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THE UNIVERSITY of ADELAIDE

How does phenological stage influence grapevine water requirements for Shiraz and Chardonnay in the Riverland?



FINAL REPORT TO WINE AUSTRALIA

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1 Abstract

Under an increasingly water scarce environment, optimising irrigation scheduling in vineyards is critical to conserving freshwater, controlling vine size, and achieving target yields. We used a whole-canopy gas exchange approach over two growing seasons, 2019-20 and 2020-21, in the Riverland viticultural region of South Australia to quantify grapevine (*Vitis vinifera* L. cvs. Shiraz and Chardonnay) water use in order to inform irrigation practices in the region for the improvement of crop water use efficiency (yield per unit of water applied [t ML^{-1}]). We quantified vine water use at key phenological stages of grapevine development (flowering, bunch closure, véraison, pre-harvest, and post-harvest. We also compared the whole canopy approach with micrometeorological (evapotranspiration (ET)) and sap flow approaches. Cultivar-specific crop factors (K_c) were determined at each phenological stage for the estimation of crop ET (ET_c). Canopy water use ranged from 26-39 L $vine^{-1}$ day^{-1} in Chardonnay and 24-33 L $vine^{-1}$ day^{-1} in Shiraz in 2020-21, with higher values observed in Chardonnay early in the season and Shiraz late in the season. Post-harvest water use dropped by 42% (compared to harvest) in Shiraz and by 28% in Chardonnay. Daily dry matter production exceeded 200 g $vine^{-1}$ at véraison with correspondingly highest seasonal canopy water use efficiencies observed during this time. Both ET_c and sap flow estimates of canopy transpiration were lower than whole-canopy estimates. Canopy water use increased by up to 14% during heatwaves and the additional irrigation applied during the heatwave period was adequate to support this increased transpiration rate. Quantitative information of grapevine water use throughout the season would allow growers to optimise irrigation applications while achieving specific targets of yield or grape composition.

2 Executive Summary

Climate change in South Australian viticultural regions has resulted in higher growing season temperatures leading to water scarcities for irrigators during the growing season. In this environment, optimising irrigation applications in vineyards, where grapevine water needs are matched with irrigation, is essential for sustainable viticulture. A mismatch between irrigation water applied and actual crop water use is one of the main reasons for low water use efficiency (Yunusa et al. 2005).

In the present study, we quantified the seasonal water requirements of productive Chardonnay and Shiraz grapevines in the warm, inland region of Riverland, South Australia over two growing seasons, 2019-20 and 2020-21. Three approaches were used for this purpose: (i) whole canopy gas exchange in which canopy transpiration, dry matter production, and water use efficiency were quantified; (ii) crop evapotranspiration (ET_c); and, (iii) sap flow sensors to estimate canopy transpiration (2020-21 season only). These measurements were taken at key phenological stages of the growing season – flowering, bunch closure, véraison, harvest, and post-harvest on a diurnal (24 h) basis.

2019-20 was a slightly cooler season based on the growing degree days (accumulated heat units) compared to 2020-21, which, in addition to the higher soil moisture levels in the second season, may have contributed to the higher canopy transpiration rates quantified using the whole-canopy chambers. Daily water consumption by the vines ranges from 12-20 L $vine^{-1}$ (2.2-3.6 mm) in the first season and 24-39 L $vine^{-1}$ (4.3-7.1 mm) in the second season. Chardonnay tended to use more water early in the season, while Shiraz had higher water consumption during the veraison and post-veraison periods. On a leaf area basis, however, both cultivars were similar in transpiration rates throughout the season. Irrigation applied over the season was lower than the water requirements of Chardonnay, but matched that of Shiraz. There were no indications of water stress on any of the vines, based on measurements of stem water potential.

Dry matter production for Chardonnay was lower than Shiraz, reaching a peak of 238 g $vine^{-1}$ day^{-1}, while Shiraz peaked around 284 g $vine^{-1}$ day^{-1}. On a leaf area basis, Chardonnay tended to have higher rates than Shiraz during flowering and bunch closure stages, while Shiraz was higher during the véraison and pre-harvest stages. Whole canopy water use efficiencies (WUE) were

highest early in the day between 0800-1000 h. On a seasonal basis, canopy WUE was highest around véraison in Shiraz and around flowering in Chardonnay.

Various methods to estimate vine water use were evaluated in the present study including whole-canopy chambers (E_{canopy}), crop evapotranspiration (ET_c), and, additionally in the second season, sap flow (E_{sf}). For the estimation of ET_c, crop factors (K_c) were measured throughout the season using the 'Paso Panel' (light interception) method. Results overall indicate a good agreement of all three methods with ET_c only slightly underestimating water requirements compared to the other two methods. It was determined that the sap flow sensors require in-field calibration with an independent and robust method to provide reliable estimates of canopy transpiration rates.

In the second season, 2020-21, we used the calibrated sap flow sensors to quantify vine water use before, during and after two heatwaves received during the post-veraison period in both cultivars. Canopy water use (E_{sf}) increased between 2-14% during heatwaves, representing an additional water use of between 1.0-7.5 L vine^{-1} day^{-1}. Additional irrigation provided during the heatwaves (~1.7 mm day^{-1}) would have likely alleviated the effects of heat stress on the vines. Our calculations suggest that not all this additional water may have been used for transpirational cooling although an overall benefit to vine microclimate would have occurred alleviating physiological heat stress.

3 **Background**

Sustainable water management in irrigated vineyards and orchards is becoming more critical given the increasing scarcities of freshwater in semi-arid and arid regions worldwide based on recent climate change predictions (IPCC 2014). More recently, water scarcities are also increasing in regions where adequate rainfall is received but where the timing of rainfall does not always coincide with when the crop needs it (Pereira et al. 2002, Reynolds et al. 2007). Vineyards in many parts of Australia where viticulture is prevalent are located in arid and semi-arid climates that have inadequate precipitation during the growing season, and rely on supplemental irrigation at nearly every stage of vine and fruit development. However, increasing water scarcities in these regions such as the Riverland, where the present study was based, that typically have high evapotranspiration (*ET*) are forcing growers to continually seek opportunities to maximize the efficient use of the scarce freshwater resource.

One technique to improve the sustainable use of freshwater in irrigated vineyards is by reducing the amount of water applied during the growing season (Fereres and Soriano 2007). Reduced irrigation practices such as sustained deficit irrigation (SDI) and regulated deficit irrigation (RDI), where less than 100% of crop *ET* (ET_c) is applied, have been used in horticultural crop production since the early 1980s when Chalmers first showed that RDI could be an effective strategy to increase water use efficiency (WUE) in peach orchards (Chalmers et al. 1981, Mitchell and Chalmers 1982). Reduced irrigation practices have been used to improve crop WUE in several other horticultural crops including pear (Chalmers et al. 1986, Mitchell et al. 1989), olive (Fernandez et al. 2013, Grijalva-Contreras et al. 2013), citrus (Ballester et al. 2013, Gasque et al. 2016), and apple (Caspari et al. 2004). In viticulture, reduced irrigation practices such as RDI and SDI are widespread in semi-arid regions and have been shown to be effective in controlling vegetative growth without sacrificing yield or quality while concurrently improving WUE (Costa et al. 2007, Loveys et al. 2004, Medrano et al. 2010, Romero et al. 2010) with differences between grapevine cultivars reported to have a genetic basis (Flexas et al. 2010, Medrano et al. 2015, Tomas et al. 2014). The physiological basis of RDI lies in the differential sensitivity of grapevines to water stress at different phenological stages (Medrano et al. 2015).

Simultaneous estimation of canopy water use (E) and dry matter production (A) can be done by using portable infrared gas analysers (IRGA) at the single leaf level and scaled up to the canopy using canopy leaf area, by micrometeorological (chamberless) methods such as eddy correlation or covariance (Greco and Baldocchi 1996), or by enclosing canopies in open system flow-through chambers in which water vapour and CO_2 fluxes are measured using an IRGA (Garcia et al. 1990,

Pagay 2016). Single leaf-level measurements offer significant advantages over whole-canopy systems allowing for the survey of plant communities across a large area or multiple sites. The main disadvantage of this system to estimate canopy gas exchange are errors associated with the non-destructive estimation of canopy leaf area and the overestimation of whole-canopy CO_2 assimilation rates due to the proportion of non-photosynthesising or respiring leaves in a given canopy (Poni et al. 1997). Furthermore, the heterogeneous architecture of grapevine canopies mean that individual leaves vary in terms of their position on the canopy, e.g. interior (shaded) vs. exterior (exposed) leaves (Schultz 1993), age (Petrie et al. 2000, Zufferey et al. 2000), temperature (Alleweldt et al. 1982, Kriedemann 1968), and position on the shoot, e.g. proximity to sinks such as grape clusters (Petrie et al. 2000), all of which affect leaf physiological performance such as stomatal conductance and CO_2 assimilation rate (Petrie et al. 2009).

Whole-canopy systems have been used in several studies of grapevines in order to quantify gas exchange since they were first developed to measure respiration of field-grown apple trees (Heinicke and Childers 1937). Recent work in this area has focused on estimating canopy gas exchange (Tarara and Pena 2015, Tarara et al. 2011) and WUE (Merli et al. 2015, Pagay 2016) under deficit irrigation, and with multiple fully-automated chambers (Poni et al. 2014). Many of these studies were done either on potted grapevines or where only different RDI regimes were implemented without comparisons to full replacement of water (100% ET_c) or moderate SDI, the latter being a routine irrigation practice in many commercial vineyards in semi-arid regions worldwide.

The goals of this study were to: (i) estimate the seasonal and daily canopy water use, dry matter production, and WUE of well-watered Shiraz and Chardonnay grapevines using custom-built whole canopy gas exchange chambers; (ii) estimate seasonal crop factors for use in ET_c estimates; (iii) compare daily vine water use estimates obtained from whole-canopy transpiration with Penman-Monteith-based ET_c using data from an on-site weather station as well as with commercial sap flow sensors. Quantitation of grapevine water use would provide insights on appropriate irrigation requirements in vineyards such that improvements in water use efficiency can be achieved.

4 Project Aims

	Output	Target Date	Activities
A	Identify vineyard site and specific Shiraz and Chardonnay vines for measurements	31/07/2019	Identify vineyard site in Riverland; visit site and identify a Shiraz and Chardonnay block for trial; tag vines for measurement.
B	Paso Panel built for measurement of seasonal crop coefficients Infrastructure for six whole-canopy gas exchange built	31/09/2019	Purchase flexible solar panel and ammeter; assemble in a frame. Purchase components required for gas exchange chambers (PVC pipes, Mylar plastic sheets, anemometer, tubing, gas multiplexer; blowers) Build six whole canopy gas exchange chambers
C	Data acquired on crop coefficients and diurnal canopy water use at several phenological stages: flowering bunch closure, véraison, pre-harvest, post-harvest. Leaf area per vine acquired	31/01/2020 (S1) 31/03/2021 (S2)	Install whole canopy chambers around six vines per measurement and collect 24 h data of water use; measure crop coefficients using Paso Panel; LAI using ceptometer. Harvest all leaves of vine and measure total leaf area In Season 2 (S2), install sap flow sensors and evaluate performance. Repeat all measurements from S1 for four phenological stages. Collect post-harvest data from sap flow sensors.
D	Data analysed	31/05/2021	Data analysis including statistics, water budgets
E	Final Report	30/06/2021	Present written and verbal report of project findings and implications to Regional Partner (Riverland Wine) Submit final report to Wine Australia

5 **Method**

5.1 Vineyard site, plant material and experimental design

The trial was conducted at Yalumba Oxford Landing Estate, a commercial vineyard in the Riverland viticultural region of South Australia (34°06'06.29" S and 139°50'39.21" E) over two seasons, 2019-20 and 2020-21. The trial used mature Chardonnay grapevines (on Schwarzmann rootstock; vine age 20 years) and Shiraz (on Ru140 rootstock; vine age 21 years) grapevines each, planted at 1.83 m between vines and 3.0 m between rows (vine density: approx. 1,821 vines ha^{-1}). Rows were oriented east-west. The soil type was predominantly loamy-sand in the top 25 cm of the profile with sandy-loam to loam below this layer. Row middles were resident vegetation with an herbicide strip maintained under the vines. The vines were mechanically box pruned and trained to a four-cordon sprawl canopy. The vines were not shoot thinned during the growing season. Irrigation was applied using a single drip line (diameter 21 mm) with dripper spaced at 0.3 m with a nominal flow rate of 1.0 L h^{-1}. Typical seasonal irrigation ranged between 6-7 ML ha^{-1}. Prior to and during heatwaves, irrigation increased from 6 mm day^{-1} 5 days per week (165 L $vine^{-1}$ $week^{-1}$) to 6 mm day^{-1} 7 days per week (231 L $vine^{-1}$ $week^{-1}$). Integrated pest management practices typical for the region were applied at the cooperating grower's discretion.

In each cultivar, three vines were selected for quantitation using whole canopy gas exchange chambers (Fig. 1), one vine per row in three contiguous rows per block.



Figure 1: Whole canopy gas exchange chambers used in the present study.

5.2 Environmental parameters

In each treatment, one TinyTag sensor (Model: TGP 4017, Hastings Data Loggers, Port Macquarie, NSW, Australia) was placed in the canopy interior to continuously record ambient temperature and relative humidity (RH) every 15 min over the growing season. Seasonal weather data was obtained from the NRM Qualco weather station located on site approx. 500 m from the trial blocks. Reference evapotranspiration (ET_0) was calculated using the weather station data and the Penman-Monteith (FAO 56) energy balance relationship. Vapour pressure deficit (VPD) in each canopy was calculated using the canopy temperature and RH obtained from the TinyTag sensors. Light was measured both outside and inside the chambers using a ceptometer (AccuPAR Model LP-80, METER Group, Pullman, WA, USA) and quantum sensor (Model LI-190, LI-COR, Inc., Lincoln, NE) attached to the IRGA (see below).

5.3 Physiological measurements

5.3.1 Canopy light interception, leaf area index, canopy porosity

Canopy light interception in the bunch zone, leaf area index (LAI) and canopy porosity (T) was determined using a portable ceptometer (Model LP-80, Decagon Devices, Pullman, WA, USA). Two measurements per vine were made, one on each side of the trunk and parallel to the cordons. Measurements were made at solar noon between 1100 h and 1400 h on the measurement days at each phenological stage.

Seasonal crop factors were estimated using a 'Paso Panel' that was constructed using a flexible solar panel attached to an ammeter as per Battany (2012). ET_c was calculated from ET_0 and crop coefficients determined using the 'Paso Panel' approach (Battany 2012).

5.3.2 Total leaf area

In the 2019-20 season, following the grape harvest, primary and lateral leaves from all canopies were excised and taken to the lab for measurement of total leaf area per vine using a custom-built light box (Doerflinger and Pagay 2018) and ImageJ software (National Institutes of Health, Bethesda, MD). In the 2020-21 season, total leaf area per vine was estimated (non-destructively) by collecting 30 shoots of varying lengths from adjacent vines at each time point (phenological stage) and measuring their leaf areas (as per the procedure described above) to determine the average leaf area per shoot. All primary and secondary (lateral) shoots on each sentinel vine were counted prior to the first measurement date (flowering) and multiplied with the average leaf area per shoot obtained from the destructive sampling at each time point. This resulted in an estimate of total leaf area per vine per time point.

5.3.3 Soil and vine water status

Stem water potential (Ψ_s) was measured every four hours over the 24 h measurement period using a leaf pressure chamber (Model: 1505-EXP, PMS Instruments, OR, USA). Stem water potential was measured using the pressure chamber by bagging leaves using opaque bags and equilibrating for over one hour prior to measurement. During the nocturnal period (2100 h – 0500 h), leaf water potential measurements were made. The soil matric potential was estimated from the leaf water potential measured at approx. 0500 h, shortly before the first light of dawn. Additionally, *in situ* capacitance probes (Enviroscan, SENTEK, Magill, SA) were present adjacent to the experimental vines providing continuous (1 h) data of soil moisture at multiple depths from 20 cm down to 1.2 m. The soil moisture values in the top 60 cm (i.e. top three sensor readings) were averaged as most of the roots were in that horizon.

5.3.4 Whole canopy gas exchange

Whole-canopy gas exchange chambers ("balloons") were constructed as per the schematic shown in Fig. 2. The balloons were designed as rectangular boxes with a hemispherical cap to allow for maximum sunlight interception as the incident angle of radiation would be perpendicular to different sections of the balloon at various times of the day (Corelli-Grappadelli and Magnanini 1997). Balloons dimensions were approx. 4.0 × 2.0 × 0.5 m (volume ~ 4 m^3), slightly larger than the volume of canopy to be enclosed, and were constructed using a Mylar® clear polyester film of thickness 0.05 mm (Vic Plastics, Ravenhall, VIC, Australia). Light transmission of this film in the photosynthetically-active radiation (PAR) region was approx. 90%, tested using a quantum sensor (Model LI-190, LI-COR, Inc., Lincoln, NE). Each chamber was supported by a custom-built rectangular PVC frame that was attached to the trellis wires at several points between the cordon wire (height: 1.2 m) and the top wire (height: 2.2 m) to reinforce support to the balloons under windy conditions. The balloons were attached to the frame using short strips of Velcro® heavy-duty hook and loop tape and cable ties. Given the thin PVC frame thickness of ca. 1.5 cm, minimal shadow was cast on the canopy during the day.

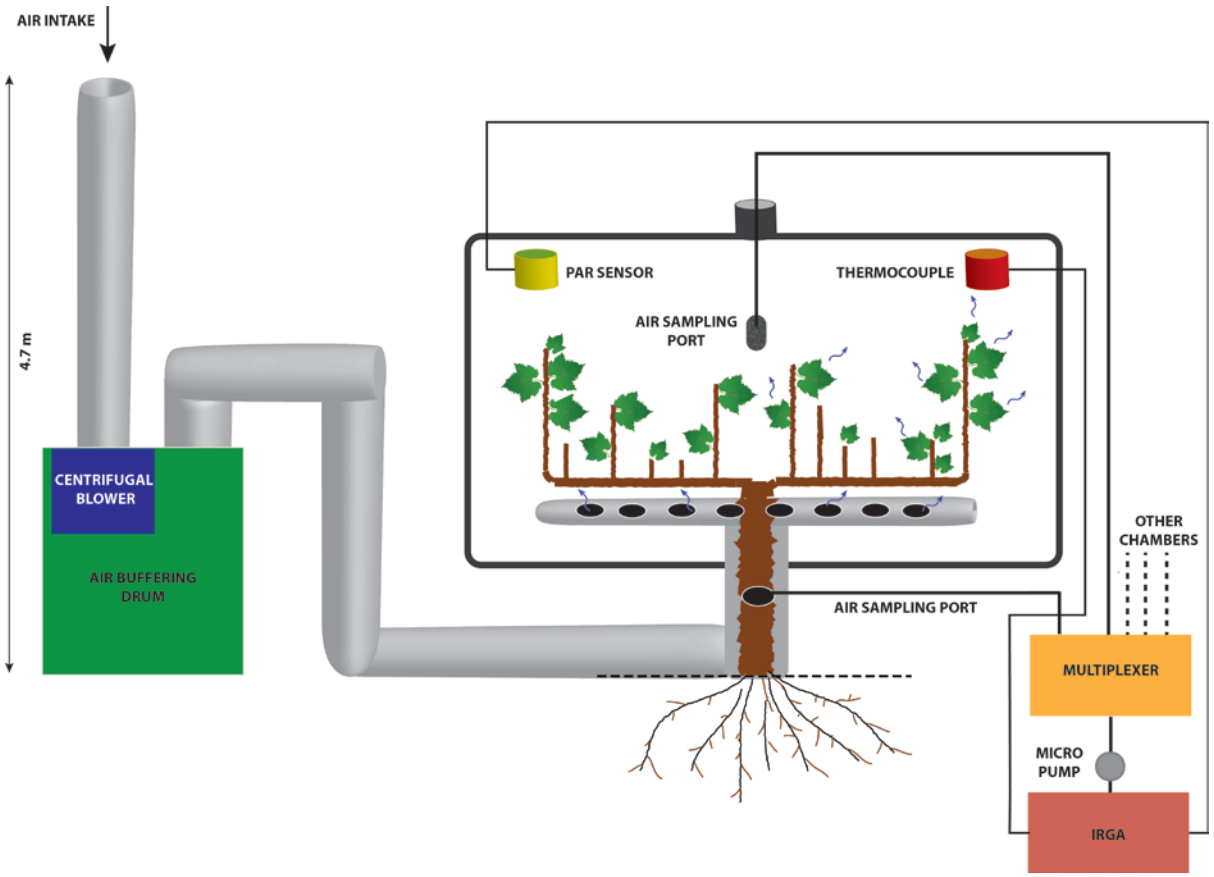


Figure 2: Schematic of the whole canopy gas exchange chambers.

Ambient air was delivered to the balloon using an alternating current (AC) centrifugal inline fan blower (Model UNI766112, Air Wholesalers, Clovelly Park, SA; 240 V, 1 A), diameter 300 mm, housed inside a steel drum (see below) delivering air via an adaptor to a 150 mm flexible aluminium duct into the chambers. A 210 L food-grade steel mixing drum (height: ~1.0 m) was used to buffer any fluctuations in ambient CO_2 concentrations delivered to the balloons (Garcia et al. 1990). In this setup, ambient air intake was at ~ 4.7 m above the ground and ~ 3 m above the top of the canopy. The air velocity and flow rate into each balloon were measured using a hand-held hot wire anemometer (Tenmars Model TM-4002, Instrument Choice, Dry Creek, SA). This flow rate corresponded to an average chamber air volume turnover rate of nearly four-fold per min in order to maintain internal balloon temperatures no higher than 2°C relative to ambient temperatures on warm days. Air was distributed into the lower balloon section using a branched T-junction with diameter approx. 100 mm. Horizontal aluminium ducts were connected to the T-junction with 50 mm diameter perforations. The system of three blowers per cultivar (block) was powered by one 2000 W portable petrol generator (Model PEG2000i, Paramount Browns, Totness, SA) that was placed over 50 m away from the nearest chamber and in a different row.

Air temperature and RH at the balloon inlets (downstream from the blower) were measured using the same thermo-anemometer described above several times over the course of each measurement period. Air temperature at the outlet was measured using a shielded thermocouple (Model 6400-04, LI-COR, Inc., Lincoln, NE). Incident radiation (PAR) inside the balloons and above the canopy was measured using a quantum sensor (Model LI-190, LI-COR, Inc., Lincoln, NE). Air temperatures and RH were measured continuously (15 min intervals) inside the balloons at cordon height using TinyTag sensors (Model: TGP 4017, Hastings Data Loggers, Port Macquarie, NSW, Australia). Both inlet and outlet air streams from each chamber were sampled using an 8 mm diameter Teflon low gas absorption tubing (BL Shipway, Richmond, SA) into a custom-built gas multiplexer connected to a portable open-system IRGA (Model LI-6400XT, LI-COR, Inc., Lincoln, NE). Air was delivered from the balloon inlet and outlets via a custom-built gas multiplexer to the IRGA sensor head through two direct current micro diaphragm pumps with a

nominal flow rate of 1.3 L min^{-1} (Model E161A-11-060, Parker Hannifin Corp., Hollis, NH). In each round of measurements, individual chambers were sampled hourly over a 24 h period. Data of each chamber was recorded by the IRGA every 15 min and the last five minutes of the data of each chamber was averaged; this time was higher than needed to flush out the dead volume of air in the tubing connecting the chambers with the IRGA. The IRGA was matched (sample and reference [CO_2] and [H_2O] equalled) before each round of measurements.

Canopy transpiration (E) and net CO_2 exchange rates ($NCER$) at each time point were calculated using equations given in Long et al. (1996) (Eqns. 1 and 2 below), and these values were integrated to obtain the cumulative or daily values of dry matter production and water use (transpiration; E) of each canopy.

$$E = u_e \times \frac{e_e - e_o}{S(e_e - e_o) + X_e} \qquad \text{(Eqn. 1)}$$

$$NCER = u_e \times \frac{c_e - c_o}{S} - c_o E \qquad \text{(Eqn. 2)}$$

where u_e is the airflow rate at the inlet [mol s^{-1}], e_e is the H_2O vapour concentration at the inlet of the chamber, and e_o is at the outlet of the chamber. S is the total leaf area of the measured vine [m^2], X_e refers to the partial pressure of H_2O vapour at the inlet [mbar], c_e and c_o are mole fractions of CO_2 at the inlet and the outlet of the chamber, respectively.

Instantaneous WUE was calculated using the ratio of $NCER$ and E at each time point per period. Nocturnal transpiration (E_{night}) was obtained by calculating cumulative transpiration over the period 2000 h to 0600 h.

Measurements were made for only the véraison and pre-harvest phenological stages during the 2019-20 season (due to delays in constructing the chambers), and during flowering, bunch closure, véraison and pre-harvest during the 2020-21 season. The harvest dates were 9th February, 2021 and 31st March, 2021 for Chardonnay and Shiraz, respectively.

5.3.5 Sap flow measurements

Heat pulse velocity sap flow sensors (Implexx Sap Flow Sensor, Implexx Sense, Melbourne, VIC, Australia) were installed in September 2020 in three grapevines each of Chardonnay and Shiraz that were used for the whole canopy gas exchange measurements. The sensors are pre-calibrated to measure sap flow of grapevine stems using the Dual Method Approach (Forster 2019) and details of the sensor can be found in Forster and Englefield (2021). The three sap flow sensors per block, one per vine, were connected to one datalogger each (Model CR1000, Campbell Scientific, QLD), and measurements were made every hour for the entire 2020-21 growing season through to the post-harvest period in late May 2021. The post-harvest date analysed had a similar daily maximum VPD as the harvest date for each cultivar. For precise quantitation of sap flow, various trunk and wood parameters were measured at the end of the season including trunk diameter, and from trunk cores, bark depth, moisture content, sapwood dry density, and thermal diffusivity and used to make corrections to the sap flow data (sap velocity, transpiration rate) collected over the season. The correction procedure is described in Forster and Englefield (2021). Due to initial (very low) values obtained from the correction procedure, an additional in-field calibration was applied to the dataset using values obtained from the whole-canopy chambers on the same vines.

5.4 Statistical analysis

Statistical analysis and graphing of all data was performed using GraphPad Prism software (v.7.02, GraphPad Software, Inc., La Jolla, CA, USA). One-way analysis of variance (ANOVA) was performed on the datasets followed by a post-hoc analysis of treatment means using Tukey's

Honestly Significant Difference (HSD) test at $P \leq 0.05$. Results reported as statistically significant refer to the probability of committing a Type I error at the given significance level (P-value) for the means comparisons.

6 **Results and Discussion**

6.1 Environmental parameters

Climatic data for the 2019-20 season as obtained from the Qualco automatic weather station is presented in Table 1 and Fig. 3, and for the 2020-21 season in Table 2 and Fig. 4. The four measurements days, for Shiraz and Chardonnay at véraison and harvest, were relatively mild with daily maximum temperatures around 25 °C and maximum VPDs between 1.5-2.5 kPa. Reference evapotranspiration, ET_0, was between 3-6 mm day^{-1}. By the end of the growing season (harvest), 1,350 and 1,712 degree days had been accumulated for Chardonnay and Shiraz, respectively.

Table 1: Environmental conditions for Chardonnay and Shiraz grapevines within the whole canopy chambers on the two measurements days at véraison and harvest, 2019-20. Data source for ET_0: NRM Qualco automatic weather station. Measurement dates provided in parentheses below phenological stage.

CULTIVAR/Parameter	**Veraison**	**Harvest**
CHARDONNAY	**(12.01.2020)**	**(03.02.2020)**
Diurnal temperature range (°C)	12.3 - 25.6	13.25 - 24.5
Diurnal relative humidity range (%)	29.0 - 77.7	47.2 - 84.8
Maximum VPD (kPa)	2.5	1.5
Maximum incident solar radiation (W m^{-2})	1039	1089
Growing degree days (2-Sep - measurement date, base 10 °C)	1071	1350
Reference evapotranspiration, ET_0 (mm day^{-1})	6.3	3.0
SHIRAZ	**(01.01.2020)**	**(08.03.2020)**
Diurnal temperature range (°C)	12.0 - 25.1	12.0 – 25.0
Diurnal relative humidity range (%)	30.6 - 86.3	30.1 - 86.3
Maximum VPD (kPa)	4.0	2.5
Maximum incident solar radiation (W m^{-2})	1074	948
Growing degree days (2-Sep - measurement date, base 10 °C)	935	1712
Reference evapotranspiration, ET_0 (mm day^{-1})	4.9	5.1

For the 2020-21 season, microclimatic conditions within the canopies (chambers) of each cultivar and time point are presented in Table 2. The season was characterised as relatively mild with few heatwaves (shown as red shaded regions). The maximum ET_0 values were around 8 mm day^{-1} on the warmest days, but tended to range between 2-6 mm day^{-1} for most of the growing season. Soil moisture was maintained between 20-30% (Shiraz sometimes approached 35%) for the duration of the season, with Shiraz having consistently higher volumetric water content than Chardonnay. The daily maximum temperatures were between 20 °C and 30 °C across the growing season, with moderate VPDs ranging from 1.4 to 3.8 kPa. Conditions were very similar for both cultivars at their specific phenological stages, making it convenient to compare their performance. Reference ET (ET_0) was highest during the véraison stage at over 5 mm day^{-1}. By the end of the growing season, 1,475 and 1,879 degree days had been accumulated for Chardonnay and Shiraz, respectively.

Table 2: Environmental conditions for Chardonnay and Shiraz grapevines within the whole canopy chambers on the five measurements days from véraison to post-harvest, 2020-2021. Data source for ET_0: NRM Qualco automatic weather station. Measurement dates provided in parentheses below phenological stage.

CULTIVAR/Parameter	Flowering	Bunch Closure	Veraison	Harvest	Post-harvest
CHARDONNAY	**(09.10.20)**	**(17.11.20)**	**(28.12.20)**	**(03.02.21)**	**(15.02.21)**
Diurnal temperature range (°C)	6.1 - 20	6.0 - 26.9	6.9 - 29.8	13.6 - 28.3	12.4 - 27.5
Diurnal relative humidity range (%)	43.0 - 97.5	16.0 - 92.4	17.3 - 86.2	22.9 - 79.2	24.4 - 87.4
Maximum VPD (kPa)	1.4	3.0	3.8	3.0	2.8
Maximum incident solar radiation (W m^{-2})	1244	1067	1154	1144	1029
Growing degree days (2-Sep - measurement date, base 10 °C)	221	546	1031	1475	1594
Reference evapotranspiration, ET_0 (mm day^{-1})	2.9	4.6	5.3	4.7	4.4
SHIRAZ	**(20.10.20)**	**(24.11.20)**	**(06.01.21)**	**(14.03.21)**	**(11.04.21)**
Diurnal temperature range (°C)	8.3 - 23.9	9.4 - 27.6	12.3 - 26.5	4.6 - 22.1	11.7 – 22.0
Diurnal relative humidity range (%)	26.6- 94.1	30.0 - 94	25.2 - 79.7	37.1 - 96.6	36.2 - 77.7
Maximum VPD (kPa)	2.2	2.6	2.6	1.7	1.7
Maximum incident solar radiation (W m^{-2})	1214	1212	1092	864	1127
Growing degree days (2-Sep - measurement date, base 10 °C)	306	641	1133	1879	2124
Reference evapotranspiration, ET_0 (mm day^{-1})	3.6	3.5	5.3	4.0	2.8

Figure 3: Seasonal climate data at Oxford Landing Estates as obtained from the NRM Qualco automatic weather station during 2019-20.

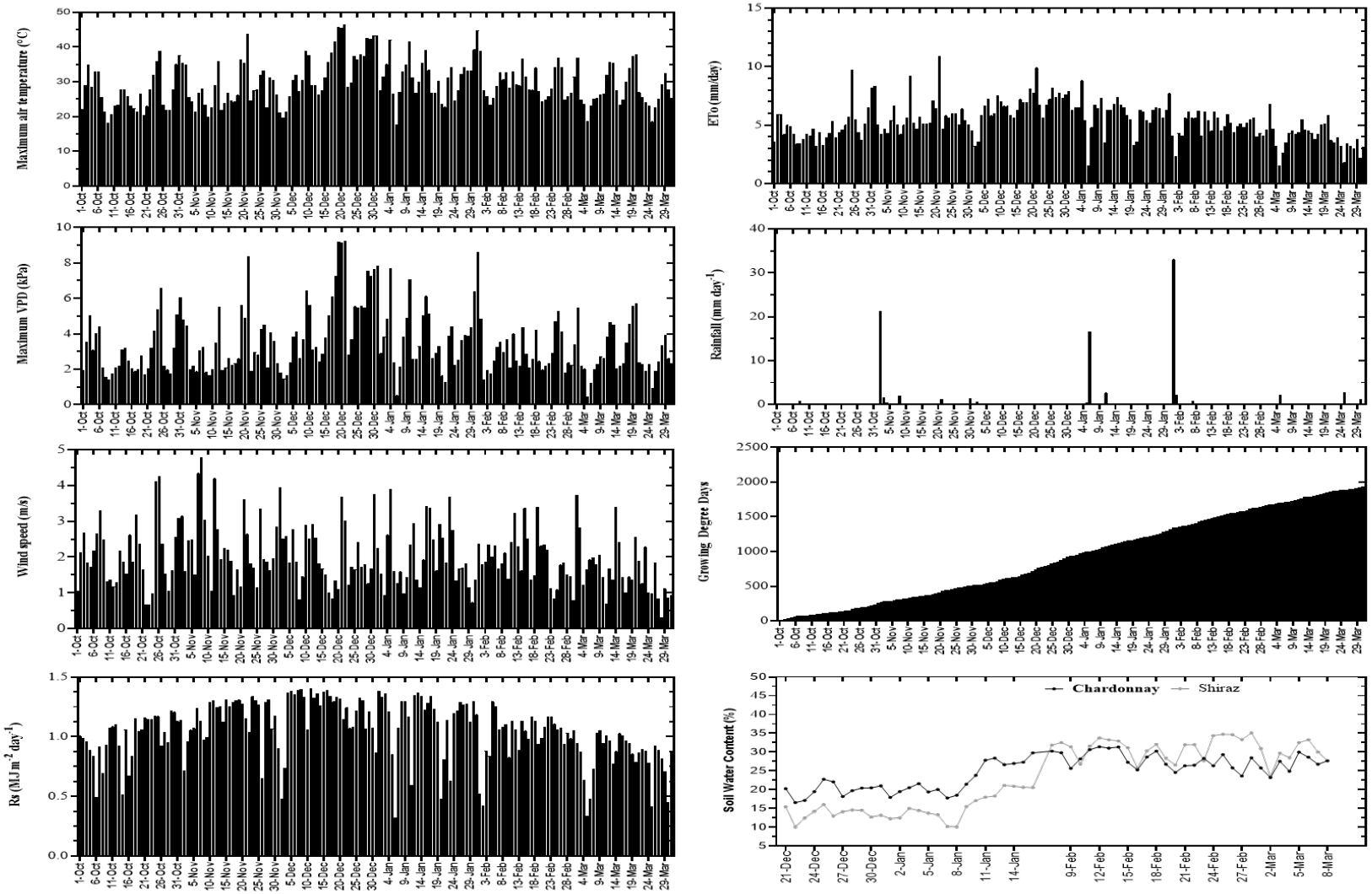
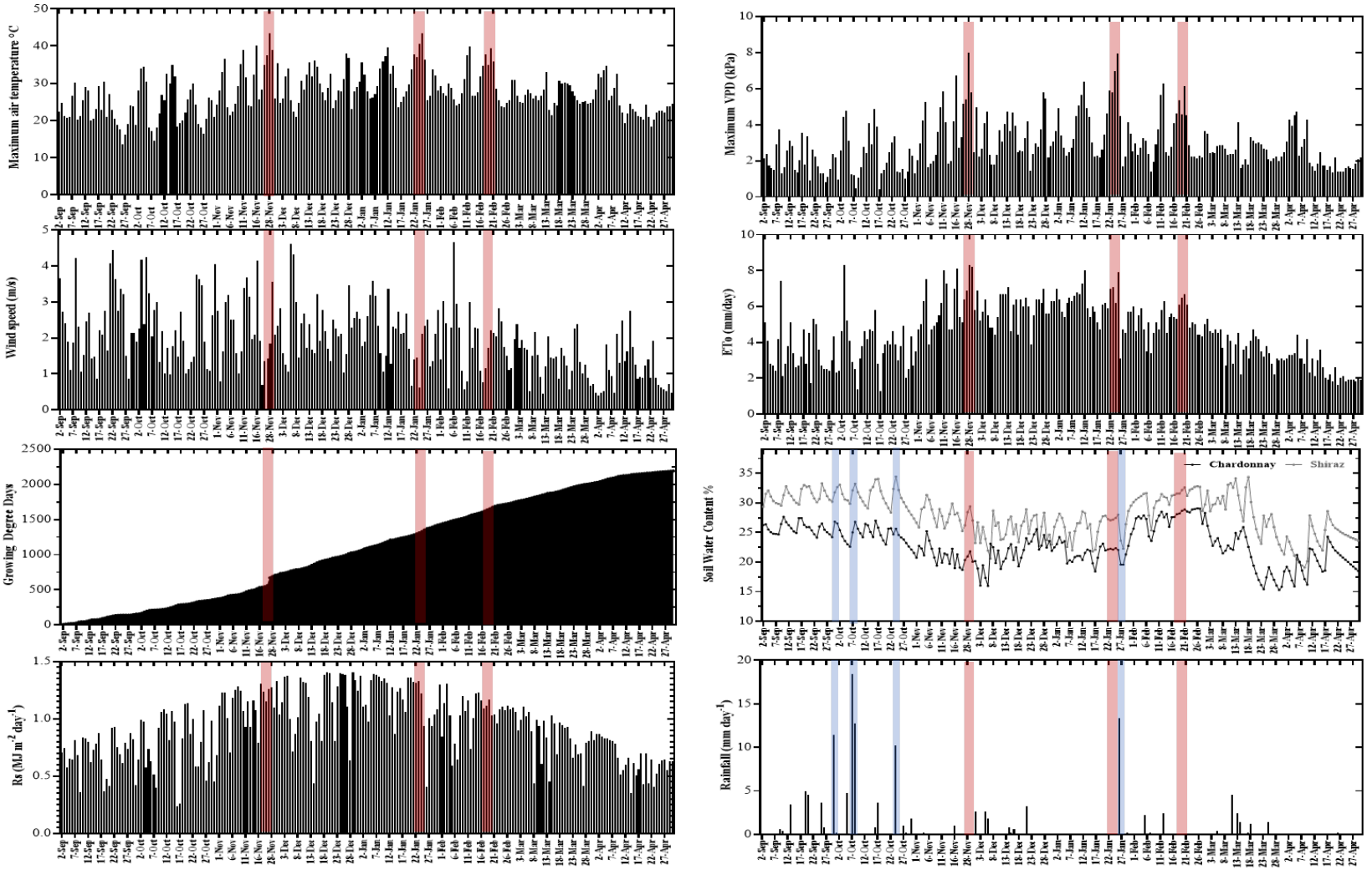


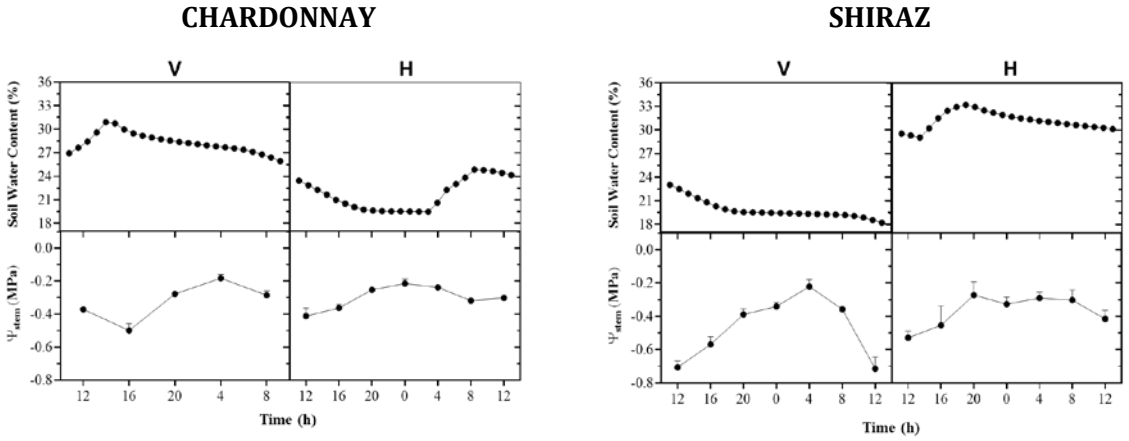
Figure 4: Seasonal climate data at Oxford Landing Estates as obtained from the NRM Qualco automatic weather station during 2020-21. Heatwaves are highlighted in shaded red windows while major precipitation events are highlighted in shaded blue windows.



6.2 Diurnal soil and vine water status

Diurnal measurements of soil moisture and canopy water status, were measured during the 2019-20 growing season for both cultivars, Chardonnay and Shiraz, and shown in Fig. 4. Both cultivars had soil moisture levels above 20% VWC with Shiraz having higher water availability at harvest. The diurnal patterns of vine water status as given by the stem water potential (Ψ_{stem}) reflected the soil moisture patterns, with Ψ_{stem} values ranging from -0.2 to -0.5 MPa in Chardonnay, and -0.2 to -0.7 MPa in Shiraz, the lowest of these values observed around veraison. These values can be considered relatively well watered or non-water stressed for grapevines. The lowest values of Ψ_{stem} occurred around midday (1200 h) in Shiraz and around 1600 h in Chardonnay.

Figure 4: Diurnal patterns of soil moisture (% volumetric water content) average value of top 60 cm of soil profile and stem water potential (Ψ_{stem}) for Chardonnay at the véraison (V) and harvest (H) phenological stages during the 2019-20 season.



Diurnal measurements of soil moisture and canopy water status, were measured during the 2020-21 growing season for both cultivars, Chardonnay and Shiraz, and shown in Figs. 5 and 6, respectively. Both cultivars had soil moisture levels above 20% VWC and in some cases, exceeding 30% following an irrigation. The diurnal patterns of vine water status as given by the stem water potential (Ψ_{stem}) reflected the soil moisture patterns, with Ψ_{stem} values ranging from -0.15 to -0.6 MPa in both cultivars. These values can be considered relatively well watered or non-water stressed for grapevines. In Chardonnay, the highest diurnal value of Ψ_{stem}, which is the pre-dawn value reflecting the soil matric potential (Ψ_m), occurred around 0600 h for much of the season until véraison, and advanced to around 2200 h by pre-harvest. In comparison, Shiraz had the highest diurnal Ψ_{stem} consistently between 0600 h – 0700 h, shortly after dawn. The lowest values of Ψ_{stem} occurred around or shortly after solar noon in both cultivars.

Figure 5: Diurnal patterns of soil moisture (% volumetric water content) average value of top 60 cm of soil profile and stem water potential (Ψ_{stem}) for Chardonnay at various phenological stages during the 2020-21 season. FL=flowering; BC=bunch closure; VE=véraison; HA=harvest.

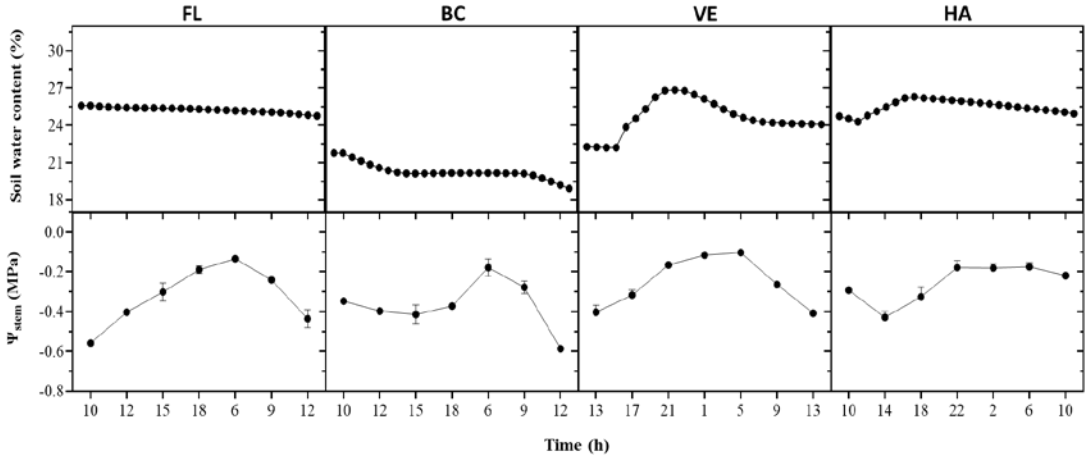
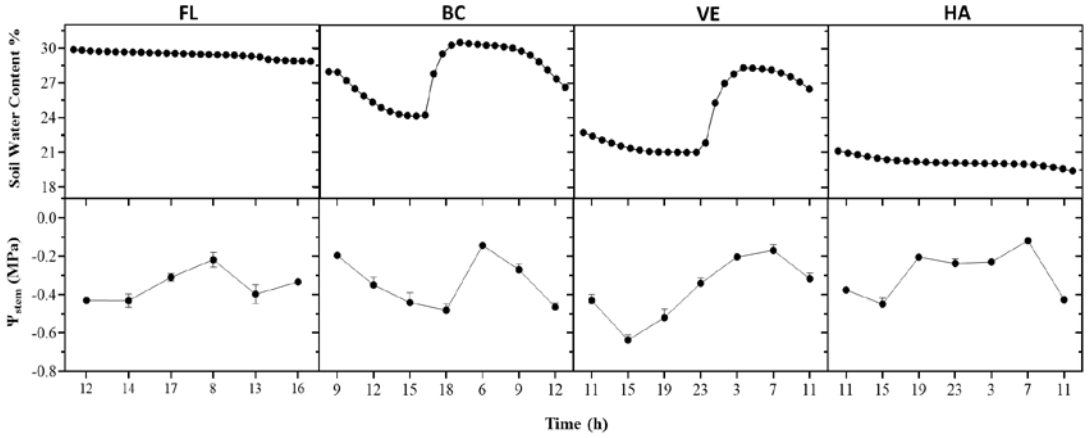


Figure 6: Diurnal patterns of soil moisture (% volumetric water content) average value of top 60 cm of soil profile and stem water potential (Ψ_{stem}) for Shiraz at various phenological stages during the 2020-21 season. FL=flowering; BC=bunch closure; VE=véraison; HA=harvest.

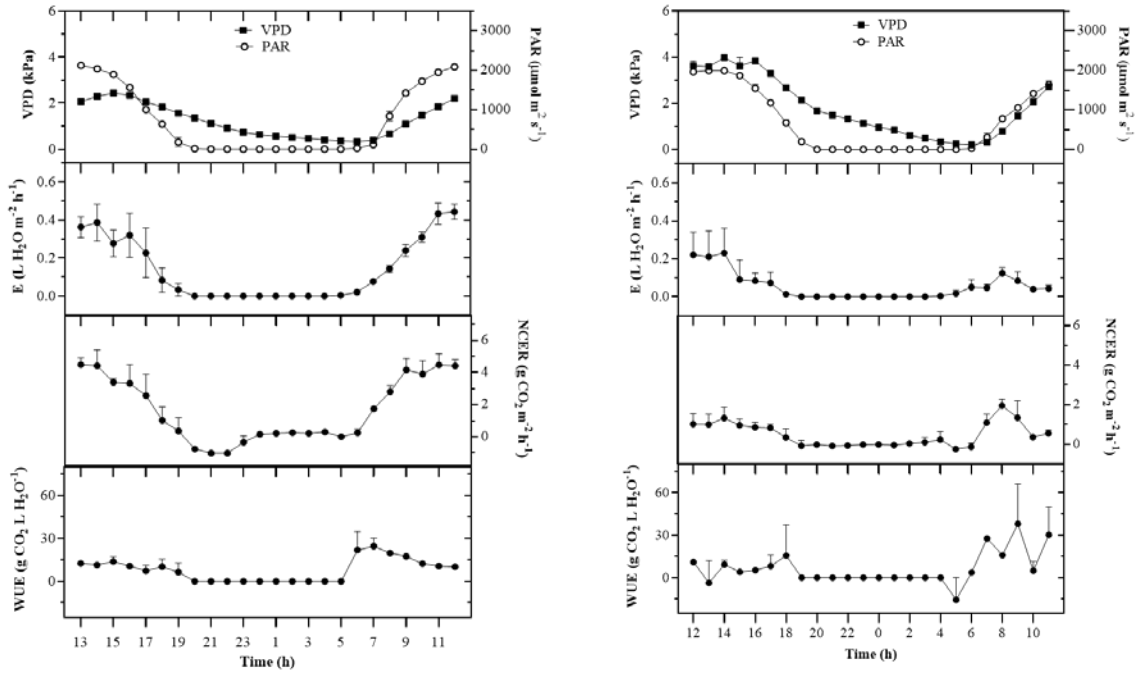


6.3 Diurnal canopy water use, dry matter production, water use efficiency

Diurnal patterns of environmental conditions (VPD), canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) are shown in Figs. 7 and 8 for the véraison and harvest stages in 2019-20.

Figure 7: Diurnal patterns of vapour pressure deficit (VPD, chamber interior) canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) during the véraison stage in 2019-20.

CHARDONNAY- VE **SHIRAZ – VE**



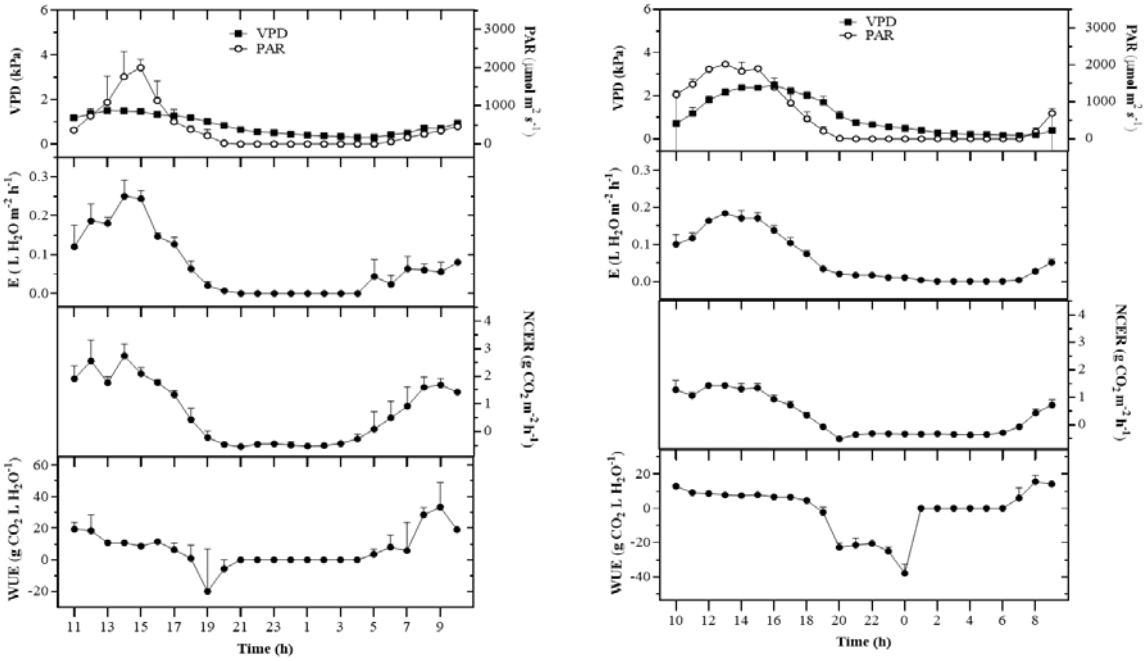
Diurnal patterns of VPD followed the solar radiation and ambient temperature profiles, with maximum VPD of approx. 2.3 kPa and 4.0 kPa (reached around 1500 h) on the days when the Chardonnay and Shiraz grapevines were measured, respectively. The canopy E for Chardonnay started to rise at 0600 h, and the highest canopy E was approx. 0.4 L H_2O m^{-2} h^{-1} reached around solar noon. At 2000 h, canopy E dropped to 0. Daily NCER trends for both varieties followed canopy E. For Shiraz vines at mid-veraison, canopy E commenced to rise at 0400 h and peaked to around 0.25 L H_2O m^{-2} h^{-1} at 1400 h. No nocturnal transpiration was observed in either cultivar, probably reflecting the mild environmental conditions during this period.

For Chardonnay, NCER peaked at between 1100 h and 1500 h, and dropped rapidly after 1600 h. The maximum NCERs were approx. 5 g CO_2 m^{-2} h^{-1}. For Shiraz, NCER peaked at 0800 h around 2 g CO_2 m^{-2} h^{-1} then dropped to 0.5 g CO_2 m^{-2} h^{-1}at 1000 h. The value was stable around 1.5 g CO_2 m^{-2} h^{-1} between 1200 h and 1500 h, dropping rapidly after 1700 h.

Whole canopy water use efficiency (WUE) for Chardonnay peaked at 0700 h around 24.6 g CO_2 L H_2O^{-1} then decreased gradually in the afternoon. Shiraz canopy WUE peaked at 0900 h at approx. 38 g CO_2 L H_2O^{-1}, which was higher than Chardonnay. The value dropped to 0 at 1900 h and started to increase from 0500 h.

Figure 8: Diurnal patterns of vapour pressure deficit (VPD, chamber interior) canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) shortly prior to harvest in 2019-20.

CHARDONNAY- H **SHIRAZ – H**



At the pre-harvest stage in Chardonnay, the canopy E started to rise at around 0400 h and reached the highest value of approx. 0.25 L H_2O m^{-2} h^{-1} between 1200 h to 1600 h; the canopy E dropped to 0 around 2100 h. For Shiraz vines at pre-harvest, canopy E rate started to increase at 0600 h. Between 1200 h and 1500 h, the highest diurnal E rates were observed. No nocturnal transpiration was observed in either cultivar probably reflecting the cool nights.

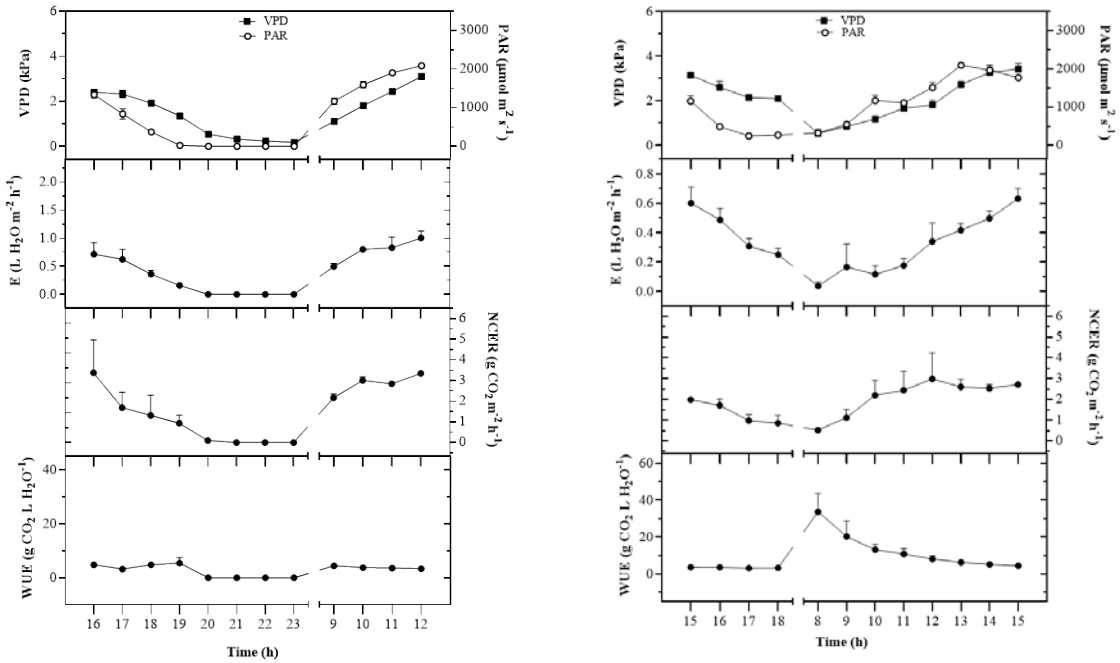
Daily NCER trends for both varieties followed canopy E. For Chardonnay at pre-harvest, NCER peaked at between 1200 h and 1500 h with a maximum of around 3.2 g CO_2 m^{-2} h^{-1}. NCER began to decrease after 1400 h. For Shiraz, the maximum diurnal NCER was around 1.5 g CO_2 m^{-2} h^{-1} observed around the same time as Chardonnay. After 1600 h, the NCER dropped sharply.

The canopy WUE of Chardonnay at pre-harvest had a maximum early in the day, around 0900 h at around 33.4 g CO_2 L H_2O^{-1}, decreasing slowly thereafter during the day, and increasing again from 0400 h the next morning. For Shiraz, canopy WUE peaked at 0800 h around 15.6 g CO_2 L H_2O^{-1} which was considerably lower than at veraison and compared to Chardonnay at the same stage. The WUE had a decreasing trend in the afternoon and started to increase again from 0600 h the next day.

Diurnal patterns of environmental conditions (VPD), canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) are shown in Figs. 9-12 for each phenological stage during the 2020-21 season.

Figure 9: Diurnal patterns of vapour pressure deficit (VPD, chamber interior) canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) during the flowering stage as measured on October 10, 2020 for Chardonnay and October 20, 2020 for Shiraz.

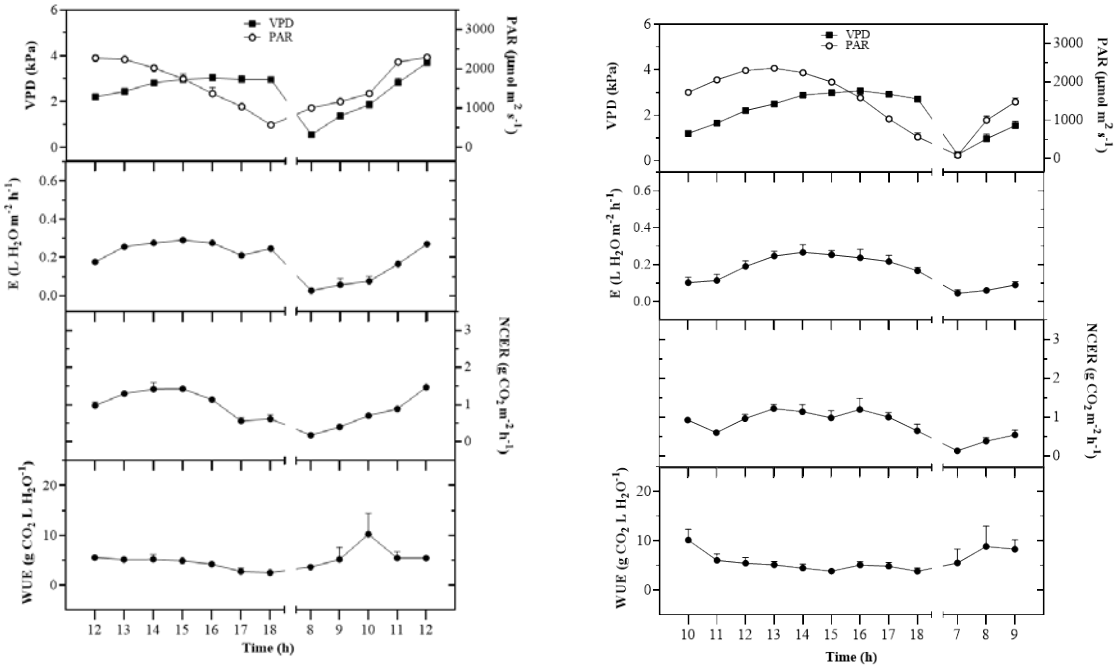
CHARDONNAY- FL **SHIRAZ - FL**



Diurnal patterns of VPD reflected patterns of both ambient temperature inside the chambers as well as relative humidity. The highest values were found around solar noon (1200-1400 h), and the early season also was one of the coolest periods of our measurement. The highest canopy transpiration rates as measured by the chambers were in the order of 1 L m^{-2} h^{-1} while the canopy CO_2 assimilation rates peaked around 4 g CO_2 m^{-2} h^{-1}. The highest WUE was observed early in the day, around 0800 h, followed by a steady decrease as the VPD increased, possibly resulting from the rapidly increasing canopy E during the day until mid-afternoon. Chardonnay canopies tended to have generally higher levels of gas exchange during this stage compared to Shiraz despite lower total leaf areas. This may reflect their more advanced phenological and morphological development.

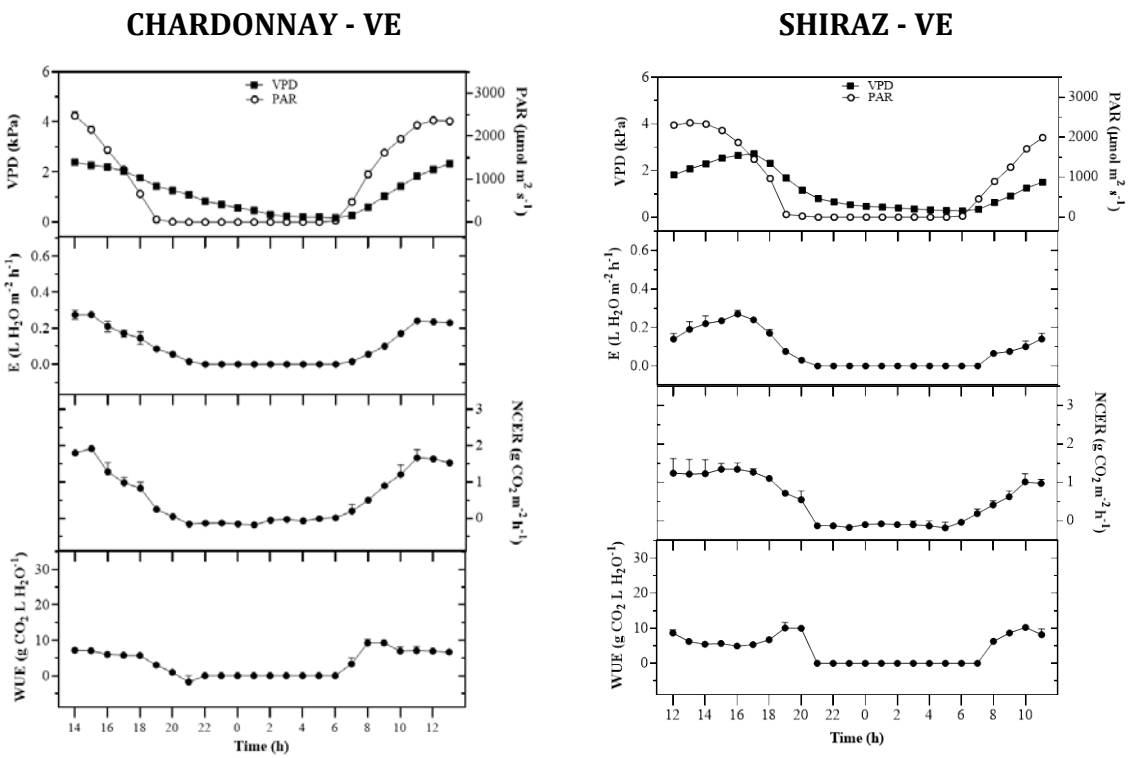
Figure 10: Diurnal patterns of vapour pressure deficit (VPD, chamber interior) canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) during the bunch closure stage as measured on November 17, 2020 and November 24, 2020 for Shiraz.

CHARDONNAY - BC **SHIRAZ - BC**



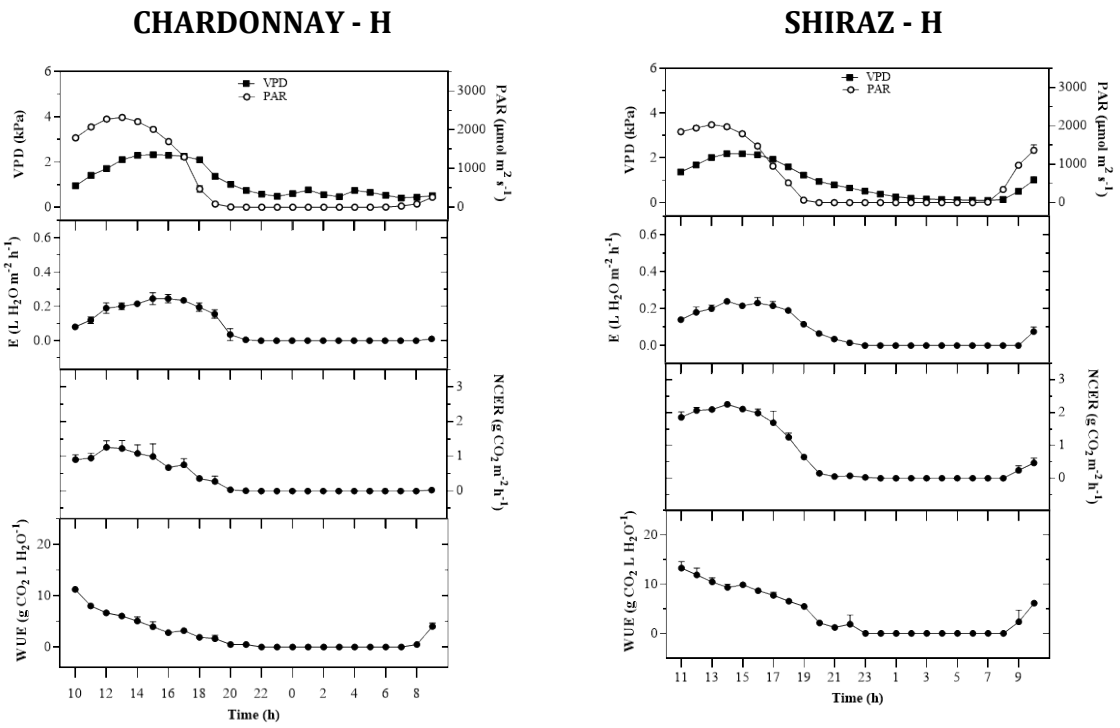
During the bunch closure stage, the highest values of VPD were found in the mid-afternoon (1300-1500 h) under warmer conditions with maximum VPD values exceeding 4 kPa. The highest canopy transpiration rates as measured by the chambers were in the order of 0.5 L m^{-2} h^{-1} while the canopy CO_2 assimilation rates peaked around 1.5 g CO_2 m^{-2} h^{-1}. The highest WUE was observed early in the day, around 1000 h, followed by a steady decrease as the VPD increased, possibly resulting from the rapidly increasing canopy E during the day until mid-afternoon.

Figure 11: Diurnal patterns of vapour pressure deficit (VPD, chamber interior) canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) during the veraison stage as measured on December 28, 2020 and January 6, 2021 for Shiraz.



Veraison in late-December to early January was the warmest period during the growing season with maximum VPD value reaching 3.8 kPa on December 28, 2020. The highest diurnal values of VPD were found in the early-afternoon (1300-1400 h) resulting in canopy transpiration rates of around 0.5 L m^{-2} h^{-1} and canopy CO_2 assimilation rates of around 2 g CO_2 m^{-2} h^{-1}. These values for Chardonnay were lower than earlier in the season (Table 2). In Shiraz, the maximum diurnal transpiration rates were similar to Chardonnay, however, peak NCER values were lower at around 1.5 g CO_2 m^{-2} h^{-1}. The highest WUE was observed in the mid-morning, around 0800 h for Chardonnay and 1000 h for Shiraz.

Figure 12: Diurnal patterns of vapour pressure deficit (VPD, chamber interior) canopy water use as measured by the whole canopy chambers (E), net canopy exchange rate of CO_2 (NCER), and canopy instantaneous water use efficiency (WUE) during the pre-harvest stage as measured on February 3, 2021 and March 14, 2021 for Shiraz.



By late season, approx. one week before commercial harvest, the VPD values peaked around 2 kPa in both cultivars. The highest diurnal values were found in the early-afternoon (1300-1500 h) resulting in canopy transpiration rates of around 0.25 L m^{-2} h^{-1} (in both cultivars) and canopy CO_2 assimilation rates of around 1.5 g CO_2 m^{-2} h^{-1} in Chardonnay and 2 g CO_2 m^{-2} h^{-1} in Shiraz. As during véraison, Chardonnay transpiration rates remained low compared to pre-veraison E measurements (Table 2). The highest WUE was observed in the mid-morning, around 1000-1100 h for both cultivars.

Comparing the canopy gas exchange metrics at different phenological stages, diurnal patterns did not vary drastically and were driven to a large degree by environmental conditions – VPD and incident radiation (PAR) – and to a degree by vine age and cultivar (Chardonnay having higher values early season while Shiraz being higher post-veraison).

6.4 Canopy size, light interception, daily water use and dry matter production

Integrated (daily) values of canopy size (leaf area), crop coefficient, and gas exchange are shown in Table 3 for the véraison and harvest phenological stages in 2019-20.

Table 3: Canopy size and performance metrics at véraison and harvest in 2019-20. Date of measurement is shown in parentheses below the phenological stage. Total leaf areas obtained destructively at harvest (see Materials and Methods for procedure, Sec. 5.3.2).

CULTIVAR/Parameter	Veraison	Harvest
CHARDONNAY	**(12.01.2020)**	**(03.02.2020)**
Total leaf area (m^2 $vine^{-1}$)	*	12.3 ± 0.9
Crop Factor (K_c)	0.86	0.87
E_{canopy} (L $vine^{-1}$ day^{-1})	30 ± 5.8	15 ± 2
$E_{nocturnal}$ (L $vine^{-1}$ day^{-1})	0.2 ± 0.1	0.4 ± 0.2
NCE_{canopy} (g CO_2 $vine^{-1}$ day^{-1})	347.6 ± 86.4	135.0 ± 27.0
WUE_{canopy} (g CO_2 L H_2O^{-1} day^{-1})	156.6 ± 11.3	189.7 ± 30.2
ET_c (L $vine^{-1}$ day^{-1})	42.7	24.9
Irrigation applied, Dec –Mar (L $vine^{-1}$ day^{-1})	23.7	
Total seasonal irrigation (ML ha^{-1})	7.5	
Yield (t ha^{-1})	18.5	
Crop WUE (t ML^{-1})	2.5	
SHIRAZ	**(01.01.2020)**	**(08.03.2020)**
Total leaf area (m^2 $vine^{-1}$)	*	8.7 ± 0.3
Crop Factor (K_c)	0.85	0.85
E_{canopy} (L $vine^{-1}$ day^{-1})	12.2 ± 1.6	17.3 ± 0.2
$E_{nocturnal}$ (L $vine^{-1}$ day^{-1})	0.1 ± 0.03	1.1 ± 0.02
NCE_{canopy} (g CO_2 $vine^{-1}$ day^{-1})	124 ± 10.8	83 ± 9.6
WUE_{canopy} (g CO_2 L H_2O^{-1} day^{-1})	154.3 ± 34.0	-22.4 ± 17.4
ET_c (L $vine^{-1}$ day^{-1})	35.6	28.5
Irrigation applied, Dec –Mar (L $vine^{-1}$ day^{-1})	20.5	
Total seasonal irrigation (ML ha^{-1})	6.5	
Yield (t ha^{-1})	20.0	
Crop WUE (t ML^{-1})	3.1	

* Data not collected

Canopy size, daily canopy water use, and dry matter production of Shiraz and Chardonnay during the véraison and harvest stages of the 2019-20 season is shown in Table 2. The average leaf area, measured destructively at the end of the season, of three Chardonnay vines was 12.3 m^2, while for Shiraz a lower average value of 8.7 m^2 was estimated. The crop coefficient or crop factor, which is proportional to the light interception of the canopy and leaf area, was stable between véraison and harvest for both cultivars, around 0.85-0.87.

The daily water use for Chardonnay at veraison was approx. 30 L $vine^{-1}$ day^{-1} (2.5 L m^{-2} day^{-1}), while at the pre-harvest stage, the value dropped to around 15 L $vine^{-1}$ day^{-1} (1.25 L m^{-2} day^{-1}). In Shiraz, there was less variation of daily canopy water use between the two phenological stages. The canopy water use at veraison was around 12 L $vine^{-1}$ day^{-1} (1.4 L m^{-2} day^{-1}), while at pre-harvest, the water use increased to around 17 L $vine^{-1}$ day^{-1} (1.9 L m^{-2} day^{-1}). Nocturnal transpiration was higher at pre-harvest than at véraison, around 0.4 L $vine^{-1}$ day^{-1} and 1.1 L vine-

^{1} day^{-1} in Chardonnay and Shiraz, respectively, reflecting the relatively warmer nights during this period. In a deficit irrigation study, nocturnal transpiration was observed only under well-watered and warm conditions (Pagay 2016). In comparison to the canopy E values, daily ET_c values on a per vine basis in the present study were higher in both cultivars and time points; for Chardonnay, ET_c was estimated at around 43 L vine^{-1} day^{-1} and 25 L vine^{-1} day^{-1} at véraison and harvest, respectively; for Shiraz, these values were 36 and 29 L vine^{-1} day^{-1}. This indicates that irrigations applied based on ET_c may be in excess of that used by the vines (as indicated by the lower E_{canopy} values), providing an opportunity for water savings by growers.

Daily cumulative CO_2 assimilation at veraison for Chardonnay vines was approx. 348 g CO_2 vine^{-1} day^{-1} (28 g CO_2 m^{-2} day^{-1}) while for Shiraz the value was much lower at 124 g CO_2 vine^{-1} day^{-1} (14 g CO_2 m^{-2} day^{-1}). The total dry matter production sharply decreased at the pre-harvest stage in both cultivars. In Chardonnay, the average value was 135 g CO_2 vine^{-1} day^{-1} (11 g CO_2 m^{-2} day^{-1}) while for Shiraz it averaged 83 g CO_2 vine^{-1} day^{-1} (9.5 g CO_2 m^{-2} day^{-1}).

Canopy WUE for Chardonnay was similar to Shiraz at véraison, around 154-157 g CO_2 L H_2O^{-1} day^{-1}, however diverged quite significantly at harvest. Chardonnay increased its WUE to approx. 190 g CO_2 L H_2O^{-1} day^{-1} while, significant dark respiraiton in Shiraz resulted in negative WUE values around -22 g CO_2 L H_2O^{-1} day^{-1}.

Actual irrigation applied over the season was approx. 7.5 and 6.5 ML ha^{-1} in Chardonnay and Shiraz, respectively, with average daily irrigation values between December and March of approx. 24 L vine^{-1} and 21 L vine^{-1}. As a fraction of this irrigation amount, E_{canopy} represented 127% of Chardonnay's irrigation and only 60% of Shiraz's irrigation by véraison, while by harvest, these values were around 63 and 84% of the total irrigation applied. In comparison, ET_c represented 180% of Chardonnay's and 174% of Shiraz's irrigation by véraison, and 105% and 139% by harvest. Finally, E_{canopy} represented 70% (CHA) and 34% (SHI) of ET_c at véraison, and approx. 60% of ET_c for both cultivars at harvest. With block level yields of 18.5 and 20.0 t ha^{-1}, the crop WUE equated to 2.5 and 3.1 t ML^{-1} in Chardonnay and Shiraz, respectively.

Integrated (daily) values of canopy size (leaf area), light interception, gas exchange and related transpiration rates from ET and sap flow sensors are shown in Table 4 for the various phenological stages in 2020-21.

Table 4: Canopy size and performance metrics at various phenological stages in 2020-21. Date of measurement is shown in parentheses below the phenological stage. Total leaf areas at each time point were estimates (see Materials and Methods for procedure, Sec. 5.3.2).

CULTIVAR/Parameter	Flowering	Bunch Closure	Veraison	Harvest	Post-harvest
CHARDONNAY	**(09.10.20)**	**(17.11.20)**	**(28.12.20)**	**(03.02.21)**	**(15.02.21)**
Total leaf area (m^2 $vine^{-1}$)	5.1 ± 0.2	15.6 ± 0.6	16.8 ± 0.6	17.9 ± 0.7	*
Leaf Area Index (m^2 m^{-2})	4.7 ± 0.9	9.4 ± 1	9.3 ± 1.1	8.9 ± 0.2	*
Canopy porosity (%)	8.7 ± 2.2	2.5 ± 1.1	4.7 ± 4.2	1.3 ± 0.4	*
Crop Factor (K_c)	0.7	0.8	0.8	0.8	0.7
E_{canopy} (L $vine^{-1}$ day^{-1})	25.7 ± 3	33.6 ± 2.2	38.7 ± 0.6	35.1 ± 0.5	*
$E_{nocturnal}$ (L $vine^{-1}$ day^{-1})	*	*	1.2 ± 0.3	0.7 ± 0.7	*
NCE_{canopy} (g CO_2 $vine^{-1}$ day^{-1})	103.9 ± 10.3	154.5 ± 14.3	238.1 ± 0.5	155.8 ± 16.9	*
WUE_{canopy} (g CO_2 L H_2O^{-1} day^{-1})	33.3 ± 1.3	54.5 ± 2.9	83.2 ± 2	55.8 ± 0.7	*
ET_c (L $vine^{-1}$ day^{-1})	16.1	30.7	33.7	25.9	25.6
E_{SF} (L $vine^{-1}$ day^{-1})	8.5 ± 2.7	37.4 ± 6.4	36.7 ± 3.4	41.0 ± 5.1	29.6 ± 4.7
Irrigation applied (L $vine^{-1}$ day^{-1})	9.1	10.7	22.0	21.5	21.5
Total seasonal irrigation (ML ha^{-1})			6.21		
Yield (t ha^{-1})			31		
Yield (kg $vine^{-1}$)			17.0		
Crop WUE (t ML^{-1})			5.0		
SHIRAZ	**(20.10.20)**	**(24.11.20)**	**(06.01.21)**	**(14.03.21)**	**(11.04.21)**
Total leaf area (m^2 $vine^{-1}$)	6.9 ± 0.3	14.4 ± 0.5	16.5 ± 0.6	16.7 ± 0.7	*
Leaf Area Index (m^2 m^{-2})	3.6 ± 0.6	9.3 ± 0.7	8.4 ± 0.6	7.7 ± 0.7	*
Canopy porosity (%)	7.1 ± 1.7	1.3 ± 0.3	3.7 ± 1.9	1 ± 0.3	*
Crop Factor (K_c)	0.7	0.8	0.8	0.8	0.7
E_{canopy} (L $vine^{-1}$ day^{-1})	23.5 ± 1	27.8 ± 2.2	32.7 ± 2.3	32.6 ± 1.5	*
$E_{nocturnal}$ (L $vine^{-1}$ day^{-1})	*	*	0.1 ± 0.1	2 ± 0.7	*
NCE_{canopy} (g CO_2 $vine^{-1}$ day^{-1})	136.7 ± 15.2	137.1 ± 14.3	201.7 ± 17.7	283.7 ± 6.2	*
WUE_{canopy} (g CO_2 L H_2O^{-1} day^{-1})	110.2 ± 9.8	71.5 ± 5.5	100.1 ± 4.1	97 ± 0.4	*
ET_c (L $vine^{-1}$ day^{-1})	21.3	22.7	34.2	29.6	16.24
E_{SF} (L $vine^{-1}$ day^{-1})	34.8 ± 2.2	48.0 ± 1.5	58.3 ± 1.6	38.8 ± 1.4	22.5 ± 1.9
Irrigation applied (L $vine^{-1}$ day^{-1})	9.6	11.3	26.0	10.9	4.2
Total seasonal irrigation (ML ha^{-1})			6.56		
Yield (t ha^{-1})			27		
Yield (kg $vine^{-1}$)			14.8		
Crop WUE (t ML^{-1})			4.1		

* Data not collected.

Canopy size, daily canopy water use, and dry matter production of Shiraz and Chardonnay during various phenological stages of the 2020-21 season is shown in Table 4. The estimated average

leaf area increased from 5.1 to 17.9 m^2, while for Shiraz, it increased from 6.9 to 16.7 m^2. The crop coefficient or crop factor was relatively stable increasing from 0.7 at flowering to 0.8 by bunch closure. This indicated a rapid canopy development occurring early in the season prior to flowering. Light interception measurements indicated the LAI increased from 4.7 to 9.4 in Chardonnay, and 3.6 to 9.3 in Shiraz. The corresponding canopy porosity values, as measured in the bunch zone or lower cordon, were 8.7% at flowering decreasing to 1.3% by harvest for Chardonnay, and 7.1% at flowering decreasing to 1% by harvest for Shiraz.

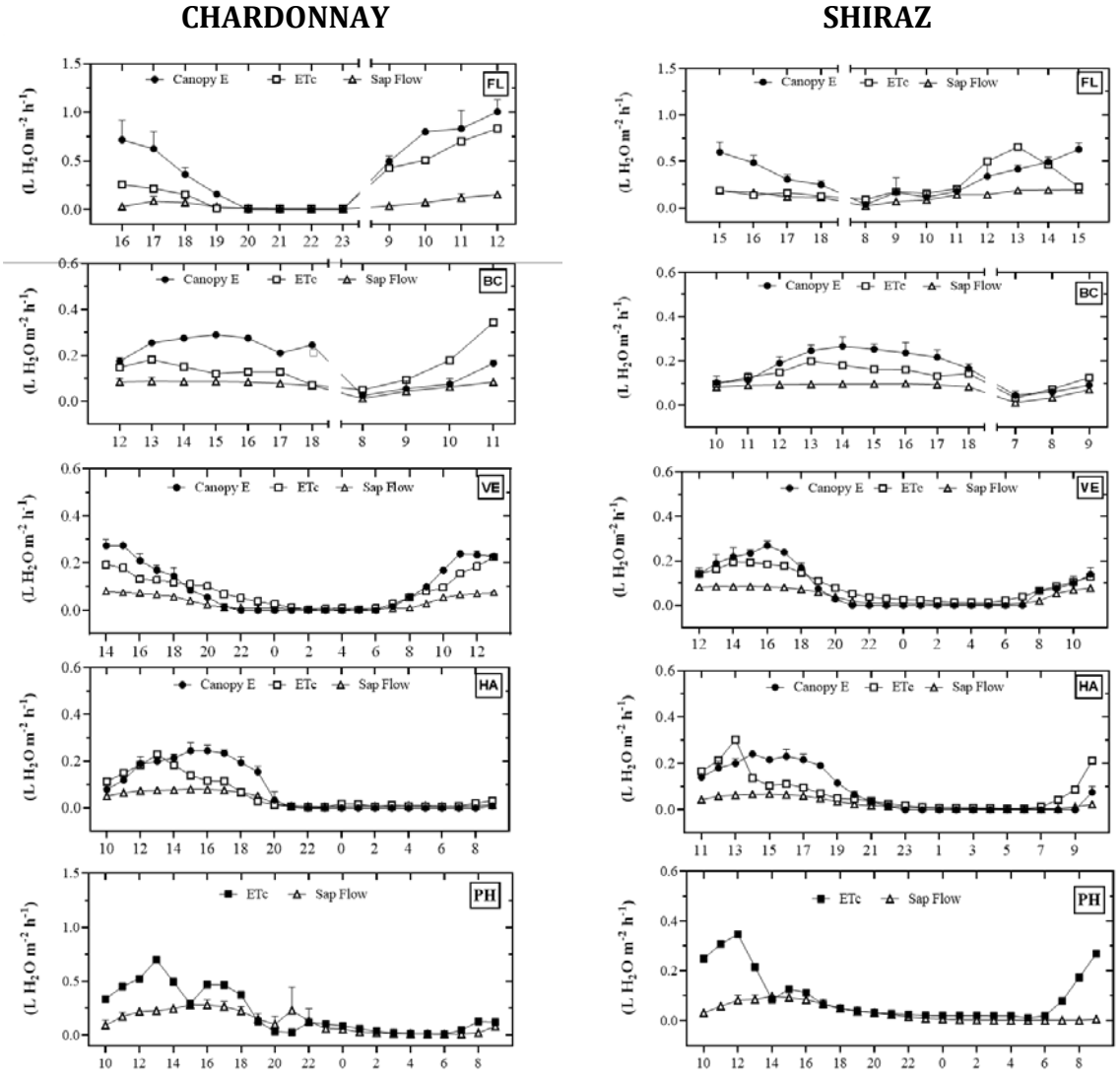
The daily water use for Chardonnay at flowering was approx. 26 L $vine^{-1}$ day^{-1} (5 L m^{-2} day^{-1}), increasing to nearly 39 L $vine^{-1}$ day^{-1} (2.3 L m^{-2} day^{-1}) by veraison. At the same time (véraison), nocturnal transpiration was minimal, around 1 L $vine^{-1}$ $night^{-1}$. Shiraz started the season with lower E_{canopy} values at 23 L $vine^{-1}$ day^{-1} (3.4 L m^{-2} day^{-1}), increasing to nearly 33 L $vine^{-1}$ day^{-1} (2 L m^{-2} day^{-1}). In comparison, for Chardonnay, ET_c values ranged from 16-34 L $vine^{-1}$ day^{-1} while corrected sap flow values ranged from approx. 9-41 L $vine^{-1}$ day^{-1}. In Shiraz, the early phenological stages had higher water demand than Chardonnay, with ET_c ranging from 21-34 L vine-1 dsay-1 and E_{sf} ranging from 35-58 L $vine^{-1}$ day^{-1}. Sap flow values ranged from 9-41 L $vine^{-1}$ day^{-1} in Chardonnay and 35-58 L $vine^{-1}$ day^{-1} in Shiraz. Irrigation applied was lower than all estimates of Chardonnay water use, but was better matched in Shiraz. Tempranillo grapevines in Southern Oregon (USA), a warm climate viticultural region, used approx. 22-28 L $vine^{-1}$ day^{-1} (3.2-4.0 L m^{-2} day^{-1}) under full irrigation (Pagay 2016). In the cool, humid region of Finger Lakes of New York (USA), Dragoni and colleagues reported Concord grapevines (*Vitis labruscana* Bailey) using between 15-40 L $vine^{-1}$ day^{-1} of water with hourly rates peaking at around 4 L $vine^{-1}$ (Dragoni et al. 2006), in the range found in the present study.

Overall, there appeared to be good agreement between the various methods of measurement of vine transpiration rates with the exception of the low E_{sf} values early in the season in Chardonnay. The water demand of vines in the present study was higher than the irrigation applied early in the season, while it was slightly lower during the mid- to late-season. The lower values suggest that some water was likely being drawn out of the soil reserves.

Canopy dry matter production in Chardonnay ranged from 104-238 g CO_2 $vine^{-1}$ day^{-1} while for Shiraz the range was 137-284 g CO_2 $vine^{-1}$ day^{-1}. The highest values were observed around véraison in Chardonnay and by harvest in Shiraz. These ranges for Shiraz were comparable to those reported in other studies on Tempranillo (Pagay 2016), and higher than values obtained under regulated deficit irrigation (60-70% ET_c) of Cabernet Sauvignon (Tarara et al. 2011). The highest canopy WUE values were observed early season, around flowering, as well as around véraison in both cultivars. Consistent with this observation, another study on Sangiovese grapevines in Italy observed that canopy WUE values were highest early in the season as well as early in the day, around 0600-0800 h, although these (potted) vines were subjected to water stress via deficit irrigation (Merli et al. 2015). Similar diurnal results were reported by Poni et al. (2014). Crop WUE, the ratio of yield to water applied, was 5.0 and 4.1 t ML^{-1} in Chardonnay and Shiraz, respectively.

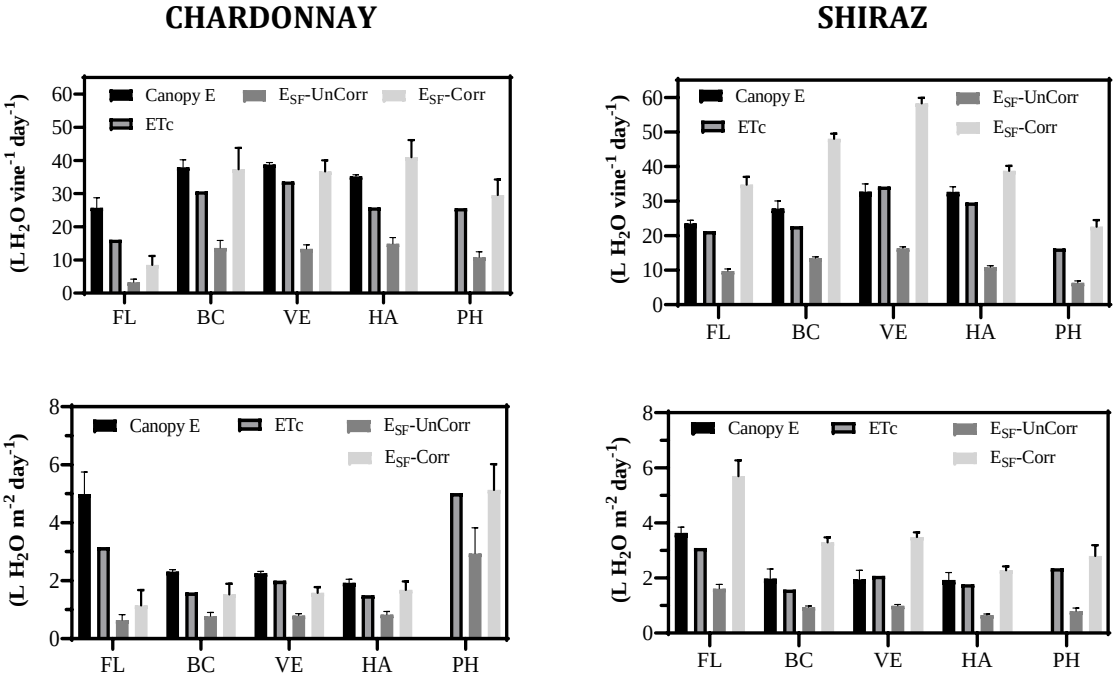
6.5 Comparison of techniques to quantify canopy transpiration

Figure 13: Diurnal and seasonal patterns of vine water use in 2020-21 measured with whole-canopy chambers (Canopy E), crop evapotranspiration (ET_c), and Implexx sap flow sensors (Sap Flow) at various phenological stages: FL=flowering; BC=bunch closure; VE=véraison; HA=pre-harvest; PH=one week post-harvest.



Diurnal and seasonal patterns of canopy transpiration rates as measured by the whole canopy chambers, ET_c, and sap flow sensors (E_{sf}) are shown in Figs. 13 and 14. Similar to the trend observed in the whole canopy transpiration measurements with the chambers, Chardonnay had the higher E_{sf} values early in the season until bunch closure compared to Shiraz, while Shiraz E_{sf} was higher following véraison. Chardonnay appeared to have a more rapid increase in transpiration rate early in the day compared to Shiraz even if maximum daily values were lower than Shiraz (later in the season). This has implications on canopy CO_2 assimilation and dry matter production. In both cultivars, peak E_{sf} values were observed in the early afternoon between 1200-1400 h. Somewhat surprisingly, there was no evidence of nocturnal transpiration in either cultivar at any of the phenological stages assessed in the present study, which was in contrast to the first season's data as well as findings by Pagay (2016) in Tempranillo grapevines under similar climatic conditions in Southern Oregon, USA.

Figure 14: Seasonal patterns of vine transpiration as measured by the whole canopy chambers, crop evapotranspiration (ET_c), and corrected (calibrated vs whole canopy chambers) and uncorrected (manufacturer/default calibration) sap flow sensor-based transpiration rates (E_{SF}) at various phenological stages: FL=flowering; BC=bunch closure; VE=véraison; HA=pre-harvest; PH=one week post-harvest. Values shown on a per vine basis as well as normalised based on vine size (per m^2 of leaf area). n=3.



A comparison of daily E values at various phenological stages over the growing season in 2020-21 using various methods is shown in Figure 14. In general, it was found that the whole canopy chambers tended to have the highest daily E values, around 25-38 L $vine^{-1}$ for Chardonnay and 23-32 L $vine^{-1}$ for Shiraz. Crop ET (ET_c) was slightly lower than E_{canopy} across most time points for Chardonnay, while in Shiraz the values were in better agreement with each other. In contrast, E_{sf} was considerably lower than both these E metrics by as much as ca. 80%. This discrepancy between E_{sf} and the other E measures needs to be investigated further as the sap flow sensors are apparently calibrated by the manufacturer (as reported on the manufacturer's website). We applied a second level of calibration to the sap flow sensors based on corresponding readings with the whole canopy chambers; results are shown in Fig. 14 as E_{SF}-Corr. The corrected values of E_{sf} had a far better agreement with both E_{canopy} and ET_c compared to the default calibration (E_{SF}-UnCorr). Results of this study indicate that, while diurnal patterns of E_{sf} match those of E_{canopy} and ET_c, further in-field calibration is required of individual sap flow sensors using independent methods such as those employed in this trial, e.g. whole canopy chambers, if absolute E_{sf} values are to be used for irrigation scheduling purposes. A similar calibration was done by other researchers in the Finger Lakes region of New York for estimation of canopy transpiration of Concord grapevines (*V. labruscana* Bailey) (Dragoni et al. 2006). This calibration procedure will minimise the risk of underestimating vine water use and, therefore, irrigation requirements that might lead to undesired vine water stress and consequent impacts thereof.

During the post-harvest period, due to (partial) defoliation by the grape harvester (during harvest), whole-canopy chambers were not employed, and E was estimated from ET_c and E_{sf} on days with similar VPD to the harvest dates. In Chardonnay, E_{sf} values during the post-harvest period were lower than the harvest period by approx. 10 L $vine^{-1}$ day^{-1}, while in Shiraz the post-harvest E_{sf} decreased by approx. 15 L $vine^{-1}$ day^{-1} compared to harvest. On a leaf area basis, Chardonnay leaves increased their transpiration rates nearly three-fold during the post-harvest period while Shiraz leaves maintained their transpiration rates.

6.6 Impact of heatwaves on canopy water use

Heatwaves are becoming regular weather events in inland regions of Australia, including the Riverland. To mitigate against negative effects on vine performance and fruit composition, growers apply additional irrigation applications prior to a heatwave. At this site, irrigation was increased by 50% starting the day preceding a heatwave period and applied each day of the heatwave. The standard irrigation amounts (non-heatwave conditions) between late December and late February were 6 mm day^{-1}, 5 days week^{-1} (33 L vine^{-1} day^{-1}; 165 L vine^{-1} week^{-1}), increasing to 6 mm day^{-1}, 7 days week^{-1} (231 L vine^{-1} week^{-1}) under heatwave conditions. This represents an additional water application of 66 L vine^{-1} week^{-1} (average 9.4 L vine^{-1} day^{-1}; 1.7 mm day^{-1}) during heatwaves. The additional irrigation did not alter soil moisture levels (Fig. 15).

We quantified the changes in vine transpiration rate (canopy water use) prior to, during, and following two heatwaves experienced in the post-veraison period of 2020-21 using sap flow sensors that were part of this trial. The sap flow sensors were calibrated using field measurements versus the whole canopy chambers to provide accurate values of absolute transpiration rates (E_{sf}) to avoid underestimation (uncalibrated E_{sf} values were approx. one-third the calibrated E_{sf} values; see Fig. 14). The environmental conditions and canopy water use during these periods are presented in Fig. 15.

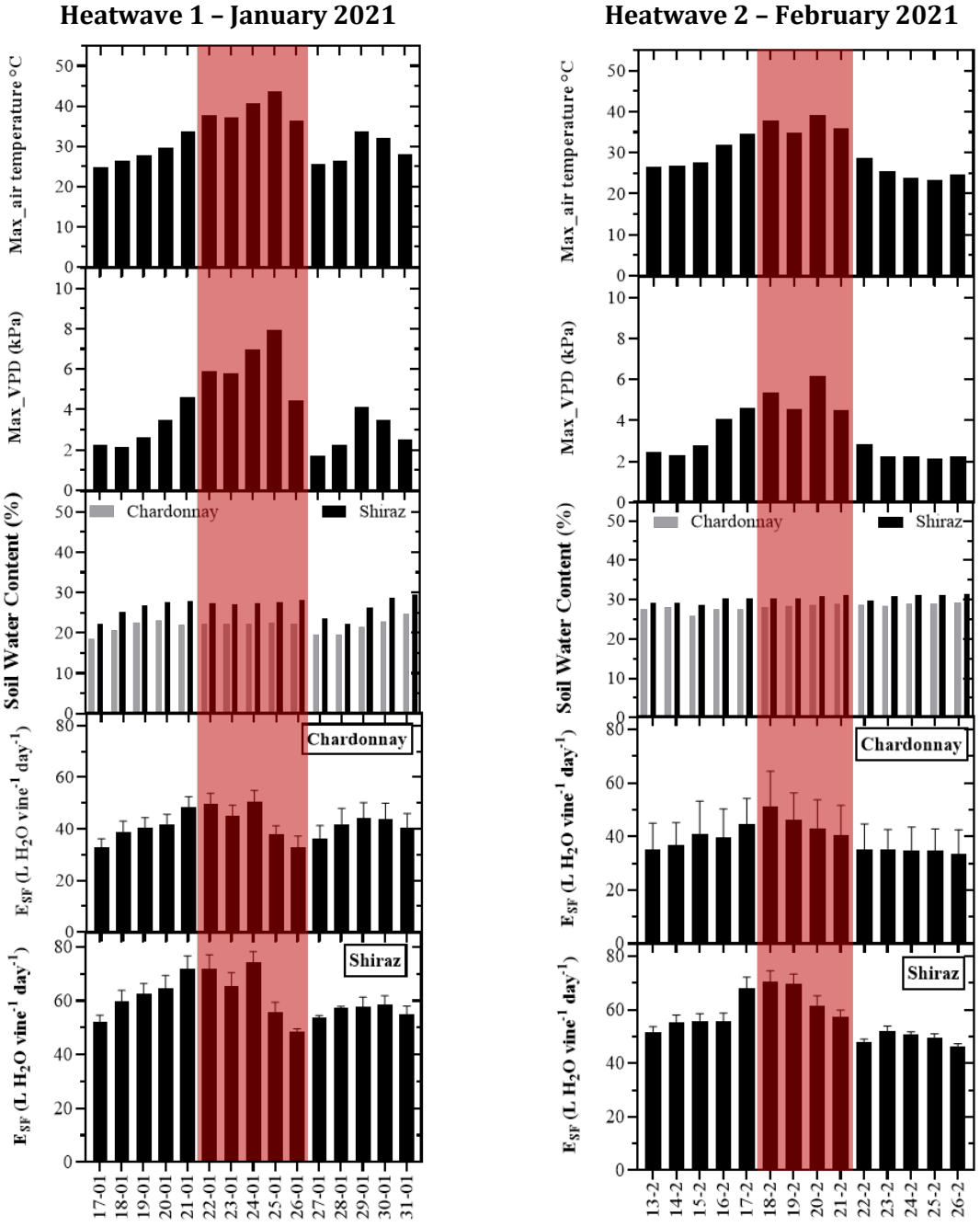
The two heatwaves experienced in January and February 2021 had four days with daily maximum ambient temperatures at or above 35 °C as measured at the on-site Qualco automatic weather station. The corresponding VPD values on the heatwave days exceeded 6 kPa, and reaching nearly 8 kPa during the late-January heatwave (Fig. 15). Canopy transpiration rates, as measured by the trunk-embedded sap flow sensors (calibrated using whole canopy chambers), increased by approx. 3 L vine^{-1} day^{-1} (7%) and 1 L vine^{-1} day^{-1} (2%) for Chardonnay and Shiraz, respectively, at the onset of the heatwave in January (Fig. 15; Table 5); in February, the increase was higher at 5.6 L vine^{-1} day^{-1} (14%) and 7.5 L vine^{-1} day^{-1} (13%) for Chardonnay and Shiraz, respectively. The more severe heatwave in late January had less of an effect on (increasing) canopy transpiration rates, possibly owing to a degree of stomatal closure despite the higher VPDs observed during that period compared to the mid-February heatwave.

Table 5: Environmental conditions, soil moisture, and average daily canopy transpiration (E_{sf}) as measured by sap flow sensors in Shiraz and Chardonnay grapevines around and during two heatwaves received post-veraison 2021. Sap flow rates (E_{sf}) were corrected using in-field calibrations vs whole-canopy chambers. The ΔE_{sf} (% change) values shown are relative to the pre-heatwave average E_{sf} values. E_{sf} shown as Mean ± SEM. n=3.

Period	Date range	Max. T_a (° C)	Max. VPD (kPa)	Avg. Soil Moisture Chardonnay (% VWC)	Avg. Soil Moisture Shiraz (% VWC)	Avg. ET_0 (mm day^{-1})	Chardonnay		Shiraz	
							E_{sf} (L day^{-1})	ΔE_{sf}* (%)	E_{sf} (L day^{-1})	ΔE_{sf}* (%)
Pre-heatwave	17/1-21/1	28.4	3	21.4	25.9	5.6	40.4 ± 1.3	--	62.2 ± 2.1	--
Heatwave	22/1-26/1	39	6.2	22.2	27.4	6.2	43.2 ± 1.9	7	63.2 ± 2.8	2
Post-heatwave	27/1- 31/1	29.1	2.8	21.6	26.1	5.3	41.3 ± 1.6	2	56.4 ± 1.0	-9
Pre-heatwave	13/2-17/2	29.4	3.2	27.4	29.6	5.2	39.6 ± 3.3	--	57.2 ± 1.7	--
Heatwave	18/2-21/2	36.9	5.1	28.4	30.7	6.3	45.2 ± 4.4	14	64.7 ± 2.1	13
Post-heatwave	22/2-26/2	25.2	2.3	28.7	30.8	4.7	34.9 ± 2.7	-12	49.3 ± 0.7	-14

* relative to the pre-heatwave period

Figure 15: Environmental conditions (T_a, VPD), soil moisture, and canopy water use (E_{sf}) around and during the first two heatwaves of 2021 estimated using sap flow sensors (E_{sf} values corrected using whole canopy chamber calibrations; Error bars are SEM) installed in Chardonnay and Shiraz grapevines. Shaded areas in red highlight heatwave days with maximum air temperatures (T_a) > 35 °C for three or more contiguous days. n=3.



The recovery in sap flow rate post-heatwave nearly complete in Chardonnay, but higher in Shiraz, with E_{sf} decreasing by 5.8 L vine^{-1} day^{-1} (9%) compared to the pre-heatwave condition in January. For the February heatwave, E_{sf} values decreased by 5-8 L vine^{-1} day^{-1} (12-14%) compared to pre-heatwave averages indicative of incomplete recovery in physiological condition and decreased canopy conductance (g_c). The cumulative effective of heatwaves may have resulted in more progressively more conservative g_c and consequently lower E_{sf} values when compared to the pre-heatwave period. These physiological changes to g_c are likely the result of internal regulation of stomata via both hydraulic (e.g. water potential, root and leaf aquaporins) and chemical (e.g. abscisic acid, root peptides) signals (Dayer et al. 2020, Rodrigues et al. 2008, Takahashi et al. 2018) even though these were not specifically measured in the present study.

A recent study undertaken in the Riverina region of Australia, with similar climatic conditions to the Riverland region, using the same sap flow sensors found that heatwaves had virtually no effect on canopy transpiration rates in four *Vitis vinifera* L. cultivars – Chardonnay, Merlot, Shiraz, and Cabernet Sauvignon (Forster and Englefield 2021). A plausible explanation for the contrasting results compared to the present study is that the Riverina study had warmer conditions leading up to the heatwave (T_a > 35 °C) whereas the present study had cooler conditions (25 °C < T_a < 30 °C) prior to the heatwave. Both vineyards had vines that were well-watered, i.e. non-water stressed, so water was not a limiting factor at either location.

Under well-watered conditions, increased canopy transpiration rates (E) are expected under higher VPD conditions, but these high E rates may result in transient water deficits in the rhizosphere (root-soil interface) resulting from the rapid depletion of plant available water in the soil and, consequently, vine water stress and lower g_c (Pagay et al. 2016). Heatwave conditions with higher VPDs would have also likely depleted water in the top horizons of the soil, and, in conjunction with the sandy soils of the Riverland, resulted in lower soil moisture availability to the vine despite the increased irrigation application the day before the heatwave commenced. In this study, the higher irrigation rate during heatwaves, approx. 6 mm day^{-1} (daily) nearly matched the reference ET (ET_0), approx. 6.2-6.3 mm day^{-1} (Table 5), and was higher than the crop ET (ET_c) of approx. 5 mm day^{-1} (based on a crop factor, K_c, of 0.8 measured at véraison). In comparison, vine water use, based on calibrated sap flow (E_{sf}), increased by approx. 0.5 mm day^{-1} for Chardonnay and approx. 0.2 mm day^{-1} for Shiraz during the late January heatwave (compared to their pre-heatwave values). This suggests that the additional irrigation of ~1.7 mm day^{-1} applied during heatwaves was not entirely utilised by the vine for transpirational cooling to reduce heat stress, and that some of the additional irrigation may have been lost through a combination of evaporation from the soil surface and deep percolation. It is also possible that a degree of stomatal closure during this hot period reduced water uptake rates such that some of the additional irrigation water remained in the rootzone. These losses would have been lower during the February heatwave in which E_{sf} values increased by 1.0 and 1.4 mm day^{-1} for Chardonnay and Shiraz, respectively, which was only slightly less than the extra irrigation applied (~1.7 mm day^{-1}).

The higher E observed during heatwaves (compared to the preceding cooler period) in the present study can be attributed to several factors: (i) adequate soil moisture *both* before and during the heatwaves; (ii) milder environmental conditions (relatively low ambient temperatures) leading up to the heatwave period, therefore lower physiological stress and potentially more open stomata (higher stomatal conductance, g_s) during the heatwaves; and, (iii) higher maximum daily VPD during the heatwave period compared to the preceding period. In a previous study on heatwaves in the same Riverland vineyard, we observed a 66% reduction of g_s, but a 50% increase in E, in Sauvignon blanc grapevines during heatwaves where daily max. T_a > 40 °C (Pagay 2018). This finding, in conjunction with observations of E in the present study, suggests that, under well-watered conditions, E is driven by VPD even under heatwave conditions and that a reduction in g_s (and g_c) does not necessarily decrease E due to higher VPDs typical of heatwave conditions. Under limiting soil moisture, however, this relationship might be altered as a strong water deficit-induced regulation (i.e. decrease) of g_s would likely decrease E.

7 Outcome / Conclusions

This is the first known study in Australia to develop and use whole-canopy chambers to continuously measure water use, dry matter production, and water use efficiency of field-grown grapevines. The system developed here allowed us to characterise the diurnal and seasonal patterns of gas exchange of mature Chardonnay and Shiraz grapevines in the warm-hot climate of the Riverland viticultural region of South Australia over two growing seasons, 2019-20 and 2020-21. In the second season, a financial contribution by Riverland Wine allowed us to purchase

and install six commercial sap flow sensors, one per vine or chamber, to compare their performance versus the chamber measurements as well as crop evapotranspiration.

Results of our study indicated that, during both seasons and at all phenological stages, both cultivars received adequate water based on the high values of soil moisture (> 20% VWC) and stem water potential (> -0.8 MPa). Diurnal patterns of gas exchange tended to follow that of solar (incident) radiation as well as VPD, with E_{canopy} values being higher early in the season for Chardonnay, and later in the season for Shiraz. As the season progressed, it was clear that, on a diurnal basis, the rate of increase of E in the morning slowed, likely owing to larger canopies as well as leaf age; the leaves were more efficient in transpiring water early in the season in both cultivars. This resulted in a higher dry matter production and WUE leading up to véraison, dropping after that time point. Canopy water use peaked at véraison at around 39 L vine^{-1} day^{-1} and 33 L vine^{-1} day^{-1} for Chardonnay and Shiraz, respectively. Across both cultivars, actual irrigation applied over the 2020-21 season averaged between 9-26 L vine^{-1} day^{-1}, which was lower than the water demand of the vines of between 21-39 L vine^{-1} day^{-1}. However, based on measurements of vine water status, there were no indications of water stress, suggesting that the vines had access to adequate soil moisture in the rootzone. Post-harvest water use dropped by one-third (compared to harvest) in both cultivars, however in Chardonnay, the leaves were transpiring at the same rate, indicating that a reduced leaf area and not transpiration was contributing to the reduction in water use. NCE values also peaked at véraison with both cultivars producing over 200 g vine^{-1} day^{-1} of dry matter, resulting in the highest water use efficiencies observed over the season during this time.

In comparing various methods of estimating canopy water use, all methods were relatively similar in their estimates of vine transpiration rates. ET_c tended to slightly underestimate vine water requirements compared to the whole-canopy and sap flow methods. ET_c was in better agreement with E_{canopy} (chamber data) in Shiraz than in Chardonnay, with only minimal discrepancies, indicating that it may be a reliable metric to guide irrigation scheduling (application rates). Uncorrected sap flow sensor values deviated further from the chambers, and E_{sf} values tended to be 50-80% lower than E_{canopy} at all timepoints of the growing season. This suggests that, although reportedly factory calibrated, these sap flow sensors require in-field calibration once installed in the vine, a procedure that has precedents in published studies. Once calibrated versus the chambers, the sap flow estimates were in close agreement with the chambers (E_{canopy}) and ET_c.

In the second season, access to sap flow sensors allowed for the characterisation of canopy water demand during heatwaves, which are becoming more frequent in many Australian viticultural regions. We found that heatwaves increased sap flow rates and canopy water requirements by 2-14% depending on the severity and frequency of the heatwave. With an increase in irrigation rate by 40% during heatwaves (avg. 30 mm week^{-1} increased to 42 mm week^{-1}), we estimated that only approx. half (or sometimes less) of the extra daily irrigation was being utilised by the vine for transpirational cooling. Therefore, there appears to be an opportunity to fine-tune irrigation rates based on environmental conditions during heatwaves in order to increase vineyard water use efficiency without imposing physiological stress on the vines.

8 Recommendations

This study provided, for the first time in Australian vineyards, quantitative estimates of grapevine water use based on both direct and indirect measurements. These estimates are critically important for growers seeking to optimise their irrigation practices, i.e. matching the water requirements of the vine with irrigation application volumes. Optimisation in this manner can result in increased water use efficiencies and thereby water savings without yield and grape quality penalties, and increasing the economic return for the grower. Our estimates of peak seasonal canopy water use of around 39 L vine^{-1} day^{-1} for Chardonnay and 33 L vine^{-1} day^{-1} for

Shiraz was generally higher than the ET_c estimates. Since water uptake rates are the highest early in the day, irrigations should be applied overnight, if possible, to ensure maximum soil moisture availability to the vine and to avoid transient vine water stress during this period. In order to increase water retention in the rootzone, vineyard floor management practices including use of undervine cover crops, mulches, and biochar should be considered. Sap flow sensors require in-field calibration to avoid under-estimation of canopy transpiration rates (water use).

Future studies in this area should include an extension to other commercially-important cultivars and regions, e.g. cool-climate regions, across Australia. Furthermore, with the advent of new plant-based sensors to optimise irrigation scheduling, the chambers built for this study could be used to quantify whole-vine water use under specific thresholds of vine water status to quantify changes in irrigation water use over the season. In premium vineyards, deficit irrigated vines could also be evaluated for their water use and productivity.

Appendix 1: Communication

The information from this trial has been featured or presented at the following sites and locations:

- Riverland Wine Technical Committee Meeting, Loxton, SA (14/08/2020)
- Yalumba Oxford Landing Viticulture Group, Qualco, SA (27/08/2020)
- 2021 American Society of Enology and Viticulture National Meeting (virtual), Irrigation Session (21/06/2021)
- One peer-reviewed manuscript currently in preparation for publication and another for an industry journal.
- Masters of Viticulture and Oenology Thesis of Hongkai Pei, The University of Adelaide (July 2020).

Appendix 2: Intellectual Property

There is no intellectual property arising from this study.

Appendix 3: References

Alleweldt, G., Eibach, R. and Ruhl, E. (1982) Investigations on gas exchange in grapevine. I. Influence of temperature, leaf age and time of day on net photosynthesis and transpiration. *Vitis* **21**, 93-100.

Ballester, C., Castel, J., Intrigliolo, D. S. and Castel, J. R. (2013) Response of Navel Lane Late citrus trees to regulated deficit irrigation: yield components and fruit composition. *Irrig. Sci.* **31**, 333-341.

Battany, M. (2012) *Using the Paso Panel to quickly measure the canopy shaded area and estimate vineyard irrigation crop coefficients*, Available: http://cesanluisobispo.ucanr.edu/Viticulture/Paso_Panel/.

Caspari, H. W., Neal, S. and Alspach, P. (2004) Partial rootzone drying - a new deficit irrigation strategy for apple? *Acta Hort.*, 93-100.

Chalmers, D. J., Burge, G., Jerie, P. H. and Mitchell, P. D. (1986) The mechanism of regulation of 'Bartlett' pear fruit and vegetative growth by irrigation withholding and regulated deficit irrigation. *J. Am. Soc. Hort. Sci.* **111**, 904-907.

Chalmers, D. J., Mitchell, P. D. and Heek, L. v. (1981) Control of peach tree growth and productivity by regulated water supply, tree density, and summer pruning. *J. Am. Soc. Hort. Sci.* **106**, 307-312.

Corelli-Grappadelli, L. and Magnanini, E. (1997) Whole-tree gas exchanges: can we do it cheaper? *Acta Hort.* **451**, 279-285.

Costa, J. M., Ortuno, M. F. and Chaves, M. M. (2007) Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. *J. Integr. Plant Biol.* **49**, 1421-1434.

Dayer, S., Scharwies, J. D., Ramesh, S. A., Sullivan, W., Doerflinger, F. C., Pagay, V. and Tyerman, S. D. (2020) Comparing Hydraulics Between Two Grapevine Cultivars Reveals Differences in Stomatal Regulation Under Water Stress and Exogenous ABA Applications. *Frontiers in Plant Science* **11**.

Doerflinger, F. C. and Pagay, V. (2018) Objective assessment of dried sultana grape quality using digital image analysis. *Australian Journal of Grape and Wine Research* **24**, 234-240.

Dragoni, D., Lakso, A. N., Piccioni, R. M. and Tarara, J. M. (2006) Transpiration of grapevines in the humid Northeastern United States. *Am. J. Enol. Vitic.* **57**, 460-467.

Fereres, E. and Soriano, M. A. (2007) Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **58**, 147-159.

Fernandez, J. E., Perez-Martin, A., Torres-Ruiz, J. M., Cuevas, M. V., Rodriguez-Dominguez, C. M., Elsayed-Farag, S., Morales-Sillero, A., Garcia, J. M., Hernandez-Santana, V. and Diaz-Espejo, A. (2013) A regulated deficit irrigation strategy for hedgerow olive orchards with high plant density. *Plant Soil* **372**, 279-295.

Flexas, J., Galmes, J., Galle, A., Gulias, J., Pou, A., Ribas-Carbo, M., Tomas, M. and Medrano, H. (2010) Improving water use efficiency in grapevines: potential physiological targets for biotechnological improvement. *Aust. J. Grape Wine Res.* **16**, 106-121.

Forster, M. A. (2019) The Dual Method Approach (DMA) Resolves Measurement Range Limitations of Heat Pulse Velocity Sap Flow Sensors. *Forests* **10**.

Forster, M. A. and Englefield, A. (2021) The water use and growth response of grapevines to extreme temperature events. *Theoretical and Experimental Plant Physiology*.

Garcia, R. L., Norman, J. M. and McDermitt, D. K. (1990) Measurements of canopy gas exchange using an open chamber system. *Remote Sens. Rev.* **5**, 141-162.

Gasque, M., Marti, P., Granero, B. and Gonzalez-Altozano, P. (2016) Effects of long-term summer deficit irrigation on 'Navelina' citrus trees. *Agr. Water Manage.* **169**, 140-147.

Greco, S. and Baldocchi, D. D. (1996) Seasonal variations of CO_2 and water vapour exchange rates over a temperate deciduous forest. *Glob. Change Biol.* **2**, 183-197.

Grijalva-Contreras, R. L., Macias-Duarte, R., Martinez-Diaz, G., Robles-Contreras, F., Valenzuela-Ruiz, M. d. J., Nunez-Ramirez, F. and de J. Valenzuela-Ruiz, M. (2013) Effect of regulated deficit irrigation on productivity, quality and water use in olive cv "Manzanilla". *Am. J. Plant Sci.* **4**, 109-113.

Heinicke, A. J. and Childers, N. F. (1937) Influence of respiration on the daily rate of photosynthesis of entire apple trees. *Proc. Am. Soc. Hort. Sci.* **34**, 142-4.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Kriedemann, P. E. (1968) Photosynthesis in vine leaves as a function of light intensity, temperature, and leaf age. *Vitis* **7**, 213-20.

Long, S. P., Farage, P. K. and Garcia, R. L. (1996) Measurement of leaf and canopy photosynthetic CO_2 exchange in the field. *J. Exp. Bot.* **47**, 1629-1642.

Loveys, B. R., M. Stoll, M. and Davies, W. J. (2004) Physiological approaches to enhance water use efficiency in agriculture: exploiting plant signalling in novel irrigation practice. in Bacon, M. A., (ed.) *Water use efficiency in plant biology*: CRC Press. pp. 327.

Medrano, H., Pou, A., Tomas, M., Martorell, S., Escalona, J. M., Flexas, J., Galmes, J., Ribas-Carbo, M. and Gulias, J. (2010) Water use efficiency improvement in grapevines under Mediterranean conditions. *Asp. Appl. Biol.*, 47-55.

Medrano, H., Tomas, M., Martorell, S., Escalona, J. M., Pou, A., Fuentes, S., Flexas, J. and Bota, J. (2015) Improving water use efficiency of vineyards in semi-arid regions. A review. *Agron. Sustain Dev.* **35**, 499-517.

Merli, M. C., Gatti, M., Galbignani, M., Bernizzoni, F., Magnanini, E. and Poni, S. (2015) Water use efficiency in Sangiovese grapes (*Vitis vinifera* L.) subjected to water stress before veraison: different levels of assessment lead to different conclusions. *Func. Plant Biol.* **42**, 198-208.

Mitchell, P. D. and Chalmers, D. J. (1982) The effect of reduced water supply on peach tree growth and yields. *J. Am. Soc. Hort. Sci.* **107**, 853-856.

Mitchell, P. D., Ende, B. v. d., Jerie, P. H., Chalmers, D. J. and Van den Ende, B. (1989) Responses of 'Bartlett' pear to withholding irrigation, regulated deficit irrigation, and tree spacing. *J. Am. Soc. Hort. Sci.* **114**, 15-19.

Pagay, V. (2016) Effects of irrigation regime on canopy water use and dry matter production of 'Tempranillo' grapevines in the semi-arid climate of Southern Oregon, USA. *Agr Water Manage* **178**, 271-280.

Pagay, V. (2018) *Using in-canopy misters to mitigate the negative effects of heatwaves in grapevines*. Final report to Wine Australia (Project UA 1502).

Pagay, V., Zufferey, V. and Lakso, A. N. (2016) The influence of water stress on grapevine (*Vitis vinifera* L.) shoots in a cool, humid climate: growth, gas exchange and hydraulics. *Funct. Plant Biol.* **43**, 827-837.

Pereira, L. S., Oweis, T. and Zairi, A. (2002) Irrigation management under water scarcity. *Agr. Water Manage.* **57**, 175-206.

Petrie, P. R., Trought, M. C. T. and Howell, G. S. (2000) Influence of leaf ageing, leaf area and crop load on photosynthesis, stomatal conductance and senescence of grapevine (*Vitis vinifera* L cv Pinot noir) leaves. *Vitis* **39**, 31-36.

Petrie, P. R., Trought, M. C. T., Howell, G. S., Buchan, G. D. and Palmer, J. W. (2009) Whole-canopy gas exchange and light interception of vertically trained *Vitis vinifera* L under direct and diffuse light. *Am. J. Enol. Vitic.* **60**, 173-182.

Poni, S., Magnanini, E. and Rebucci, B. (1997) An automated chamber system for measurements of whole-vine gas exchange. *HortSci.* **32**, 64-67.

Poni, S., Merli, M. C., Magnanini, E., Galbignani, M., Bernizzoni, F., Vercesi, A. and Gatti, M. (2014) An improved multichamber gas exchange system for determining whole-canopy water-use efficiency in grapevine. *Am. J. Enol. Vitic.* **65**, 268-276.

Reynolds, A. G., Lowrey, W. D., Tomek, L., Hakimi, J., Savigny, C. d. and de Savigny, C. (2007) Influence of irrigation on vine performance, fruit composition, and wine quality of Chardonnay in a cool, humid climate. *Am. J. Enol. Vitic.* **58**, 217-228.

Rodrigues, M. L., Santos, T. P., Rodrigues, A. P., de Souza, C. R., Lopes, C. M., Maroco, J. P., Pereira, J. S. and Chaves, M. M. (2008) Hydraulic and chemical signalling in the regulation of stomatal conductance and plant water use in field grapevines growing under deficit irrigation. *Functional Plant Biology* **35**, 565-579.

Romero, P., Fernandez-Fernandez, J. I. and Martinez-Cutillas, A. (2010) Physiological thresholds for efficient regulated deficit-irrigation management in winegrapes grown under semiarid conditions. *Am. J. Enol. Vitic.* **61**, 300-312.

Schultz, H. R. (1993) Photosynthesis of sun and shade leaves of field-grown grapevine (*Vitis vinifera* L) in relation to leaf age Suitability of the plastochron concept for the expression of physiological age. *Vitis* **32**, 197-205.

Takahashi, F., Suzuki, T., Osakabe, Y., Betsuyaku, S., Kondo, Y., Dohmae, N., Fukuda, H., Yamaguchi-Shinozaki, K. and Shinozaki, K. (2018) A small peptide modulates stomatal control via abscisic acid in long-distance signalling. *Nature* **556**, 235-+.

Tarara, J. M. and Pena, J. E. P. (2015) Moderate water stress from regulated deficit irrigation decreases transpiration similarly to net carbon exchange in grapevine canopies. *J. Am. Soc. Hortic. Sci.* **140**, 413-426.

Tarara, J. M., Pena, J. E. P., Keller, M., Schreiner, R. P. and Smithyman, R. P. (2011) Net carbon exchange in grapevine canopies responds rapidly to timing and extent of regulated deficit irrigation. *Funct. Plant Biol.* **38**, 386-400.

Tomas, M., Medrano, H., Escalona, J. M., Martorell, S., Pou, A., Ribas-Carbo, M. and Flexas, J. (2014) Variability of water use efficiency in grapevines. *Environ. Exp. Bot.* **103**, 148-157.

Yunusa, I. A. M., Lu, P., Eamus, D. and Walker, R. R. (2005) Matching irrigation to vine water-requirements: Limitations of using sap-flow technology for scheduling irrigation. *Proceedings of the International Symposium on Harnessing the Potential of Horticulture in the Asian-Pacific Region*, 165-171.

Zufferey, V., Murisier, F. and Schultz, H. R. (2000) A model analysis of the photosynthetic response of *Vitis vinifera* L cvs Riesling and Chasselas leaves in the field: I Interaction of age, light and temperature. *Vitis* **39**, 19-26.

Appendix 4: Staff

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