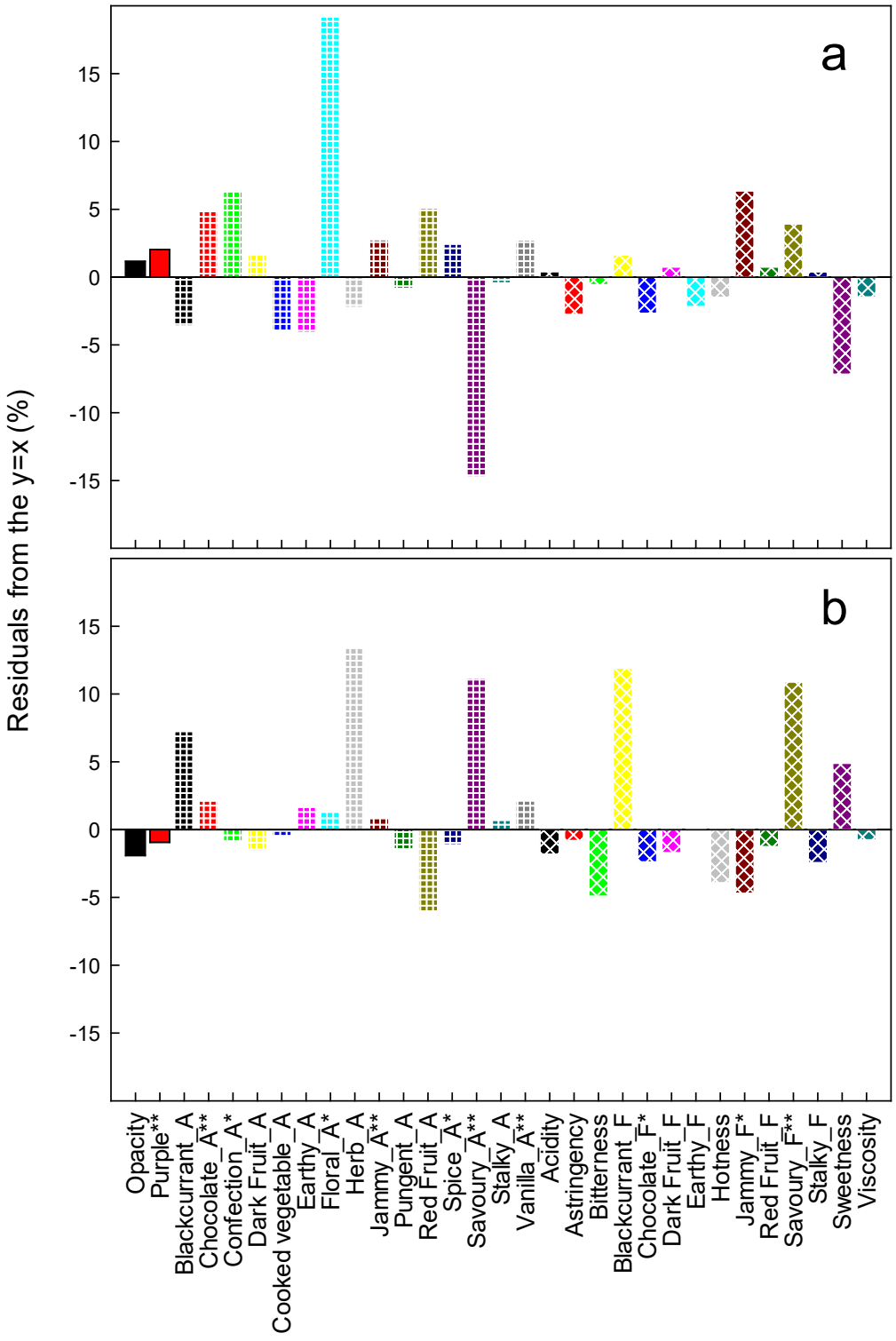


Figure 9:7 Residuals from the y=x line from the relationship between the normalised scores for the (a) two irrigation methods (D, dripper in a single lateral; TD, in multiple laterals) and (b) two times of irrigation (Bb, budburst to 10 cm shoot; Bb-set, budburst to fruit set). Asterisk in the legend indicates presence of the attribute one (*), two (**) or three seasons (absence of *) in the wine of scores for appearance (solid bars), aroma ('_A') and flavour ('_F') attributes.

10 OUTCOMES AND CONCLUSIONS

This project successfully developed and implemented experimental treatments designed to better understand the management of dry winters for the three seasons 2018-19 through to 2020-21. 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 designed to improve our knowledge on the influence of water availability during winter and spring on vine growth and development, including the impacts on root and canopy physiology were implemented. Treatments were established where the irrigation application systems/methods resulted in vineyard productivity being maintained despite dry winters. Generally, the experimental program progressed as expected.

In addition to a Control treatment, which was defined as the long-term average (LTA) of recorded rainfall, the irrigation treatments were designed to compare alternative times and methods of irrigation following a dry winter. Treatments were arranged in a factorial design with four replicates combining two methods of irrigation (D, Drippers located on a single lateral; and, TD, drippers located on three laterals) and two times of application (Bb, budburst to 10 cm shoot growth; and, Bb_set, budburst to fruit set). The irrigation treatments were defined as follows: 1) vines exposed to natural rainfall (Control) with top-up irrigation using under-canopy micro-sprinklers, if necessary, to match mean May-August LTA rainfall. Vines with winter rainfall exclusion and reduced irrigation during winter, receiving 30% of LTA during vine dormancy and 70% after budburst with 2) a single lateral of drippers under the vines (D-Bb), or 3) with three laterals, one under the vines and one approx. 150 mm each side (TD-Bb). Vines with the same irrigation in winter (30% of LTA) but with the remaining 70% applied from budburst to fruit set with 4) a single lateral of drippers (D-Bb_set) or 5) with three laterals (TD- Bb_set).

We compared Ψ_{stem} during the period between flowering and fruit set, between irrigation treatments and the unsheltered Control vines. Control vines were more water stressed than the treated vines regardless of the treatment. The stable carbon isotope composition in grape juice has been shown to be an indicator of vine water status during ripening. We measured $\delta^{13}C$ at harvest during the three vintages. In agreement with the analysis of stem water potential during the season we found that $\delta^{13}C$ was higher in Control vines, indicating that vines under this treatment suffered a higher level of water stress. The measurements of the vines water status were also reflected in the plant available water (PAW) measurement in the soil. The Control treatment showed comparatively higher values during the wet months but a lower PAW from approximately budburst to harvest. The opposite pattern was observed on the irrigation treatments which had lower PAW than Control during winter but a higher PAW after irrigation started at budburst.

Neither the method nor the time of irrigation had a consistent effect on the timing of budburst. The vines that received irrigation during spring recorded an advancement in the timing of EL-31 in S2 and S3, coinciding with larger differences in berry mass between treated and Control vines in these seasons. Control vines showed lower LAI than the remaining treatments during seasons S1 and S2 starting from the very early stages of canopy growth and extending until leaf fall. In season S3, LAI of Control vines diverged from the other treatments

during the period between veraison to leaf fall. Irrigation with a single lateral under the row increased LAI compared to the multilateral treatments from approximately pea size to harvest in S1, and from approximately anthesis to harvest in S2.

There was more root growth (dry mass) in the wet season (S3) than in the dry seasons (S1 and S2). An additive effect of the method and the time of irrigation on root dry mass and root length density was observed. Irrigation with multiple laterals and irrigation from budburst to fruit set both increased root dry mass and root length density. The extra growth with multiple laterals was mainly confined to the position adjacent to the trunk, challenging the hypothesis that, under the conditions of this experiment, the extra lateral of irrigation in the mid-row space may favour root growth in this area.

Average yield across treatments was approximately 5 kg/vine in season 2018/19, 4 kg/vine in season 2019/20 and 7 kg/vine in 2020/21. Irrespective of the timing of the irrigation, application using a single lateral was more effective in maintaining or increasing yield compared to multiple laterals. The multiple laterals increased the proportion of the soil surface that was wetted, while the amount of water applied was consistent across treatments. There was a lower density of vine roots in the mid row and applying the water across the soil surface with the triple dripper may have reduced the ability of the vines to access the irrigation. The more exposed moist soil surface in the mid-row under multiple-lateral irrigation could also have contributed to increased soil evaporation and, therefore, to reduced water availability. Irrespective of the causes, the differences observed in yield between the methods of irrigation support the use of dripper irrigation with a single lateral over the use of multiple laterals. Irrigation during spring and until fruit set increased yield over the unirrigated Control, and these differences in yield were mainly explained by bunch mass and the number and mass of individual berries. Yield on the Control vines fell short by 25% (1.3 kg/vine) in S1, 30% in S2, and was similar (5% or 0.3 kg/vine higher) than the other treatments in S3 (which was also the wettest season).

Across the seasons, the irrigation treatments impacted on the wine sensory attributes relative to the Control. For the appearance attributes, both ‘opacity’ and ‘purple’ were rated lower in the irrigated than in Control wines, but with no significant differences between irrigation treatments. The ‘cooked vegetables’ and ‘savoury’ aromas were increased by the irrigation in relation to the Control; in contrast the aromas ‘chocolate’, ‘confection’, ‘jammy’, ‘spice’ and ‘herb’ were decreased in relation to the Control wines. The flavours ‘savoury’, ‘blackcurrant’ and ‘sweetness’ were perceived higher in the irrigation treatments than in Control, while the opposite occurred for the flavours ‘chocolate’ and ‘jammy’.

The yield response of vines to the spring irrigation occurred in the dry seasons (2018-19 and 2019-20). While a detailed model to link climate to yield and vineyard economics would be needed to provide a more definitive result, a rough estimate of the potential economical return by maintaining yield during dry seasons reflects the importance of irrigation during spring. The average crush in the Barossa has been approximately 50,000 t over the last ten years (Anon 2022) and in the 2013, 2014, 2015 and 2020 seasons the yield was below average. If the yield in these low yielding seasons could be increased to the long-term average (an increase of approximately 38,000 t total across the four seasons) this would add a farm gate

value of $6.8 million to the region (assuming a grape value of $1,800 /t) without counting the flow-on effects to the finished wine. Similar responses would also be expected in regions where additional irrigation water is available in spring from aquifers (e.g. Padthaway), the Murray River (e.g. Langhorne Creek) or from recycled municipal wastewater (e.g. McLaren Vale).

11 RECOMMENDATIONS

There were two clear conclusions from this experimental program.

1. By maintaining some moisture in the profile over winter and then applying irrigation from budburst, the vineyard yield could be substantially increased in dry seasons.

2. The use of multiple laterals to increase the volume of soil wetted by irrigation did not increase the vineyard yield.

On this basis we would recommend that growers be encouraged to modify their irrigation practices. By monitoring rainfall and soil moisture during winter they can ensure that some moisture is maintained in the profile – it is likely that there will be sufficient rainfall for this to occur except in the driest of seasons or in arid regions. When winter rainfall has been poor and the profile is not full at the beginning of spring, growers would be encouraged to commence irrigation from budburst and to maintain water availability as the canopy develops through to flowering.

This project provides general guidance to growers about how to modify irrigation practices and highlights the importance of soil moisture before budburst and during spring on vine productivity. The results suggest that the fraction of total available water (FTAW) needed to be above 70% from budburst to fruit set to maximise yield. In this trial we obtained this FTAW by applying approximately 70 mm of irrigation in winter - which would normally be provided by rainfall in Barossa - and 165 mm from budburst to fruit set. We do not know however, if these FTAW values are the minimum water requirements to maintain yield. Fine tuning of irrigation recommendations during each period of development and for different regions and soil types may be obtained using a detailed model that links climate to canopy growth and yield under different levels of irrigation.

12 COMMUNICATION

Presentations:

- Petrie P.R. and Bonada M. (2022) Managing dry winters (and springs), AWRI Roadshow seminar. McLaren Vale 29 September.

- Bonada M. and Petrie P.R. (2022) Managing dry winters (and springs), AWRI Roadshow seminar. Clare Valley 28 September.

- Bonada, M., Sepulveda, G.C. and Petrie, P.R. 2022. Managing irrigation in vineyards during dry winters and springs. Australian Wine Industry Technical Conference Poster. June 2022.

- Petrie P.R. and Bonada M. (2022) Managing dry winters (and springs), AWITC workshop - Building a climate resilient vineyard. Adelaide 26 June.

- Bonada, M. and Petrie, P.R. (2020) Managing dry winters (and springs). AWRI Roadshow seminar. Langhorne Creek 22 October.

- Petrie P.R. and Bonada M. (2020) Managing dry winters (and springs), ASVO Seminar – Winning the Long Game, Webinar, 30 June.

- Petrie P.R., and Bonada, M. (2020) Winter or spring irrigation in Barossa vineyards? What is the research telling us? Barossa Wine Vimeo. https://vimeo.com/448748401

- Petrie P.R., and Bonada, M. (2019) Managing dry winters and springs. AWRI Roadshow seminar. McLaren Vale 14 November.

- Petrie P.R., and Bonada, M. (2019) Managing dry winters and springs trial site visit. Roland Flat Agricultural Bureau. Nuriootpa 4 November.

- Petrie P.R., and Bonada, M., (2019) Managing dry winters and springs. Treasury Wine Estates grower field day. McLaren Vale 17 October and Barossa 18 October.

- Petrie P.R., and Bonada, M. (2019) Managing dry winters and springs trial site visit. AWRI Advanced Viticulture course. Nuriootpa 14 October.

- Petrie P.R., (2019) Methods for growers to adapt to climate change. AWRI Roadshow seminar. Rutherglen 10 September, Bendigo 11 September and Avoca 12 September.

- Bonada M., (2019) Managing irrigation during dry winters. Effects on vine balance and grape and wine composition. AgXtra Technical Day. Langhorne Creek 16 July.

- Petrie, P.R., and Bonada M., (2019) Managing winter drought. Treasury Wines Estates management meeting, Angaston 27 June.

- Petrie, P.R., and Bonada M., (2019) Managing winter drought. Elders growers day. Nuriootpa 14 May.

- Petrie P.R., (2019) Methods for growers to adapt to climate change. AWRI Roadshow seminar. Yarra Valley 30 January, Mornington Peninsula 31 January, and Geelong 1 February.

- Bonada M. and Edwards, E.J. (2018) Managing dry winters and springs trial site visit. The 5th International Plant Phenotyping Symposium. Nuriootpa 5 October.

- 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 25-26 September.

- Petrie, P.R., (2018) Climate change – adaptation techniques for the wine industry. Romeo Bragato Conference, Wellington, New Zealand 30 August.

- Petrie P. (2018) Managing a challenging climate. Rathbone Wine Group Technical Day, Yarra Valley 20 July.

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

- Petrie, P.R. and Bonada, M., (2018) Managing winter drought. AWRI Roadshow seminar. Langhorne Creek.

Industry articles (online and in print):

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- 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.

- Anon 2018. Managing dry winter conditions. AWRI e-bulletin. August. (https://www.awri.com.au/information_services/ebulletin/2018/08/07/managing-dry-winter-conditions/)

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

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- Wine Australia RD&A News Article, May 2018. Replacing rain can't be a one-off exercise. https://www.wineaustralia.com/news/articles/replacing-rain-cant-be-a-one-off-exercise

- Wine Australia RD&A News Article, June 2019. Keep up the water during winter. https://www.wineaustralia.com/news/articles/keep-up-the-water-during-winter

- Bonada, M., Edwards, E.J., McCarthy, M.G., Sepúlveda, G.C. and Petrie, P.R. (2020), Impact of low rainfall during dormancy on vine productivity and development. Australian Journal of Grape and Wine Research, 26: 325-342. https://doi.org/10.1111/ajgw.12445

- Wine Australia RD&A News Article, December 2020. Study on impact of elevated temperature and water deficit recognised. https://www.wineaustralia.com/news/articles/asvo-dr-peter-may-award-2020-dr-marcos-bonada

- Bonada, M., Catania, A.A., Gambetta, J.M., Petrie, P.R. 2021. Soil water availability during spring modulates canopy growth and impacts the chemical and sensory composition of Shiraz fruit and wine. Australian Journal of Grape and Wine Research, 27: 491-507. https://doi.org/10.1111/ajgw.12506

- Wine Australia RD&A News Article, February 2023. Award for research into the impact of low winter rainfall. https://www.wineaustralia.com/news/articles/award-for-research-into-the-impact-of-low-winter-rainfall

13 STAFF

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