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ORIGINAL PAPER

Data-driven irrigation scheduling increases the crop water use efficiency of Cabernet Sauvignon grapevines

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Abstract

In the context of water management in agriculture, irrigation scheduling is critically important as it optimises water application to crops and can also target specific production goals. However, there is no consensus on the ideal irrigation scheduling strategy regarding crop water use efficiency (WUE_c). In a premium Cabernet Sauvignon vineyard in Coonawarra, South Australia, over three growing seasons, irrigation scheduling strategies based on experience or historical knowledge ('GROW' treatment) were compared to data-driven strategies including crop evapotranspiration, and plant and soil water status thresholds to evaluate their effects on leaf- and vine-level WUEs. A final treatment, GROW +, that doubled the GROW level of irrigation was also evaluated in the third season. The WUE metrics were determined at the leaf, vine, and fruit scales as intrinsic WUE (WUE_i), crop WUE (WUE_c), and carbon isotope ratio (δ^{13}C), respectively. Furthermore, the irrigation strategies were evaluated in the background of two contrasting soil types: Terra Rossa (light clay, well-drained) and Rendzina (heavier clay, poorly drained). Seasonal soil and vine water status, leaf gas exchange, and light interception were measured, and yield components and pruning weights were obtained following harvest. The amount of seasonal irrigation water based on the data-driven strategies was up to 65% lower across both soil types compared with the GROW or GROW + approaches. WUE_i and δ^{13}C were largely similar between treatments. However, for vines grown on Terra Rossa soil, little to no yield penalty was observed when data-driven irrigation scheduling was applied, in addition to increased WUE_c values of up to 41%. It can be concluded that irrigation scheduling decisions based on data were superior to the conventional irrigation scheduling method on account of reducing irrigation water volume and increasing WUE, particularly in Terra Rossa soils.

Introduction

Given the scarcity of freshwater resources coupled with the likelihood of a more variable climate in terms of drought and weather extremes (Dai 2011; Sharma et al. 2020), irrigation strategies that enhance water use efficiency (WUE) are critical for the long-term sustainability of irrigated agriculture. Irrigation scheduling involves both timing and volume of applied irrigation, is complex and often involves several strategies. For much of the Australian wine industry, irrigation other than rainfall, also referred to as 'supplemental irrigation', is considered necessary for sustainable production, with 91% of total vineyard plantings being irrigated in 2019–2020 (Australian Bureau of Statistics 2020). Scheduling methods that rely on experience/weather forecasts as well as tactile and visuals assessments are still a dominant approach for carrying out irrigation scheduling in Australian vineyards (Dixon 2021). However, techniques that rely on data-driven metrics (e.g., crop evapotranspiration and plant water status thresholds) have also been successful in scheduling irrigation and influencing WUE (Intrigliolo et al. 2016; Barbagallo et al. 2021).

WUE is defined as the ratio between carbon assimilated as plant biomass (or yield) and water consumption by the crop (Flexas et al. 2010; Hatfield and Dold 2019), and can be expressed and measured at leaf, fruit, plant or crop levels. Leaf WUE is defined using leaf-level metrics that rely on gas exchange measurements to determine intrinsic WUE (WUE_i) or instantaneous water use efficiency (WUE_{inst}) (Schultz and Stoll 2010). These leaf-level metrics relate

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leaf net photosynthesis (A_n) with either leaf stomatal conductance (g_s) or leaf transpiration rate (E) to define WUE_i (A_n/g_s) and WUE_{inst} (A_n/E) (Hatfield and Dold 2019). At the whole-vine or crop level, WUE_c refers to the amount of crop obtained (i.e., yield) per unit of water incident on the crop, including both rainfall and supplemental irrigation. It may also be expressed as irrigation water productivity (IWP), which typically refers to the ratio of yield and supplemental irrigation (Fernández et al. 2020). Another metric related to WUE uses carbon isotope discrimination ($\delta^{13}C$) to provide an integrated measure of seasonal water stress (Gaudillère et al. 2002; Bchir et al. 2016). Mild soil water deficits can improve WUE (Chaves et al. 2007), thus increases to WUE are generally observed when applying deficit irrigation (i.e., less than a crop's water requirement) (Chaves et al. 2007, 2010; Stoll et al. 2000). Irrigation scheduling can aid the implementation of deficit irrigation and has therefore been proposed as another means of improving WUE (Koech and Langat 2018).

Irrigation scheduling strategies can be broadly categorised as those based on (i) historical applications or experiential, (ii) evaporative demand (e.g., crop evapotranspiration, ETc), (iii) plant water status thresholds, and (iv) soil water thresholds. These strategies are briefly introduced below, but the interested reader is referred to an excellent review describing each of these approaches in detail (Rienth and Scholasch 2019). For many grape-growing regions in Australia, the most common irrigation scheduling tools are based on the interpretation of soil water availability. Their popularity is ascribed to the well-established relationship between vine physiological parameters and soil water availability (Centeno et al. 2010). Common soil water monitoring methods generally include various sensors and probes aimed at measuring volumetric water content (% VWC) or soil matric potential (Munoz-Carpena et al. 2004). However, despite their prevalence, an accurate measure of soil water is often limited by soil heterogeneity in addition to uncertain rooting depths and locations relative to the sensor (Lebon et al. 2003), both of which represent limitations to soil water-based irrigation scheduling.

In contrast, plant-based methods for irrigation scheduling are thought to take the whole soil–plant-atmosphere into account and have been suggested as the most direct way to measure plant water stress (Shackel 2011). There are several techniques for measuring plant water status as described by Fernández (2017), but for the most part, a degree of interpretation is required for a given species and cultivar (Collins and Loveys 2010). Despite the availability of several commercial plant-based sensors, a recent survey of Australian vineyards found that only approximately 5% employ plant water status sensors, and typically these are in vineyards greater than 100 ha in size (Nordestgaard 2019). Recent studies have confirmed stomatal conductance (g_s) as a highly sensitive indicator of water stress (Tuccio et al. 2019), as emphasised previously (Jones 2004). Canopy temperature has also been shown to be highly related to g_s due to the effect that stomatal aperture has on leaf temperature (Jones et al. 2002), and techniques such as infrared thermography enable canopy temperature to be accurately monitored at multiple points (Belfiore et al. 2019), improving the technique's commercial applicability. Alternatively, irrigation scheduling based on evaporative demand involves the systematic approach of determining a crop's water use (crop evapotranspiration, ETc) to dictate how much water needs to be replaced in a subsequent irrigation cycle (% ETc). One of the strengths of evapotranspiration-based scheduling is the ability to numerically determine how much water to apply based on the Penman–Monteith energy balance model (Allen et al. 1998). However, this methodology has limitations depending on the method and data used to calculate reference evapotranspiration (ET_0), in addition to obtaining and using accurate crop coefficients (k_c) (Gautam et al. 2021).

Although the aforementioned strategies have been used to schedule irrigation across a range of crops, the impact each of these strategies has on WUE is highly dependent on the specific thresholds used. The choice of threshold is influenced by a range of factors including crop growth stage (or phenology), production goals, cultivar traits, and environmental conditions. Considering that the effectiveness of commonly used decision metrics for irrigation scheduling can be impacted by a range of environmental, production, physiological, and operator-driven factors, it is difficult to compare different strategies based on published studies. To the best of our knowledge, these strategies have not been directly compared in a singular study in grapevine and with the specific goal of assessing their effects on WUE. Therefore, the primary aims of this study were to (i) compare grapevine leaf-, fruit- and crop-level WUE between data-driven irrigation scheduling methods and experiential approaches, and (ii) investigate the influence of soil type on vine performance and WUE responses under the chosen irrigation scheduling strategies. The findings from this study will identify irrigation scheduling practices that potentially enhance WUE in vineyards or other irrigated crops.

Material and methods

Field conditions, vineyard description and management

This research was carried out over three growing seasons (2018/2019; S1, 2019/2020; S2, 2020/2021; S3) in a commercial vineyard planted in 1988 in Coonawarra, South Australia (−37° 28′ 52″ S, 140° 83′ 00″ E). Coonawarra is described as having a Mediterranean climate characterised by high winter rainfall and comparatively drier summers (Longbottom et al. 2011), with an average annual precipitation of 559.8 mm (Australian Bureau of Meteorology 2022). Budburst in Coonawarra typically occurs in September, véraison in February, and harvest in April, with the specific details for phenological dates (observed during the trial) presented in Table S1. *Vitis vinifera* L. cv. Cabernet Sauvignon on Schwarzmann rootstock (*V. riparia* ×*V. rupestris*) was grown on two different soil types: Terra Rossa (TR) and Rendzina (RN), both of which are red-brown clay soils with varying depths of 0.3–1.5 m overlaying an impermeable limestone layer of approximately 2 m thickness (Longbottom et al. 2011). Soil analysis classified the TR soil as a clay loam with 25% clay, 56% sand and 19% silt, and the RN soil was identified as a silty clay with 40% clay, 33% sand and 27% silt. Vine rows were orientated east–west and had a row and vine spacing of 2.75 m and 2.2 m, respectively. Vines were spur pruned to two-node spurs with 5–6 spurs per linear metre of cordon and were trained according to a sprawl-type canopy. According to this canopy structure, shoots grow vertically early in the season and are allowed to sprawl after mid-season, thereby providing shade to the fruit. Canopy management followed the practices of the commercial vineyard and varied depending on the season, but generally included at least one pass of shoot trimming (average shoot length ~ 1 m) to minimise canopy vegetative growth. Nutrition and integrated pest management were applied as per regional convention. The vines were irrigated by surface drip irrigation (dripper flow rate of 1.6 L h^{-1}). Drippers were spaced approx. 0.75 m apart resulting in three drippers per vine.

Experimental design and irrigation treatments

The experiment was set up in a randomised incomplete block design where each treatment was replicated twice across four blocks in each soil type. Each block consisted of three rows, of which only the middle row was used for measurements; the neighbouring rows (two rows separated by each block) were maintained as buffers. Each treatment comprised eight contiguous vines of which the middle four were used as experimental vines. Irrigation treatments were defined by irrigation thresholds using a specific metric. Two different irrigation scheduling treatments were applied in the first season, 2018/2019: (1) irrigation decisions that were experiential or grower-driven (GROW); (2) decisions that were driven by plant water status (PWS) thresholds. The number of treatments was increased to four in the second season, to also include decisions based on crop evapotranspiration (ETc) and measurements of soil volumetric water content using soil water status (SWS) thresholds. Each of the data-driven treatments (PWS, ET and SWS) was also assessed in the third season; a description of specific metrics and their thresholds is provided below. Furthermore, the GROW treatment was replaced by the GROW + in the third season. The GROW + treatment used the same vines as the GROW treatment in S1 and S2, however, double the number of drip emitters were used to provide a well-watered condition (relative to the data-driven treatments).

The GROW and GROW + treatments were scheduled by the grower according to experiential or historical grower knowledge. Grower decision-making typically included the use of historical irrigation records, weather forecasts, and periodic visual assessments of vine water stress. The frequency and volume of irrigation varied from season to season and soil type, but typically ranged between 0.5–0.6 ML ha^{-1} in TR and 0.35–0.45 ML ha–^{1} in RN, with irrigation applied in 4–5 h cycles (generally during the evenings), with additional irrigation applied in advance of heatwaves (T_{max} > 40 °C). As is typical of this region, application of supplemental irrigation (including irrigation of the experimental vines) began around mid-to-late December each season, approximately between fruit-set and the pea-sized berry growth stage (E-L stage 27 and 31) (Dry and Coombe 2004). The initiation of irrigation was the same for each treatment. The ET treatment included a weekly calculation of ETc. The single k_c approach was used to estimate ETc, with k_c values derived from measurements of intercepted light beneath the canopy (Williams and Ayars 2005). The k_c values were calculated according to the phenological stage each season (Table S2), and ET_0 was calculated using the Penman–Monteith equation (Allen et al. 1998). The climatic variables required for the equation were obtained from a nearby weather station located 150 m from the trial site (Bureau of Meteorology weather station, Coonawarra, station ID 026091). The PWS treatment was based on measurements of g_s carried out with a portable infrared gas analyser (LI-6400XT; LI-COR, Inc., Lincoln, Nebraska USA) in the first season (2018/2019) and proximal (infrared) canopy temperature sensors ('Transp-IR' v.1, Athena IR-Tech, Adelaide, South Australia) in the second and third seasons (2019/2020 and 2020/2021). One Transp-IR sensor was placed between the second and third vines in each PWS block. The sensors reported daily vine water index (VWI) values based on relationships between canopy temperature, vapour pressure deficit (VPD), and g_s (Pagay and Doerflinger 2023). The VWI was calculated daily on a Cloud-based server (Amazon Web Services, WA, USA) and remotely accessible. Lastly, vines in the SWS treatment were irrigated according to measurements of % VWC from capacitance-based soil water sensors (Teros 12, Meter Group, Pullman, USA), with one sensor per SWS treatment (one sensor per two blocks). The sensors were situated approx. 30 cm from the trunk in the vine row (approx. midway between two drip emitters) and approx. 30 cm below the surface. Hourly data from these sensors was remotely accessible via a Cloud-based platform (Greenbrain, Adelaide, South Australia).

For each data-driven treatment (ET, PWS, SWS), the decision to irrigate was triggered when a reference parameter (% ETc, g_s or VWI, % VWC) fell below-predetermined thresholds. The five-year average seasonal soil water content in this vineyard was approx. 32% and the SWS treatment imposed a 30% deficit on this historical value to establish the SWS threshold of 22%. This strategy was implemented via sustained deficit irrigation (SDI) (Fereres and Soriano 2007) from fruit set to harvest, consistent with premium Cabernet Sauvignon wine grape production in the region. ET and PWS thresholds were established using data from preliminary studies in the vineyard block during the 2017/2018 season. Target thresholds for the ET treatment were similarly based on an SDI approach; pea-sized berry to pre-harvest 25% ETc and increasing to 100% ETc approx. 2 weeks before harvest. PWS thresholds were based on an empirical relationship between A_n and g_s that was established in a preliminary study in the same vineyard block during the 2017/18 season (Fig. S1). The optimum g_s to maximise WUE_i corresponded to approx. 75% to 85% of maximum A_n, which was found to be between g_s values of 120–150 mmol H_2O m^{-2} s^{-1}, depending on the season. Corresponding VWI values were used in the second and third seasons. This threshold was maintained from pea-sized berries to harvest.

Plant and soil water relations

Predawn leaf (Ψ_{PD}) and midday stem (Ψ_S) water potentials were used to assess soil and vine water status, respectively, throughout the season. Soil water content (% VWC) was also measured for vines as a part of the SWS treatment, however, these measurements were only used for the purposes of irrigation scheduling. In this trial, Ψ_{PD} was used as the main parameter to assess differences in soil water availability between irrigation treatments. Measurements of Ψ_S and Ψ_{PD} were made to coincide with major grapevine phenological stages using a Scholander-type pressure chamber (Model 1505, PMS instruments, Albany, NY, USA) (Scholander et al. 1965). There were two measurement points during the pre-véraison period and three measurement points during the post-véraison period (for a total of five measurement points across the season). To undertake Ψ_S readings, leaves were fully enclosed in an aluminium foil bag for at least one hour prior to measurements made at solar noon (11:00–14:00 h) (Choné et al. 2001). Measurements of Ψ_{PD} were made in the early morning on unbagged leaves between 03:00 and 05:00 h (Choné et al. 2001). For each vine (with a total of eight vines per treatment), one leaf was selected per each Ψ_S and Ψ_{PD} measurement. The chosen leaves were fully exposed, mature, and without obvious damage. Leaves were measured within a few seconds of excision.

Canopy light interception

Leaf area index (*LAI*) and canopy porosity (*t*) were measured during major phenological stages (pre- and post-véraison periods, as per measurements of plant and soil water relations) using an AccuPAR LP-80 Ceptometer (Meter Group, Pullman, USA). Canopy light interception was measured on both sides of the trunk, with the probe being placed horizontally next to each cordon, following measurements of the unobstructed sun made in the mid-row above the canopy. Fractional light interception (FiPAR) was calculated as the ratio of light interception to incident light as measured by the Ceptometer. The *LAI* and *t* were calculated automatically by the ceptometer. Light measurements were made between 11:00 and 13:00 h on clear sunny days.

Gas exchange

Gas exchange was measured on one leaf per vine and only included fully exposed, mature, and healthy leaves on the same shoot as leaves selected for Ψ_S measurements. The parameters A_n, g_s and E were measured at solar noon between 11:00 and 14:00 h on clear sunny days using an infrared gas exchange (LI-6400XT; LI-COR, Inc., Lincoln, Nebraska USA) equipped with a 6 cm^2 cuvette at ambient temperature. An external LED light source (LI-6400-02B) attached to the cuvette was used at a fixed photosynthetically active radiation value of 1500 μmol m^{-2} s^{-1}. Gas flow rate was 500 μmol m^{-2} s^{-1} and the reference CO_2 was 400 ppm. The sample relative humidity was maintained between 35 and 55% inside the cuvette.

Carbon isotope composition

Berries from four bunches (per vine) collected at harvest were hand-pressed and 40 mL of juice was immediately stored at − 18 °C for further compositional analysis. For carbon isotope analysis, frozen juice was defrosted at room temperature and centrifuged. Approximately 10 μL of clarified juice was transferred to pre-weighed tin capsules, re-weighed and placed in a − 20 °C freezer overnight before being freeze-dried for 24 h under vacuum (ScanVac CoolSafe, Adelab). The samples were re-weighed and analysed for $\delta^{13}C$ using a continuous flow isotope ratio mass spectrometer (Nu Horizon, Wrexham, UK) equipped with an elemental analyser (EA3000, EuroVector, Pavia, Italy). Stable isotope ratios were expressed in δ notation as deviations from a standard in parts per mil (‰):

$$\delta^{13}\mathrm{C} = \left[\left(R_{\mathrm{sample}}/R_{\mathrm{standard}}\right) - 1\right] \times 1000,$$

where R_{sample} is the ratio of abundance of $^{13}\mathrm{C}/^{12}\mathrm{C}$ in the sample, and R_{standard} is the $^{13}\mathrm{C}/^{12}\mathrm{C}$ ratio in the standard. $\delta^{13}\mathrm{C}$ was reported relative to the standard Vienna Pee Dee Belemnite (VPDB). All samples were corrected for instrument drift and normalised according to reference values using calibrated in-house standards ($n = 25$); glycine, − 31.2‰; glutamic acid, − 16.72‰; triphenylamine (TPA), − 29.2‰.

Yield components and pruning

Grape bunches were hand-harvested in line with commercial harvest dates in early April of all seasons (11th April 2019, 8th April 2020, and 14th April 2021). Yield components were measured at harvest for each experimental vine. Individual bunches were hand counted and 50 berries were randomly chosen and weighed to calculate the average berry weight. In conjunction with total yield, bunch number and average berry weight were also used to ascertain the average bunch weight and the average number of berries per bunch. Following leaf fall, all experimental vines were hand-pruned to two node spurs and the pruning weight of each experimental vine was obtained. The Ravaz Index was then calculated as the ratio of yield and pruning weight (Kliewer and Dokoozlian 2005).

Statistical analysis

Statistical analysis was carried out using R (version 4.2.0, R Core Team, Vienna, Austria). A three-way ANOVA was used to assess the combined influence of treatment, soil type, and season on WUE and yield components. A similar approach was used to investigate differences in vine physiology, however, using the factors of treatment, soil type, and phenological stage instead. As there were only two treatments in 2018/2019 (S1), an unpaired t test was used to assess differences between treatments within a single soil type, whereas Tukey's Honest Significant Difference (HSD) posthoc test ($\alpha = 0.05$) was used to assess differences between soil types. For data collected in 2019/2020 (S2) and 2020/2021 (S3), Tukey's HSD posthoc test ($\alpha = 0.05$) was also used to assess treatment differences, both within and between soil types. Additionally, both linear and non-linear regressions were used to assess the relationship between various parameters, and differences between soil types were means tested via the extra sum-of-squares F test to evaluate whether regression models were significantly different ($P < 0.05$) using GraphPad Prism software (version 9.0.0, GraphPad Software, San Diego, California).

Results

Environmental conditions and incident water

Both S1 and S2 had a similar water balance (ratio between ET_0 and growing season rainfall and irrigation), but S2 could be considered as slightly drier on account of lower winter rainfall preceding the growing season. Water received during the flowering period in S2 was also half that of S1. In contrast, S3 was largely characterised by milder conditions due to higher rainfall (up to 29% higher) and no heatwave events (Table 1). Data-driven irrigation treatments always received less irrigation compared with GROW and GROW + treatments throughout the trial (Table 2). In S1 and S2, these

Table 1 Summary of climatic conditions for each experimental season (2018/2019, 2019/2020 and 2020/2021)

		T_{max} [a] (°C)	VPD [a] (kPa)	R_s [a] ($\mathrm{MJ\ m^{-2}}$)	ET_0 [b] (mm)	Rain [b] (mm)	GDD [b]
2018/2019 (S1)	Budburst – Flowering	21.6	1.5	18.7	203	51	255
	Flowering – Fruit set	23.1	1.7	19.6	309	75	394
	Fruit set – Véraison	28.1	2.3	23.9	586	123	1031
	Véraison – Harvest	25.9	2.1	16.8	841	152	1472
2019/2020 (S2)	Budburst – Flowering	20.0	1.4	18.7	287	78	265
	Flowering – Fruit set	23.7	1.8	24.3	357	79	353
	Fruit set – Véraison	28.8	2.5	24.4	689	127	867
	Véraison – Harvest	23.6	1.6	17.3	966	167	1362
2020/2021 (S3)	Budburst – Flowering	20.7	1.4	18.9	259	94	296
	Flowering – Fruit set	24.2	1.9	23.4	335	120	369
	Fruit set – Véraison	25.6	1.8	23.0	680	191	941
	Véraison – Harvest	25.2	1.9	17.1	964	215	1432

T_{max} Maximum daily air temperature, *VPD* vapour pressure deficit, R_s solar radiation, ET_0 reference evapotranspiration, *GDD* growing degree days, base 10 °C are represented according to the major phenological stage

[a] Represented as mean values; [b] Represented as cumulative values

Table 2 Summary of rainfall and irrigation (total water received) according to the major phenological stage

			Rainfall and irrigation (mm)				Total water		Total supplemental irrigation	
			Budburst–Flowering	Flowering–Fruit set	Fruit set–Véraison	Véraison–Harvest	mm	$m^3\ ha^{-1}$	mm	$m^3\ ha^{-1}$
2018/2019 (S1)	TR	GROW	51.0	27.8	96.9	63.3	239.0	2115.0	87.0	595.0
		PWS	51.0	27.8	78.0	39.3	196.1	1817.5	44.1	297.5
	RN	GROW	51.0	24.0	81.9	56.9	213.8	1966.3	61.8	446.3
		PWS	51.0	24.0	62.9	35.5	173.4	1668.8	21.4	148.8
2019/2020 (S2)	TR	GROW	72.2	13.1	95.0	67.5	247.8	2222.1	80.8	550.1
		PWS	72.2	13.1	86.2	59.9	231.4	2110.4	64.4	438.3
		ET	72.2	13.1	86.2	54.9	226.4	2076.0	59.4	404.0
		SWS	72.2	13.1	95.0	65.0	245.3	2204.9	78.3	532.9
	RN	GROW	72.2	11.8	87.4	63.7	235.1	2136.1	68.1	464.1
		PWS	72.2	11.8	78.6	49.9	212.5	1981.4	45.5	309.4
		ET	72.2	11.8	78.6	54.9	217.5	2015.8	50.5	343.8
		SWS	72.2	11.8	87.4	49.8	221.2	2041.6	54.2	369.6
2020/2021 (S3)	TR	GROW +	93.6	26.2	159.3	84.5	363.6	3136.2	148.6	1014.2
		PWS	93.6	26.2	94.9	44.2	258.9	2422.8	43.9	300.8
		ET	93.6	26.2	86.1	39.1	245.0	2328.3	30.0	206.3
		SWS	93.6	26.2	96.2	49.2	265.2	2465.8	50.2	343.8
	RN	GROW +	93.6	26.2	126.4	71.9	318.1	2826.8	103.1	704.8
		PWS	93.6	26.2	78.6	47.9	246.3	2336.9	31.3	214.9
		ET	93.6	26.2	86.1	39.1	245.0	2328.3	30.0	206.3
		SWS	93.6	26.2	93.7	37.9	251.4	2371.2	36.4	249.3

Seasonal values for total water received and total supplemental irrigation for irrigation treatment treatments based on grower (GROW and GROW +), ETc (ET), plant (PWS), and soil (SWS) metrics are shown for each experimental season (2018/2019, 2019/2020 and 2020/2021)

decrements were between 3 and 49% for TR, and 33% and 65% for RN. In S3, data-driven treatments were compared with the GROW + treatment (double the amount of irrigation compared to GROW); consequently, comparative decreases in irrigation for data-driven treatments were larger (up to 80% in TR and 71% in RN). However, when considered in comparison with the non-intervention GROW treatment, supplemental irrigation amounts were still up to 60% and 41% lower for TR and RN, respectively (data not shown).

Soil and vine water status

Figure 1 shows mean values from measurements of water potential undertaken over the pre- and post-véraison periods. Three-way ANOVA showed there was a significant effect of the phenological stage on water potential across all seasons (Table S3). For all treatments in S1 and S2, post-véraison Ψ_{PD} values were lower compared with pre-véraison equivalents irrespective of soil type (Fig. 1). This same trend was also observed for Ψ_S values, apart from each of the GROW treatments in S1. For both S1 and S2, the lowest Ψ_{PD} value reached was -0.58 MPa (Fig. 1), observed for the PWS and SWS treatments in RN, respectively. In S3, the lowest reported minimum Ψ_{PD} value was -0.37 MPa observed for RN ET vines. In S1, TR PWS vines had lower post-véraison Ψ_S and Ψ_{PD} values compared with TR GROW, but only significantly differed based on Ψ_S values ($P < 0.0001$). For vines grown on RN soil, both Ψ_S and Ψ_{PD} were lower for PWS in comparison with GROW in S1. The effect of soil type was greater than the individual influence of treatment type in S2, particularly for values of Ψ_{PD} (Fig. 1I and J), where each of TR GROW, PWS, and SWS had higher pre-véraison Ψ_{PD} values compared with corresponding RN treatments. Post-véraison values were also lower for RN ET and SWS compared with TR in S2. In S3, both the ET and SWS treatment in RN had lower post-véraison Ψ_{PD} compared with the GROW + treatment (Fig. 1L). However, these same differences were not observed in TR during S3.

Leaf gas exchange

Trends in leaf gas exchange varied according to both season and soil type (Fig. 2). In S1, relative to GROW treatments, lower rates of post-véraison gas exchange were observed for each of the PWS treatments. Data-driven treatments (specifically PWS and SWS) were again observed to have lower

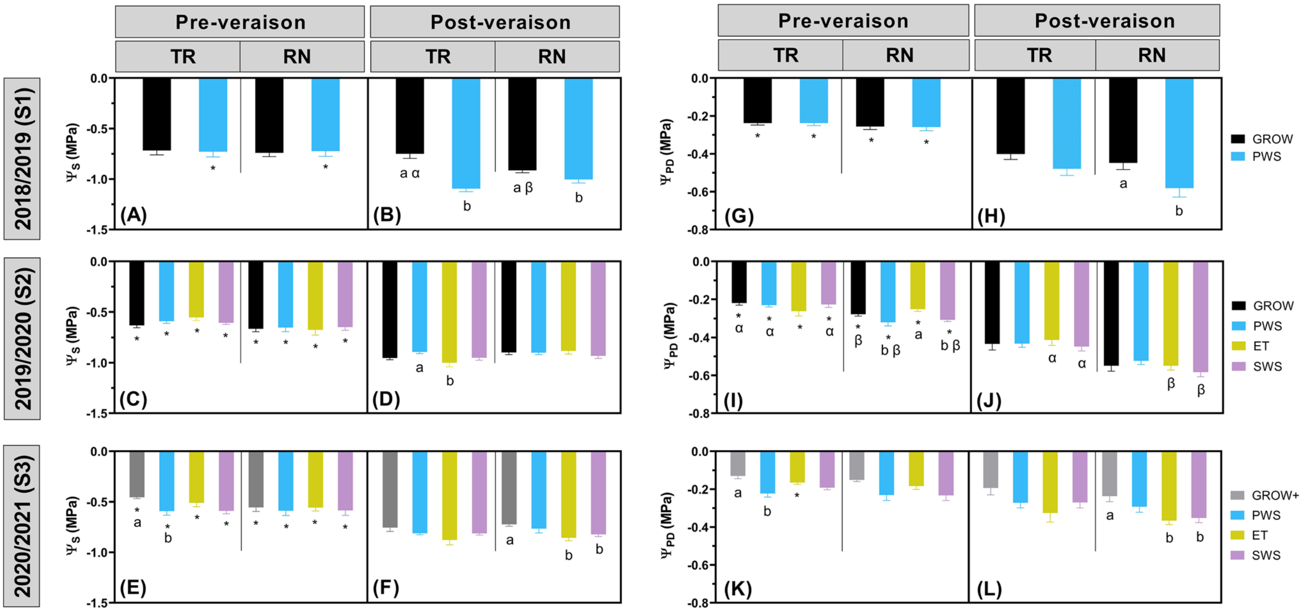

Fig. 1 Seasonal progression of predawn water potential (Ψ_{PD}) and midday stem water potential (Ψ_S). Means ± SEM are depicted according to pre- and post-véraison phenological stages. Tukey's HSD multiple comparison test ($\alpha = 0.05$) was used to assess differences between groups. Significant differences between treatments within the same vineyard and season are denoted by lowercase letters a and b, and significant differences between soil types (comparing the same treatment) are denoted by α and β. Significant differences between pre- and post-véraison values for the same treatment are denoted by a single asterisk (*) above the pre-véraison bar

rates of post-véraison gas exchange (compared to GROW) in RN S2, though this same trend was not observed for TR (Fig. 2). Concerning specific soil type comparisons in S2, pre-véraison g_s was higher for TR SWS (0.201 mol H_2O m^{-2} s^{-1}) compared with RN SWS (0.148 mol H_2O m^{-2} s^{-1}), with this trend also evident for *E* values. During post-véraison, TR PWS had higher g_s values compared with RN (0.097 mol H_2O m^{-2} s^{-1} and 0.063 mol H_2O m^{-2} s^{-1}, respectively), with similar trends also observed for *E* and A_n values. Out of all treatments in S3 TR, the GROW + treatment had the highest levels of post-véraison gas exchange. However, this difference was only significant when considering *E*. Additionally, in S3, RN PWS had similar post-véraison gas exchange values compared with RN GROW +, with each of these treatments also being shown to have either higher A_n or *E* in comparison with both RN ET and SWS (Fig. 2). When plotting leaf stomatal conductance (g_s) as a function of Ψ_{PD} (Fig. 3), regression models grouped by soil type were found to be significantly different from each other in both S1 and S2. These same trends were not observed in S3, however, when considering all seasons together, soil-type regression models were found to be significantly different from one another (Fig. 3D).

Yield components

Three-way ANOVA results showed a significant effect of soil type and season (simple main effects) on most yield components measured (Table 3). For vines grown on TR soil, yield and its components tended to be similar between treatments, whereas lower yield was obtained for the data-driven treatments in RN (compared with GROW and GROW +). No yield penalty was observed for TR PWS compared with TR GROW in S1 (Table 3). This contrasts with RN, where the PWS treatment was reported to have a lower yield compared with GROW ($P < 0.0001$). A lower yield was also observed for RN PWS compared with TR PWS ($P = 0.0332$). However, RN PWS was also noted to have a lower bunch count compared with RN GROW ($P = 0.0002$) and lower berries per bunch compared with TR PWS ($P = 0.0123$) in S1. In S2, RN GROW was again found to have a higher yield compared with RN PWS ($P = 0.0230$), in addition to a higher Ravaz Index ($P = 0.0462$) (though this trend was not reported in S3). TR SWS vines in S2 were associated with a higher yield (kg m^{-1}) in comparison with RN SWS ($P = 0.0340$), with this same trend observed for pruning weight ($P = 0.0019$) and bunch count ($P = 0.0489$). Considering average berry weight, soil type treatment differences were only found in S2, where each of GROW, SWS, and PWS treatments for RN had between 16 and 30% lower berry weights, with average bunch weight also being lower for RN PWS in comparison with TR PWS ($P = 0.0384$). When considering all seasons, there was a significant effect of season × soil type (interaction effect) on average berry weight (Table 3). In S3, RN ET vines had higher values for both berries per bunch and average bunch weight in comparison with RN SWS. The

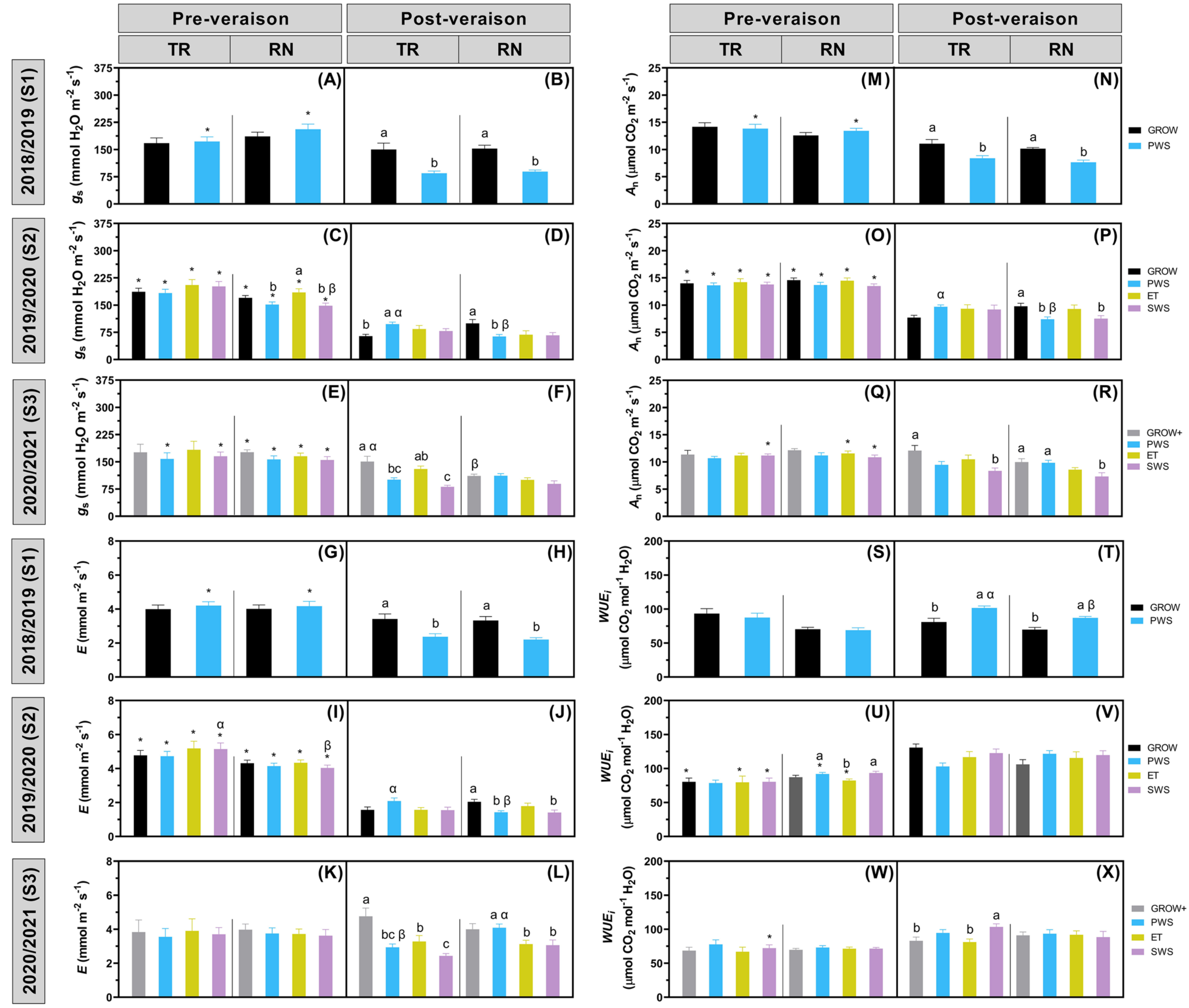

Fig. 2 Seasonal progression of leaf stomatal conductance (g_s), net photosynthesis (A_n), transpiration rate (E) and WUE_i (A_n/g_s) across each experimental season and soil type. Means ± SEM are depicted according to pre- and post-véraison phenological stages. Tukey's HSD multiple comparison test ($\alpha = 0.05$) was used to assess differences between groups. Significant differences between treatments within the same vineyard and season are denoted by lowercase letters a and b, and significant differences between soil types (comparing the same treatment) are denoted by α and β. Significant differences between pre- and post-véraison values for the same treatment are denoted by a single asterisk (*) above the pre-véraison bar

GROW + treatment was found to have significantly higher berry weight compared to the other data-driven treatments in S3 TR, though this same trend was not evident in RN. Yield and its components were also found to be largely similar across the two soil types in S3.

Water use efficiency

A significant seasonal effect (simple main effects) was shown for both seasonal WUE_i ($P < 0.0001$) and WUE_c metrics ($P < 0.0001$) (Table 4). This contrasts with δ^{13}C analysis, where treatment ($P = 0.0021$) and soil type ($P < 0.0001$) (simple main effects) were both shown to have a greater influence instead. In S1, TR PWS was associated with an increased seasonal WUE_i compared with TR GROW, though the difference was not statistically significant. By comparison, RN PWS vines had a higher seasonal WUE_i value than RN GROW ($P = 0.0176$) in this same time period, though a lower value of WUE_c ($P = 0.0422$). In S1, RN PWS had a lower seasonal WUE_i value in comparison with TR PWS. However, pairwise comparisons in S2 and S3 indicated similar WUE_i values between all treatments. There was a general trend of data-driven treatment vines having lower WUE_c in RN, while the reverse trend was typically noted for TR vines.

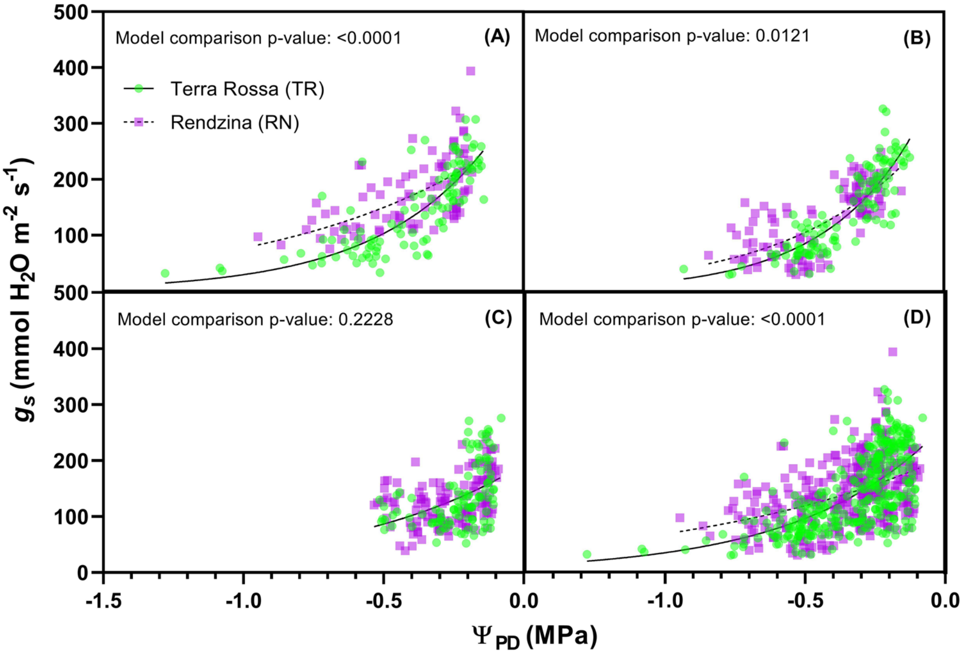

Fig. 3 Seasonal response of leaf stomatal conductance (*gs*) according to predawn water potential (Ψ_{PD}) with a comparison of regression lines for each soil type: panel A S1 (2018/2019), panel B (S2), panel C (S3), and panel D (all seasons). Soil-type regression models are compared within each panel using the extra sum-of-squares F test. Details for each regression lines are as follows: **A** S1 TR: $g_s=0.3589e^{2.503\Psi}{}_{\mathrm{PD}}$ ($r^2=0.66$), and S1 RN: $g_s=0.2893e^{1.323\Psi}{}_{\mathrm{PD}}$ ($r^2=0.32$), **B** S2 TR: $g_s=0.3971e^{3.095\Psi}{}_{\mathrm{PD}}$ ($r^2=0.73$), and S2 RN: $g_s=0.3128e^{2.193\Psi}{}_{\mathrm{PD}}$ ($r^2=0.55$), **C** S3 TR: $g_s=0.2168e^{2.145\Psi}{}_{\mathrm{PD}}$ ($r^2=0.22$), and S3 RN: $g_s=0.2893e^{1.323\Psi}{}_{\mathrm{PD}}$ ($r^2=0.19$), **D** TR: $g_s=0.3971e^{3.095\Psi}{}_{\mathrm{PD}}$ ($r^2=0.41$) and RN: $g_s=0.3128e^{2.193\Psi}{}_{\mathrm{PD}}$ ($r^2=0.20$)

Berry $\delta^{13}C$ was consistent between treatments across both soil types in S2. TR GROW + had lower $\delta^{13}C$ in comparison to the data-driven treatments in S3, though this same trend was not observed in RN. Soil types were also clearly grouped according to $\delta^{13}C$ values, with TR typically being associated with $\delta^{13}C$ values above − 26.0 ‰, while RN soils had values below − 27.1 ‰ (Table 4).

Discussion

In the context of climate change and decreasing freshwater availability for irrigated agriculture, increasing the sustainability of farm operations is critical for the continued longevity of production. In this sense, improving WUE is an important target for irrigated agriculture and the use of data-driven irrigation scheduling can provide growers with the means to target these types of improvements. In addition, data-driven irrigation scheduling is also important for effectively implementing precision irrigation strategies to combat vineyard spatial variability. Therefore, in this trial we aimed to evaluate whether data-driven irrigation scheduling can be used to improve WUE in comparison to standard irrigation practices in a premium Cabernet Sauvignon vineyard located in Coonawarra, South Australia. The study also assessed the effect that each of these strategies had on vine physiology and yield performance as a function of the different levels of water deficits imposed.

Climatic conditions and irrigation treatments

The climatic conditions observed in this trial were typical of the region, though each season varied in terms of overall water balance, with S3 having the highest rainfall (Tables 1 and 2). Growing season rainfall in S3 was slightly higher compared with long-term averages (approximately 187 mm) (Australian Bureau of Meterology 2022). There was a significant effect of the phenological stage on vine physiology parameters, with differences between treatments typically only reported during post-véraison. This is likely due to irrigation not being initiated until E-L stages 27–31 because of refilled soil profiles in the winter. Nonetheless, by post-véraison and irrespective of season, all treatments achieved a moderate level of vine water stress, defined as occurring between g_s of 50–150 mol H_2O m^{-2} s^{-1} (Medrano et al. 2002).

Table 3 Mean values for yield components are reported for each experimental season (2018/2019, 2019/2020 and 2020/2021)

	Treatment	S1		S2		S3		ANOVA				
		TR	RN	TR	RN	TR	RN	T	ST	S	T×ST	S×ST
Yield (kg m^{-1})	GROW	2.22	2.28 a	1.16	1.35 a	–	–	**	**	***	**	ns
	PWS	2.16 α	1.38 bβ	1.36	0.81 b	1.94 ab	1.60					
	ET	–	–	1.56	0.96 ab	1.80 ab	1.92					
	SWS	–	–	1.51 α	0.89 ab β	1.47 b	1.37					
	GROW +	–	–	–	–	2.66 a	2.12					
Bunch count (bunches m^{-1})	GROW	43.4	51.2 a	27.9	32.7	–	–	*	*	***	ns	ns
	PWS	41.3	34.4 b	30.8	25.3	42.2	34.8					
	ET	–	–	36.5	22.8	39.6	39.8					
	SWS	–	–	39.2 α	24.7 β	36.2	35.8					
	GROW +	–	–	–	–	49.2	52.1					
Berries per bunch	GROW	55.8	54.0	43.5	51.3	–	–	ns	*	***	ns	**
	PWS	60.1 α	47.8 β	46.1	43.3	53.3	44.1 ab					
	ET	–	–	44.9	46.9	51.9	49.6 a					
	SWS	–	–	41.2	45.1	49.0	41.0 b					
	GROW +	–	–	–	–	54.2	45.4 ab					
Average berry weight (g)	GROW	0.92	0.83	0.94	0.84	–	–	**	***	ns	ns	***
	PWS	0.86	0.85	1.00 α	0.78 β	0.88 b	0.97					
	ET	–	–	0.98	0.90	0.85 b	0.98					
	SWS	–	–	0.96 α	0.82 β	0.85 b	0.92					
	GROW +	–	–	–	–	0.98 a	1.02					
Average bunch weight (g)	GROW	51.1	44.6	41.0	41.6	–	–	*	***	***	*	ns
	PWS	51.9 α	40.7 β	46.3 α	32.6 β	46.8	42.6 ab					
	ET	–	–	44.3	42.0	44.5	48.5 a					
	SWS	–	–	39.2	36.2	41.5	37.4 b					
	GROW +	–	–	–	–	53.2	44.3 ab					
Pruning weight (kg m^{-1})	GROW	0.66	0.57	0.70	0.45	–	–	ns	***	**	ns	***
	PWS	0.67	0.46	0.84	0.56	0.51	0.42					
	ET	–	–	0.83	0.49	0.53	0.52					
	SWS	–	–	0.86 α	0.42 β	0.53	0.52					
	GROW +	–	–	–	–	0.55	0.64					
Ravaz Index (kg kg^{-1})	GROW	3.62	4.44	1.66	3.11 a	–	–	ns	ns	***	ns	ns
	PWS	3.26	3.74	1.73	1.57 b	3.77	3.52					
	ET	–	–	2.08	2.31 ab	3.52	3.92					
	SWS	–	–	1.90	2.18 ab	2.84	2.77					
	GROW +	–	–	–	–	4.62	3.65					

The results of a three-way ANOVA are also presented. However, the interaction between the factors of season × treatment and season × treatment × soil type are not reported, as neither of the interactions were found to have a significant influence on any yield component

Abbreviations are as follows treatment (T), soil type (ST) and season (S). Each season was treated as a separate data set for the application of Tukey's HSD multiple comparison test ($\alpha = 0.05$) and unpaired t-tests in S2. Significant differences for a particular component between treatments within the same vineyard and season are denoted by lowercase letters a and b, and between soil types for the same treatment are denoted by α and β. Significant differences between seasons are not reported. Levels of significance are as follows; < 0.001 (***), < 0.01 (**), < 0.05 (*), ns (> 0.05)

However, data-driven treatments tended to have lower post-véraison g_s values compared with their GROW/GROW + equivalents (Fig. 2), which was likely driven by the reduced watering demands of data-driven metrics in this trial.

Vine physiology, WUE and yield performance according to irrigation strategy

Similar to earlier studies investigating plant-based metrics to drive irrigation decisions, the decision to irrigate in this trial was triggered when a predetermined threshold was breached.

Table 4 Water use efficiency metrics for each experimental season (2018/2019, 2019/2020 and 2020/2021)

	Treatment	S1		S2		S3		ANOVA				
		TR	RN	TR	RN	TR	RN	T	ST	S	T×ST	S×ST
WUE_i (μmol CO_2 mol^{-1} H_2O)	GROW	88.0 α	70.1 b β	94.6	94.5	–	–	ns	ns	***	ns	***
	PWS	93.6 α	78.8 a β	88.4	103.8	87.6	84.3					
	ET	–	–	93.1	93.4	74.1	83.2					
	SWS	–	–	95.0	102.0	89.6	79.8					
	GROW +	–	–	–	–	76.5	81.3					
WUE_c (t ML^{-1})	GROW	3.4	3.8 a	1.7	2.0	–	–	ns	*	***	*	ns
	PWS	3.9	2.8 b	2.2	1.4	2.7	2.2					
	ET	–	–	2.6 α	1.6 β	2.8	2.7					
	SWS	–	–	2.2	1.5	1.9	2.0					
	GROW +	–	–	–	–	2.5	2.8					
$\delta^{13}C$ (‰)	GROW	–	–	− 26.1	− 27.4	–	–	**	***	ns	**	ns
	PWS	–	–	− 26.7	− 27.1	− 26.3 a	− 27.1					
	ET	–	–	− 26.0	− 27.3	− 26.1 a	− 27.6					
	SWS	–	–	− 26.1	− 27.3	− 26.0 a	− 26.5					
	GROW +	–	–	–	–	− 27.9 b	− 27.3					

WUE_i, $\delta^{13}C$, and WUE_c are represented as mean values. The results of a three-way ANOVA are also presented. However, the interaction between the factors of season × treatment and season × treatment × soil type are not reported, as neither interaction were found to be a significant influence on yield and its components

Abbreviations are as follows; treatment (T), soil type (ST) and season (S). *TR ET S2 $\delta^{13}C$ is only represented by two values. Each season was treated as a separate data set for the application of Tukey's HSD multiple comparison test ($\alpha = 0.05$) and unpaired *t* tests in S2. Significant differences between treatments within the same vineyard and season are denoted by lowercase letters *a* and *b*, and significant differences between soil types (comparing the same treatment) are denoted by α and β. However, significant differences between seasons are not reported. Levels of significance are as follows; < 0.001 (***), < 0.01 (**), < 0.05 (*), ns (> 0.05)

However, rather than using g_s as a scheduling metric, previous studies predominantly focused on using measures of water potential to delineate irrigation thresholds (Girona et al. 2006; Munitz et al. 2020; Barbagallo et al. 2021). For example, during pre- and post-véraison, Romero et al. (2010) proposed an optimum Ψ_S range between − 1.25 and − 1.4 MPa, to improve berry quality and WUE_i in Monastrell grapevines in Spain. Similarly, Acevedo-Opazo et al. (2010) reported that a Ψ_S threshold of − 1.2 MPa was most effective at maintaining a balance between yield and berry quality in Cabernet Sauvignon, with this threshold also maintained from fruit set to harvest. Within the conditions of the current experiment, pre-véraison water applications (including both irrigation and rainfall) prevented the PWS treatments from attaining the level of vine water stress considered optimum in the aforementioned studies. By comparison, post-véraison irrigation in the PWS treatment was associated with g_s values comparable to that of Romero et al. (2010), who found a g_s range targeting 65–75% max A_n to be optimal. Therefore, despite the initial threshold objective of this study (g_s range targeting 75–85% max A_n) not being met, the results of this trial still provided a measure of success when using this technique to schedule irrigation according to optimal g_s values.

Interestingly, the post-véraison Ψ_S values reported in Fig. 1 suggest that the vines were over-irrigated in the PWS treatment according to previously stated optimal thresholds, as average post-véraison Ψ_S did not drop below − 1.1 MPa. This is particularly noteworthy for RN PWS in S2, where a Ψ_S value of − 0.9 MPa was reported (Fig. 1D), despite a post-véraison g_s of 0.063 mol H_2O m^{-2} s^{-1} (Fig. 2D). These diverging results highlight an important area of consideration when using Ψ_S or g_s measurements to schedule irrigation, as the two parameters may not necessarily result in the same vine response, particularly when different cultivars or edaphoclimatic conditions are involved. This may lead to misinterpretation of Ψ_S values, potentially attributable to intrinsic cultivar differences in hydraulic/chemical regulation of g_s in response to soil water availability, commonly referred to as 'isohydricity' (Romero-Trigueros et al. 2021). Factors such as environmental conditions (e.g. soil type) during the growing season have also been proposed to influence isohydricity (Hochberg et al. 2018; García-Tejera et al. 2021). Tramontini et al. (2014) demonstrated this proposition when investigating the effects of drought on Cabernet Sauvignon planted on two different soil types ('water retaining' and 'water draining'). Their study found large variations in Ψ_S values across the two soil types despite similar values of g_s. These observations emphasise a need for further research into g_s-based thresholds for irrigation scheduling in different cultivars and regions. Nonetheless, irrigating based on proxy g_s measurements in the present trial (particularly for TR) gave yields (Table 3) that were comparable to those reported previously for Cabernet Sauvignon undergoing deficit irrigation (Acevedo-Opazo et al. 2010; Tarara et al. 2011; Intrigliolo et al. 2016; Keller et al. 2016). Small improvements to WUE_c (in comparison with GROW/GROW +) for vines grown on TR soil were also evident (Table 4).

Given that early-season rainfall is common in Coonawarra, actual soil water deficits were less than what was originally targeted for the ET treatment in the pre-véraison period for both S2 and S3 of the trial. These deficits corresponded to approximately 45% and 38% ETc for S2 and S3, respectively, whereas post-véraison deficits were approximately 24% and 18% ETc in S2 and S3, respectively, for TR ET. Deficits were similar for the RN ET treatment. Consequently, average Ψ_S values for the ET treatment were higher than what has previously been reported for 25% ETc treatments maintained from fruit-set/pea-sized berry to harvest (particularly in the pre-véraison period), with Keller et al. (2016) observing average Ψ_S values between − 1.13 and − 1.48 MPa from fruit-set to harvest across three seasons in Cabernet Sauvignon in Washington State (USA). Consistent with the lower Ψ_S, pre-véraison g_s was also reported to be lower in Keller et al. (2016), in addition to lower average berry weights. Similarly to Keller et al. (2016) and Torres et al. (2021) observed lower minimum Ψ_S values during the post-véraison period (compared to the present trial) for a similar 25% ETc irrigation treatment. In contrast, and despite a much more arid climate, water applied in a study by Tarara et al. (2011) for a late deficit ET-based treatment (70% ET_c from fruit set to véraison; 35% ETc from véraison to harvest, average total water incident equal to 246 mm) was similar to the current work (average total water incident of approx. 233 mm across both soil types), leading to similar pre-and post-véraison g_s values. Additionally, WUE_c values in Table 4 (average of 2.4 t ML^{-1}) were in line with those from Intrigliolo et al. (2016) who reported a value of 2.2 t ML^{-1} for a post-véraison 25% ETc treatment. In accordance with the results of Intrigliolo et al. (2016) and Tarara et al. (2011), the ET treatment in the current trial was found to be more similar to an ET-driven deficit in the post-véraison period, i.e., a regulated deficit irrigation (RDI) strategy, but not an SDI approach of maintaining 25% ETc from fruit-set to harvest. Taken together, the current results indicate that ET-based irrigation scheduling may not be suitable for vineyards where high winter and early season rainfall are common, due to a weaker control over soil water deficits compared to those in more arid climates. In comparison to both the ET and PWS treatments, irrigation scheduled by capacitance probe measurements was always higher (between 6 and 40%), indicating that thresholds were breached more frequently compared to both ET and PWS treatments. However, there were minimal differences in average berry weight between treatments, indicating a similar effect of irrigation.

WUE and the influence of soil type

In comparing each of the irrigation strategies investigated in this trial, significant differences in terms of both yield and WUE were rare for vines grown on TR soil. This indicates that the water received by each treatment was not large enough to cause significant differences and that the levels of soil water deficit applied were largely equivalent across treatments. As such, reduced irrigation through the data-driven approaches (particularly the ET and PWS treatments) was able to achieve similar yields as standard (GROW/GROW +) practices in the chosen vineyard, along with slightly improved WUE_c. A lack of statistical differences in WUE parameters between different irrigation scheduling treatments was also reported by Intrigliolo et al. (2016), who found rainfed, 25% ETc, and 50% ETc irrigated vines had similar WUE_c (though WUE_c improved as the deficit was increased). This is an interesting observation, considering the differences in irrigation between treatments in that study were much larger than in the present case. The only differences noted for TR (considering yield and WUE), were for yield, average berry weight and $\delta^{13}C$ in S3 (Tables 3 and 4, respectively). This result indicates that the doubling of irrigation had a marked influence on both average berry weight (and hence bunch weight) and $\delta^{13}C$, which is also reflected in higher post-véraison Ψ_{PD} and gas exchange values for GROW + (Figs. 1 and 2, respectively), despite it not translating to higher yield in two out of three data-driven treatments. Other WUE metrics were also typically lower for the GROW + (S3) and GROW treatments (S1 and S2).

The ramifications for applying data-driven irrigation scheduling for RN soil were less consistent, though similar to TR. WUE metrics (Table 4) would suggest statistically similar WUE between treatments, particularly $\delta^{13}C$ data. However, the increased irrigation received by the GROW/GROW + treatments consistently generated higher WUE_c in RN (through higher yields), whereas in TR, increased WUE_c values for data-driven irrigation treatments were the result of lower irrigation volumes that minimally affected yield (compared to GROW/GROW +). Differences in yield trends between the two soil types may potentially be attributed to differences in pre-véraison canopy architecture (Wang et al. 2019). Light measurement data suggested generally increased porosity and bunch zone light interception for TR vines in comparison with RN vines (Fig. S2). Declines in yield for data-driven RN treatments may also be the result of deficits being too severe (according to measurements of g_s), therefore negatively affecting yield. However, due to similarities in berry size and bunch weight, differences in yield (and hence WUE_c) for RN are likely to have also been driven by differences in bunch count. Bunch count has previously been shown to account for up to 60% of seasonal yield variation (Clingeleffer 2010), with this parameter largely determined by previous season growing conditions (e.g., temperature, light interception, nitrogen availability and at times, water stress) (Meneghetti et al. 2006; Guilpart et al. 2014).

The ET treatment provided the most consistent amounts of irrigation across both TR and RN with a maximum difference of 15% in irrigation volume between the two soil types across both seasons (Table 2). This could be anticipated, given that ET-based irrigation scheduling is based on reference ET (ET_0) and vine size, the latter related to leaf area and canopy light interception that determines the crop coefficient (k_c). According to k_c and LAI values, vines were a similar size across both soil types in S2 and S3 (Table S2 and Fig. S2). This contrasts with both TR PWS and SWS treatments. Each of these TR treatments were generally supplied with approx. one-third more supplemental irrigation than RN PWS and SWS vines each season. TR soils have previously been found to have both increased drainage and higher readily available water capacity compared with RN (Longbottom et al. 2011). These differences in soil textural properties are also reflected in the relationship between leaf-level gas exchange and soil water availability over the season as demonstrated by the positive curvilinear relationship between g_s and Ψ_{PD} (Fig. 3D). TR vines were more sensitive to declining soil water availability (Ψ_{PD}) with a faster reduction of g_s in comparison to vines grown on RN soil. This relationship was most prominent in the drier seasons of S1 and S2 (Fig. 3A and B), but was non-significant in S3, the mildest season (Fig. 3C). It is also noteworthy that Ψ_{PD} values extended below -0.5 MPa in S1 and S2, a range which has been associated with moderate to severe vine water stress (Van Leeuwen et al. 2009; Juan et al. 2020), whereas conditions in S3 were marked with high soil water availability according to Ψ_{PD}. This result indicated that differences in soil type potentially translate to vine water status/stress only under limiting soil water availability.

Differences in soil type have previously been shown to influence vine water status by influencing the vine or root water uptake, consequently affecting root development, canopy architecture, and leaf gas exchange (Gaudillère et al. 2002; Van Leeuwen et al. 2009; Tramontini et al. 2014; Bodin and Morlat 2006). More specifically, this influence of soil type on stomatal sensitivity to Ψ_{PD} has also been reported by Tramontini et al. (2013), although the differences between their soil types (> 60% clay soil versus gravelly soil) were more marked than considered here. Even so, a similar result was observed, with the value of g_s (for equivalent Ψ_{PD}) typically lower in the gravelly soil with a lower water holding capacity. It is, therefore, plausible that the inherent characteristics of TR soils (e.g., greater porosity, higher infiltration rate) heightened the stomatal sensitivity of those vines to changes in soil water availability compared with RN (Fig. 3), potentially contributing to the increased irrigation amounts reported for the TR PWS treatments (Table 2). Alternatively, as indicated by the soil water sensors in the SWS treatment, a much slower rate of water infiltration and drainage occurred in RN compared to TR, which would explain the lower requirement for irrigation to maintain % VWC close to the threshold range. When considering yield components, the influence of reduced irrigation for the RN SWS treatment was dependent on seasonality, particularly in relation to yield, berry weight, and pruning weight (Table 3). This is specifically reflected in S2 where each of these parameters was significantly lower (up to 50%) in RN SWS compared with TR SWS. These results are in contrast to S3 where both yield and pruning weights were equivalent across soil types, but berry weight was 7% higher for RN SWS in comparison with TR SWS. This data may indicate that during S2, the RN soil was not able to provide vines with adequate water supply due to lower plant available water, whereas in S3 the higher water holding capacity of this soil was bolstered by mild conditions, therefore, producing larger berries across all treatments. Similar trends were also observed for the PWS treatment across both soil types throughout the entirety of the trial.

Conclusion

Within the bounds of this experiment, carrying out irrigation scheduling using data-driven approaches was relatively easy to implement and was always associated with reduced water requirements in comparison with the vineyard's standard grower-conceived practices. However, the characteristically mild climatic conditions of the Coonawarra region resulted in few differences in vine physiology during the pre-véraison period, with greater control of imposed water deficits taking place in the post-véraison period instead. Data-driven irrigation scheduling generally resulted in improved WUE considering leaf-, fruit- and crop-level metrics in comparison with standard vineyard practices, though this needs to be interpreted within the context of soil type. This research also provided an example of using g_s-based measurements to direct irrigation requirements, although further research is required to assess a greater variety of thresholds in a range of cultivars. Future work could also investigate the use of g_s-based irrigation scheduling in combination with ETc for deriving irrigation volumes.

From a practical perspective, it can be recommended that irrigation scheduling for lighter, well-drained soils be carried out using data-driven methods to improve WUE_c. In heavier, poorly drained soils under dry conditions, it is suggested that applying deficit irrigation to the extent implemented in this study is not recommended to maintain WUE_c. This is due to the lower plant available water of such clay soils, which is exacerbated under dry conditions in comparison with lighter, well-drained soils. In this case, using sensors or probes that measure soil water tension (e.g., gypsum blocks or tensiometers) may offer advantages in heavier soils over the methods that were investigated, particularly when combined with other measurements such as g_s. Furthermore, differences in soil texture preclude the use of similar volumetric water content thresholds to direct irrigation across different soil types, as demonstrated in this study. Additionally, directing irrigation based on evaporative demand is not recommended for an SDI approach in cool climates due to early-season rainfall. However, using ET-based scheduling following an RDI regime that imposes late-season deficits may be a suitable alternative. Overall, there appeared to be promising benefits of adopting the data-driven approaches evaluated in this study, but other aspects such as economics, fruit and wine quality, and yield targets also need to be considered in further research designed to investigate an appropriate irrigation scheduling strategy.

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Author contributions VP conceived the project; RS, DG, CMK, and VP conducted the research; RS wrote the main manuscript text, did the data analysis, and prepared Figs. 1, 2 and 3; all authors reviewed and edited the manuscript.

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Data Availability The datasets generated during and/or analysed during the current study are available upon request from the corresponding author.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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