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*Research Article*

# Benchmarking Water-Limited Yield Potential and Yield Gaps of Shiraz in the Barossa and Eden Valleys

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*Background and Aims*. Vineyard performance is impacted by water availability including the amount and seasonality of rainfall, evapotranspiration, and irrigation volume. We benchmarked water-limited yield potential (Yw), calculated yield gaps as the difference between Yw and actual yield, and explored the underlying environmental and management causes of these gaps. *Methods and Results*. The yield and its components in two sections of 24 Shiraz vineyards were monitored during three vintages in the Barossa zone (GI). The frequency distribution of yield was L-shaped, with half the vineyards below 5.2 t·ha$^{-1}$, and an extended tail of the distribution that reached 24.9 t·ha$^{-1}$. The seasonal ratio of actual crop evapotranspiration and reference evapotranspiration was below 0.48 in 85% of cases, with a maximum of 0.65, highlighting a substantial water deficit in these vineyards. A boundary function relating actual yield and seasonal rainfall was fitted to quantify Yw. Yield gaps increased with an increasing vine water deficit, as quantified by the carbon isotope composition of the fruit. The yield gap was smaller with higher rainfall before budburst, putatively favouring early-season vegetative growth and allocation to reproduction, and with higher rainfall between flowering and veraison, putatively favouring fruit set and berry growth. The gap was larger with higher rainfall and lower radiation between budburst and flowering. The yield gap increased linearly with vine age between 6 and 33 yr at a rate of 0.3 t·ha$^{-1}$·yr$^{-1}$. The correlation between yield gap and yield components ranked bunch weight ≈ berries per bunch > bunch number > berry weight; the minimum to close the yield gap was 185,000 bunches ha$^{-1}$, 105 g bunch$^{-1}$, 108 berries bunch$^{-1}$, and 1.1 g berry$^{-1}$. *Conclusions*. Water deficit and vine age were major causes of yield gaps. Irrigation during winter and spring provides an opportunity to improve productivity. The cost of dealing with older, less productive vines needs to be weighed against the rate of increase in yield gap with vine age. *Significance of the Study*. A boundary function to estimate water-limited yield potential returned viticulturally meaningful yield gaps and highlighted potential targets to improve vineyard productivity.

## 1. Introduction

Mediterranean regions feature at least 60% of annual rainfall in the winter half-year [1]. The Barossa and Eden Valley regions, the focus of this study, have a Mediterranean-type climate where vine growth and yield rely on three sources of water: soil-stored winter rainfall, variable amounts of summer rainfall from the tails of tropical storms, and supplementary irrigation [2]. Climate change is placing increased stress on water resources and supports revisions of water management strategies and how they relate to vineyard productivity. First and most important, winter rainfall is diminishing in south-eastern Australia [3], and irrigation approaches are required to account for drier soil in spring [4]. Second, irrigation is also being increasingly used to promote evaporative cooling as the central component in the management of heat waves, which are increasing in frequency and intensity [5–7]. Third, decompressing harvest by canopy management is being used to displace critical developmental stages into cooler conditions and requires further adjustments in irrigation to account for shifts in the dynamics of canopy cover [8–12]. For example, the evapotranspiration of Malbec in Mendoza was 5% lower in vines pruned at 2-3 separated leaves and 10% lower in vines pruned at 8 separated leaves than in winter-pruned controls [13].

Production functions relating to crop yield and water use (or irrigation application) are critical for irrigation management [6]. These functions are usually tight, i.e., high $r^2$, because yield and water use are measured in experiments where water supply is the main source of variation and other factors are largely controlled [6]. In contrast, the association between yield and water use is scattered where multiple, agronomically relevant sources of variation influence crop traits; for rainfed wheat in Australia, for example, the relationship between yield and water use has a typical $r^2 \sim 0.3$ [14]. Dealing with a highly scattered yield-water use relationship, French and Schultz [15] insightfully fitted a boundary function with biophysically meaningful parameters, rather than a regression. Their boundary function is

$$\mathrm{Yw} = \mathrm{TE}_Y \cdot (\mathrm{ETc} - \mathrm{Es}), \tag{1}$$

where Yw is water-limited yield potential, ETc is actual crop evapotranspiration, the slope $\mathrm{TE}_Y$ is the maximum transpiration efficiency for yield, and the $x$-intercept Es is an approximate measure of nonproductive water loss, primarily soil evaporation. This model has many simplifications, including constant soil evaporation, a lack of consideration of the effect of timing of water supply on yield [15–17], and potential challenges in using this relation for irrigated vineyards where water stress is applied during certain developmental stages to increase quality at the expense of yield.

In a similarly simple, one-equation model, Rockström [16] relates ETc per unit yield and yield, hence accounting for the decline in Es: ETc with increasing crop vigour and yield:

$$\mathrm{ETc}\colon \text{yield} = \frac{a}{[1 - e(b \cdot \text{yield})]}, \tag{2}$$

where $a$ is the transpiration-to-yield ratio and $b$ is the rate of decline in soil evaporation (Es) with increased canopy size, and therefore also the yield at which Es:ETc reaches its minimum. This model has an element of circularity because yield is common to $x$ and $y$ [18]. In grapevine, both these models (equations (1) and (2)) further overlook yield response to water supply in the previous season, but so do the typical production functions that consider water use in the current season only [19] and more refined models of grapevine growth and yield Yang et al. [20] and references cited therein}. Likewise, these models ignore the effect of irrigation method, frequency, timing, and volume of water applied on the temporal pattern of soil evaporation under drip irrigation and their consequences on yield [21, 22].

Owing to its transparency and frugal data requirement, equation (1) has been widely adopted in the industry where rainfed cereal farmers relate their actual yield (Ya) to the water-limited yield potential, calculate a yield gap, i.e., Yw–Ya, identify its causes, and modify their practices to close the gap [14]. Sadras et al. [17] summarised four levels of yield including: (i) *theoretical yield*, defined as the maximum crop yield as determined by biophysical limits to key processes including biomass production and partitioning; (ii) *potential yield*, as the yield of a current cultivar when grown in environments to which it is adapted; with nutrients and water nonlimiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled; (iii) *water-limited yield potential* (Yw), as similar to yield potential, except that yield is also limited by water supply, and hence influenced by soil type (water holding capacity and rooting depth) and field topography; and (iv) *actual* (Ya) that reflects the current state of soils and climate, average skills of the farmers, and their average use of technology. The yield gap, its causes, and remedies have motivated a global yield gap initiative that accounts for data-rich and data-poor cropping systems (https://www.yieldgap.org/). Owing to carry-over effects across seasons affecting processes such as bud fertility that in turn drive bunch number and the dynamics of carbohydrate reserves buffering berry growth [23, 24], reliable models to predict yield are lagging in comparison with annual crops, and yield gap analysis is incipient for vineyards. For example, Yang et al. [20] modelled a single yield component, bunch weight, to calculate yield gaps in European wine regions under the explicit assumption of no variation in both plant population density and number of bunches per ha. From the more simplistic models that predicted dry matter accumulation and yield in stress-free conditions from plant and environmental parameters [25–27], modelling has advanced towards the soil-plant-atmosphere continuum under restrictive growing conditions. Daily time-step models accounting for crop, soil, climate, and management are favoured to estimate the water-limited yield potential [28], hence overcoming the limitations of simpler approaches [29]. Process-based models estimate yield under limiting growing conditions [30–33], closing the gap between the synthesis of knowledge and decision-making for vineyard management [34].

In this study, we benchmark the water-limited yield potential and calculate yield gaps (difference between potential and actual yields) of Shiraz in the Barossa and Eden Valley. We hypothesised a hierarchy of factors driving differences in productivity across these regions. By using a data set that captures viticulturally relevant sources of variation including weather, soil, vineyard age, and management across multiple seasons and vineyards, we expect to reveal, quantify, and rank the drivers of yield gaps in the region.

## 2. Methods

*2.1. Study Area and Experimental Sites.* This study was conducted in the Barossa Zone GI, which includes the Barossa and Eden Valley regions. The zone is internationally known for its full-bodied Shiraz wines. The complex system of valleys and twisting hills results in a variety of slopes, aspects, and sites [35]. The soils vary widely due to the complex geology of the region, but most of the soils primarily fall into a family of duplex soils, characterised by an abrupt texture change between the topsoil and subsoil [2]. Across the study sites, textural variations are common between the distinct demarcations of the soil profiles in the two horizons [36].

We measured yield and its components and calculated actual crop evapotranspiration in 144 samples that resulted from the full combination of six subregions, four commercial vineyards per subregion, two sections per vineyard, and three consecutive vintages since 2019. The subregions are Northern Grounds (NG), Central Grounds (CG), Eastern Edge (EE), Southern Grounds (SG), Western Ridge (WR), and Eden Valley (EV) [37]. To capture spatial variation on yield within each vineyard, low and high vigour zones were identified at the beginning of the experiment by k-means cluster analysis based on an electromagnetic (EM38) soil survey (completed on every row) and remotely sensed maps of vine canopy size (Plant Cell Density imagery at 40 cm resolution) at veraison, as described in Bramley et al. [38]. K-means clustering identifies zones through minimisation of the within-cluster variance and maximisation of the difference between cluster means [39]. Vineyard age, clone, rootstock, vine and row spacing, row orientation, pruning method, and trellising system were recorded [40]. All the vineyards were drip-irrigated, with dripper spacing and flow rates varying between vineyards. Across vineyards, dripper spacing ranged between 0.6 and 2 m and flow rates between 1.6 and 4 $l\,h^{-1}$. Growers in this study followed common irrigation practices across the region with supplementary irrigation applied mostly during ripening to maintain functional canopies and avoid premature leaf senescence, rather than earlier irrigation in order to promote yield [41]. Across the three seasons and 24 sites, irrigation averaged 160 mm with approximately half of this amount applied between veraison and harvest and less than 30% occurring before fruit set (Phogat et al. unpublished data).

*2.2. Vine Traits.* At harvest, the number of bunches and yield per metre of cordon were recorded and averaged from three sections within each sampling location (high and low vigour). We calculated the average bunch weight by dividing yield by bunch number and estimated the number of berries per bunch by dividing bunch weight by the average berry weight from a 100-berry sample. In winter, we counted the number of shoots, measured pruning weight in three one-meter canopy sections, and averaged the three sections within each sampling location. Yield, bunch number, shoot number, and pruning weight per ha were calculated based on the vine and row spacing.

To quantify crop water status, we measured carbon isotope composition ($\delta^{13}C$) in the must. This trait integrates crop water status over the growing period until sampling time and is robust in relation to the cumulative effect of environmental conditions—radiation, wind speed, temperature, vapour pressure deficit [42]—unlike traits such as stomatal conductance, leaf water potential, or canopy temperature that vary with conditions at sampling time. We measured $\delta^{13}C$ in 144 samples of must. Juice collected at harvest was centrifuged for 4 minutes at 4500 RPM, and 50 ml were sterilised the same day by autoclaving at 120°C for 20 minutes [43]. Carbon isotope composition was measured on approximately 10 μl of berry juice, freeze-dried in tin capsules (3 mg dried weight) using a continuous flow isotope ratio mass spectrometer (Nu Horizon IRMS with EuroVector EA, Wrexham, United Kingdom).

*2.3. Weather, Soil Moisture, and Water Balance.* Bonada et al. [40] describe in detail the measurements of weather components. An estimation of the components of soil water balance for the study sites is presented in Phogat et al. [44]. Briefly, 24 weather stations (MEA Junior WS, Measurement Engineering Australia, Magill, South Australia), one at each site, were installed at the beginning of the experiment to log temperature, relative humidity, wind speed and direction, solar radiation, and rainfall at 15-minutes intervals; daily reference evapotranspiration (ETo) was calculated with the method of Penman–Monteith [45]. Soil moisture was continually monitored at four depths using capacitance probes (EnviroSCAN system, Sentek, Magill, South Australia). In two sections of each vineyard, a PVC access tube was installed in the wetted area below the irrigation lateral and between drippers. For consistency, access tubes were installed approximately 15 cm away from a dripper, and the sensors were positioned at the same depths across the two sections at each vineyard. Data were logged every 15 minutes and retrieved from the logger at least monthly for processing using the IrriMax10 software (Sentek, Magill, South Australia). Details of probe calibration and calculations of plant available water are provided in Bonada et al. [40]. Crop evapotranspiration (ETc) and its components (transpiration, Tp; and evaporation, Es) were estimated using the FAO-56 dual-crop coefficient (FAO-56 DCC) approach [45] as described in Phogat et al. [44, 46]. The (FAO-56 DCC) approach is more suitable for drip-irrigated vineyards as it accounts for the fractions of vineyard floor wetted by the drippers and exposed to radiation [47].

*2.4. Statistical Analyses.* The analysis was constrained to 127 out of 144 paired yield-ET points due to missing samples of yield or ET components. We used an ANOVA to test the effect of the main sources of variation on yield, and its components, and other related traits. To explore associations between variables, we fitted least squares regression (LS, Model I) when error in $x$ was negligible in comparison to error in $y$ and reduced maximum axis regression (RMA, Model II) to account for error in both $x$ and $y$ [48]. Pearson's correlation coefficients ($r$) were calculated, with $p$ derived from a Fisher z-transformation that transforms the sampling distribution of $r$ for it to become normally distributed. For both ANOVA and regressions, we follow updated statistical recommendations and avoid the wording "statistically significant," "nonsignificant," or the variations thereof, thus avoiding dichotomisation based on an arbitrary discrete $p$ value [49]. Instead, we report $p$

as a continuous quantity, and the Shannon information transform [$s = -\log_2(p)$] as a measure of the information against the tested hypothesis [50]. Although $s$ is a function of $p$, the additional information is not redundant. With the base-2 log, the units for measuring this information are bits (binary digits). For example, the chance of seeing all heads in 4 tosses of a fair coin is $1/24 = 0.0625$. Thus, $p = 0.05$ conveys only $s = -\log_2(0.05) = 4.3$ bits of information, "which is hardly more surprising than seeing all heads in 4 fair tosses" [50].

Boundary functions were fitted using percentile regression to define the water-limited yield potential. Briefly, first, from the relationship between yield and rain resulting from the combination of vineyards, vineyard sections, and seasons, we divided the data set into six classes containing the same number of observations according to the cumulative distribution; second, we calculated the yield 95$^{th}$ percentile for each class and the average rainfall within the class; and third, we fitted a linear boundary function. Fourth, we used the fitted boundary function to calculate the water-limited yield potential. Finally, yield gaps were calculated as the difference between water-limited yield potential and actual yield; as outlined in Sadras et al. [17].

To explore the associations between yield gap and weather, location, vineyard features, and management, we used an ANOVA for discrete variables (e.g., trellising system) and regression for continuous variables (e.g., vine age).

## 3. Results

*3.1. Growing Conditions.* Weather during the growing season varied with location, vintage, and intraseasonally from budburst in spring to maturity in autumn (Figure 1). Minimum temperature varied 4.9-fold, vapour pressure deficit varied 4.3-fold, and maximum temperature and solar radiation varied 2.1-fold.

Plant-available water capacity of experimental soils was estimated by fixed and dynamic field capacity methods discussed in detail in Phogat et al. [36]. Plant available water in the soil at budburst ranged from 27 to 144 mm and averaged 91 mm with a coefficient of variation of 0.26. Rainfall was below reference evapotranspiration, particularly between flowering and veraison (Figures 1(d) and 1(e)). Seasonal irrigation varied from 0 to 335 mm and averaged 161 mm, with a coefficient of variation of 0.38. The seasonal ratio of actual crop evapotranspiration (accounting for plant available water in the soil at budburst, rainfall, and irrigation) and reference evapotranspiration was below 0.48 in 85% of cases, with a maximum of 0.65 (Figure 1(f)), highlighting the prevalence of a substantial water deficit in these vineyards. Carbon isotope composition, a trait that relates to plant water status, varied from −26.74 to −21.70‰ (Figure 1(g)).

*3.2. Yield and Its Components.* Yield averaged $3.7 \pm 0.37\,t{\cdot}ha^{-1}$ in 2020, $5.9 \pm 0.50\,t{\cdot}ha^{-1}$ in 2019, and $10.1 \pm 0.37\,t{\cdot}ha^{-1}$ in 2021. For the pooled data, the frequency distribution of yield was L-shaped (Figure 2(a)), with skewness and kurtosis departing from the normal distribution's zero and three, respectively [51]. Half the vineyards were below $5.2\,t{\cdot}ha^{-1}$, and the extended tail of the distribution reached $24.9\,t{\cdot}ha^{-1}$ (Figure 2). Yield correlated with all its components (Table 1); the strength of the correlation declined in the order of bunch number per ha, bunch weight, berries per bunch, and berry weight. Yield correlated with vegetative traits including pruning weight and shoot number (Table 1). Yield, its components, and vegetative traits all declined with a lower carbon isotope composition indicative of more severe water stress (Figure 2(b), Table 1).

*3.3. Relationship between ETc: Yield Ratio and Yield.* Rockström [16] described the relation between the ratio ETc: yield and yield with equation (2) He interpreted the declining ETc: yield ratio with increasing yield in terms of shifts in the evapotranspiration components: with increasing yield and crop vigour, the Es: ETc ratio declines, and a higher proportion of ETc is used in plant transpiration. The actual relation between ETc: yield and yield conformed to the expected model (Figure 3(a), $r = 0.98$, $p < 0.0001$, $s > 13.3$). However, this association involves a shared factor in $y$ and $x$, with the potential for spurious correlations [18]. We tested the legitimacy of the association in Figure 3(a) with two complementary approaches. Statistically, a large spurious correlation emerges when the coefficient of variation of the shared factor is more than 1.5 times larger than the coefficient of variation of the nonshared factor [18]. In our data set, the coefficient of variation of the shared factor, yield, was 73.8%, and the coefficient of variation of the non-shared factor, seasonal ETc, was 22.5%; the ratio is 3.3, indicating the spurious nature of the correlation from a statistical viewpoint. Biophysically, the association between Es: ETc and yield was weak and had a flat slope of $0.018 \pm 0.002$ $(t\,ha^{-1})^{-1}$ (Figure 3(b)). This analysis therefore supports the assumption of a conserved Es for the range of yield in our data and justifies a single relationship between yield and ETc (or rainfall), as summarised in equation (1).

*3.4. Benchmarking Water-Limited Yield Potential.* The RMA regression between yield and seasonal ETc returned a slope representing yield per unit transpiration of $0.065\,t\ ha^{-1}\ mm^{-1}$ and an $x$-intercept representing soil evaporation of 216 mm (Figure 4(a), Table 2). The strength of the relationship improved with ETc corrected by VPD, but not with ETc normalised with ETo (Figures 4(a)–4(c), Table 2). The RMA regression between yield and seasonal rainfall returned a slope of $0.117\,t\ ha^{-1}\ mm^{-1}$ and an $x$-intercept of 74 mm (Figure 4(d), Table 2); this association ($r = 0.62$, $F_{1,124} = 76.5$) did not improve with corrections by VPD or ETo (Table 2), or with the inclusion of winter rainfall ($r = 0.34$, $F_{1,124} = 16.7$).

We fitted a boundary function relating yield and seasonal rainfall for benchmarking vine yield (Figure 4(d), green line). Although seasonal rainfall is only one component of the total water input, we used rainfall instead of ETc for five

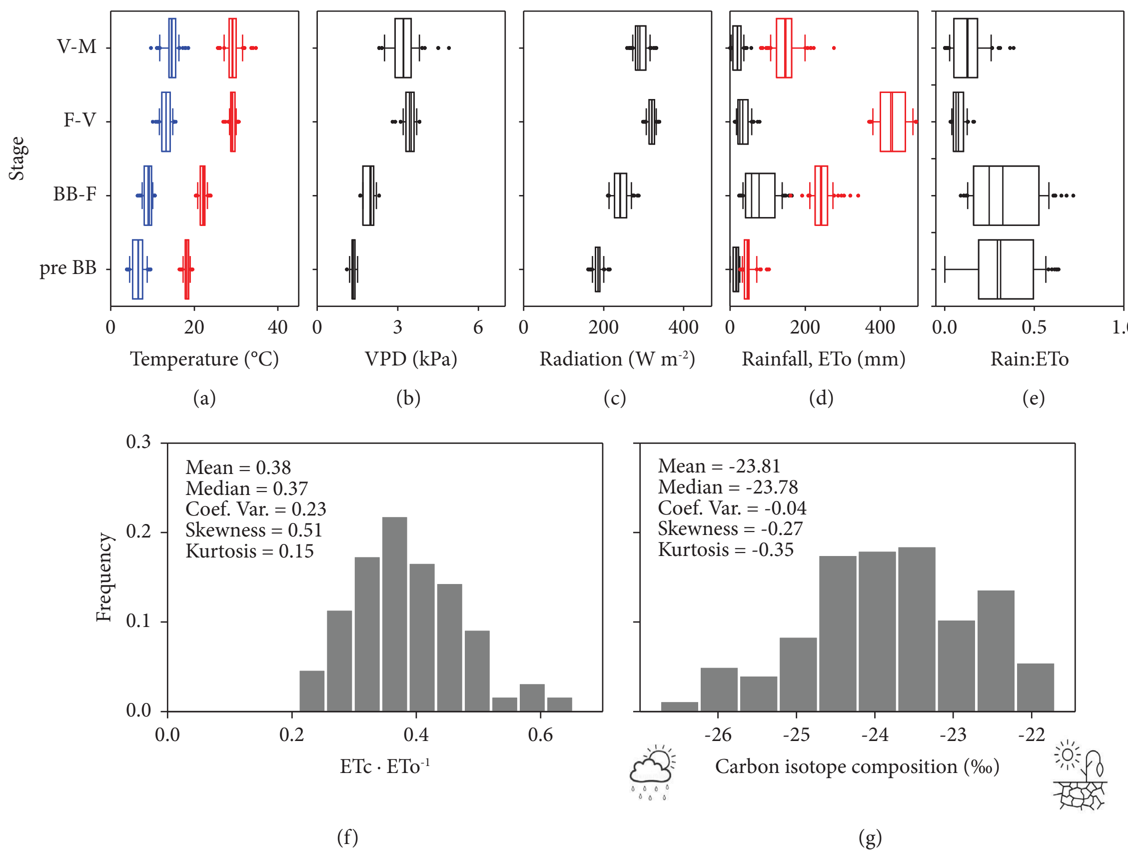



Figure 1: Frequency distribution of (a) minimum (blue) and maximum (red) temperature, (b) vapour pressure deficit, (c) solar radiation, (d) rainfall (black) and reference evapotranspiration (red), and (e) rain-to-reference evapotranspiration ratio during the periods from 29 August to budburst (pre-BB), from budburst to flowering (BB-F), from flowering to veraison (F-V), and from veraison to maturity (V-M). Frequency distribution of (f) the seasonal ratio between actual and reference evapotranspiration (ETc · $ETo^{-1}$) and (g) carbon isotope composition in must, a trait related to vine water status.

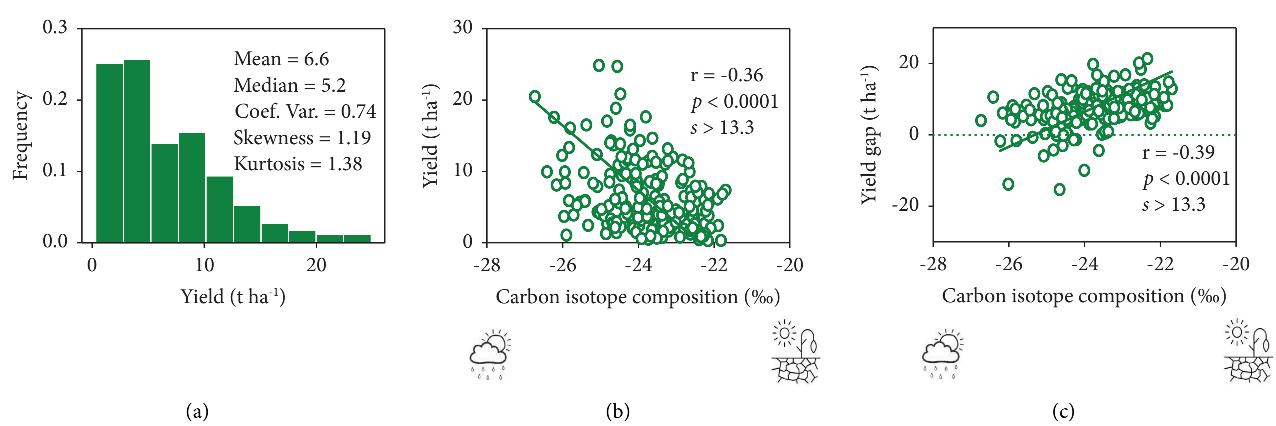



Figure 2: (a) Frequency distribution of yield of Shiraz in the Barossa zone (GI). (b) Relation between yield and carbon isotope composition. (c) Relation between yield gap and carbon isotope composition. In (b, c) lines are reduced maximum axis regressions.

reasons. First, rainfall is the main source of water for the crop in the Barossa, where supplementary irrigation is limited and normally restricted to 1 ML $ha^{-1}$ $season^{-1}$. Second, seasonal rainfall had the strongest correlation with yield (Table 2). Third, the spatial variation of seasonal rainfall in the Barossa regions correlates with the spatial variation in annual rainfall [35]. Fourth, there were more data available to fit a boundary function with rainfall than for ETc; the association between yield and seasonal rainfall for the larger data set returned $r = 0.59$, $F_{1,188} = 102.14$, $p < 0.0001$, $s > 13.3$. Fifth, rainfall is more readily available than ETc for industry applications.

Table 1: Correlation matrix of yield, its components, vegetative traits, and carbon isotope composition in must ($\delta^{13}C$) for Shiraz in the Barossa zone (GI). Sources of variation are 25 vineyard locations, two sites per vineyard, and three vintages.

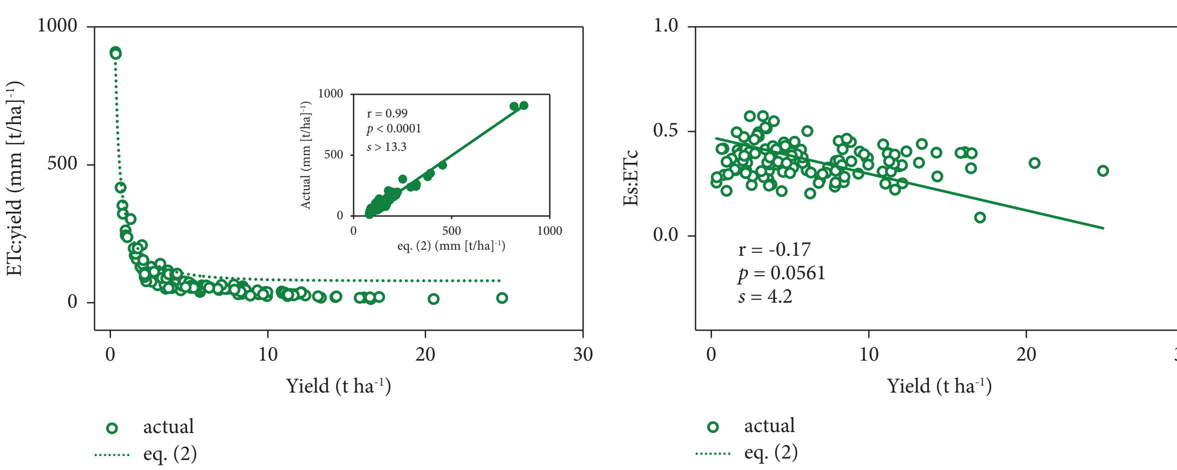
*p* scale

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0001 | 0.001 | 0.01 | 0.05 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 1 |

| | Bunch no/ha | Bunch weight (g) | Berries/bunch | Berry weight (g) | Shoot no/m | Pruning wt (t/ha) | $\delta^{13}C$ (‰) |
|---|---|---|---|---|---|---|---|
| Yield (t/ha) | *0.75* | *0.70* | *0.64* | *0.42* | *0.37* | *0.61* | *-0.36* |
| Bunch no/ha | | *0.13* | *0.14* | *0.09* | *0.65* | *0.42* | *-0.30* |
| Bunch weight (g) | | | *0.91* | *0.55* | *-0.14* | *0.50* | *-0.28* |
| Berries/bunch | | | | *0.20* | *-0.15* | *0.45* | *-0.19* |
| Berry weight (g) | | | | | *0.02* | *0.38* | *-0.26* |
| Shoot no/m | | | | | | *0.43* | *-0.26* |
| | | | | | | | *-0.18* |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Yield (t/ha) | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| Bunch no/ha | | 0.0698 | 0.0542 | 0.2296 | 0.0001 | 0.0001 | 0.0001 |
| Bunch weight (g) | | | 0.0001 | 0.0001 | 0.0516 | 0.0001 | 0.0001 |
| Berries/bunch | | | | 0.0054 | 0.032 | 0.0001 | 0.0079 |
| Berry weight (g) | | | | | 0.7929 | 0.0001 | 0.0002 |
| Shoot no/m | | | | | | 0.0001 | 0.0116 |
| Pruning wt (t/ha) | | | | | | | 0.0002 |

Numbers in italics are Pearson's correlation coefficients and numbers with coloured background are *p* from Fisher's *r* to *z* test.




(a) (b)

Figure 3: (a) Comparison of the actual relation between the ratio of crop evapotranspiration and yield and the model in equation (2). The parameters for equation (2) are $a = 80$ mm/t ha$^{-1}$ and $b = -0.3$ [16]. In the inset, the line is the least-squares regression. (b) Relation between the ratio of soil evaporation and crop evapotranspiration and yield; the line is the reduced maximum axis regression. ETc: crop evapotranspiration and Es: soil evaporation.

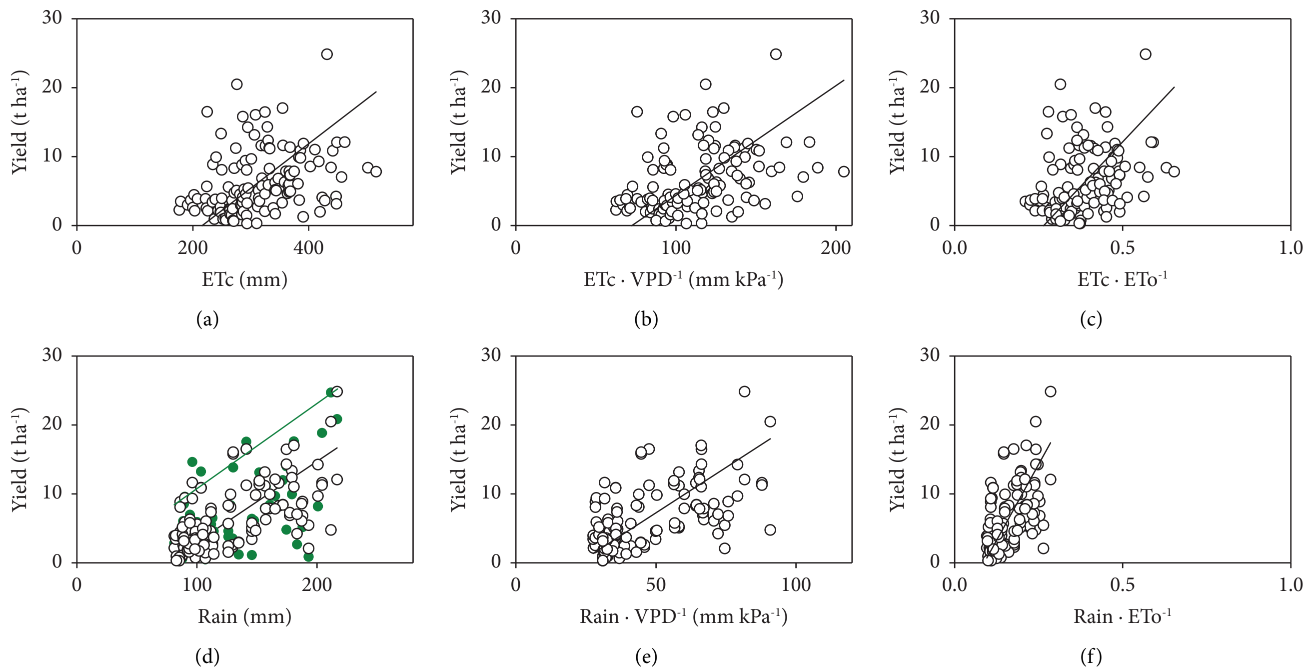



Figure 4: Relationship between vine yield and seasonal (a) crop evapotranspiration, ETc; (b) ETc corrected by vapour pressure deficit; (c) ETc corrected by reference evapotranspiration, ETo; (d) rainfall; (e) rainfall corrected by vapour pressure deficit; and (f) rainfall corrected by ETo. Black lines are reduced maximum axis regressions fitted to a common data set (open black circles), with statistics summarised in Table 2. In (d), green symbols are additional data, and the green line is the 95th percentile boundary derived from all data: $y = -1.92 + 0.124$ x.

Table 2: Statistics of reduced maximum axis regressions between yield and ETc, ETc · VPD$^{-1}$, ETc · ETo$^{-1}$, rain, rain · VPD$^{-1}$, rain · ETo$^{-1}$. Scatterplots and fitted regressions are in Figure 4.

| Variable | $r$ | $F_{1,124}$ | $p$ | $s$ | Slope | $x$-intercept |
|---|---|---|---|---|---|---|
| ETc (mm) | 0.32 | 13.99 | 0.0003 | 11.7 | 0.065 t ha$^{-1}$ mm$^{-1}$ | 216 mm |
| ETc · VPD$^{-1}$ (mm kPa$^{-1}$) | 0.38 | 21.5 | 0.0001 | 13.3 | 0.160 t ha$^{-1}$ mm$^{-1}$ kPa$^{-1}$ | 72 mm kPa$^{-1}$ |
| ETc · ETo$^{-1}$ | 0.30 | 12.6 | 0.0005 | 11.0 | 51.7 t ha$^{-1}$ | 0.265 |
| Rain (mm) | 0.62 | 76.45 | 0.0001 | 13.3 | 0.117 t ha$^{-1}$ mm$^{-1}$ | 74 mm |
| Rain · VPD$^{-1}$ (mm kPa$^{-1}$) | 0.59 | 64.87 | 0.0001 | 13.3 | 0.26 t ha$^{-1}$ mm$^{-1}$ kPa$^{-1}$ | 22 mm kPa$^{-1}$ |
| Rain · ETo$^{-1}$ | 0.56 | 56.01 | 0.0001 | 13.3 | 88.1 t ha$^{-1}$ | 0.087 |

*3.5. Yield Gap.* The average yield gap was twice as large in 2021, the highest-yielding season, compared with 2019 and 2020 (Figure 5(a)). The average yield gap varied from 9.9 t ha$^{-1}$ in the Central Grounds to 16.8 t ha$^{-1}$ in the Southern Grounds (Figure 5(b)). Part of this variation was related to elevation, with the yield gap declining to 0.038 ± 0.01 t ha$^{-1}$ m$^{-1}$ in the range from 186 to 326 m.a.s.l (Figure 5(c)); the Eden Valley departed from this trend, with a yield gap that was higher than expected from its elevation (solid symbols in Figure 5(c)).

The yield gap did not vary with the trellising system, pruning method, or row orientation (Figures 5(d)–5(f)). The yield gap increased slightly with distance between vines at 3.0 ± 1.5 t ha$^{-1}$ m$^{-1}$ ($r = 0.14$, $p = 0.051$, $s = 4.3$) and did not vary with distance between rows ($p = 0.208$, $s = 2.3$) or rectangularity ($p = 0.251$, $s = 2.0$). The yield gap increased linearly with vine age between 6 and 33 years at a rate of 0.3 ± 0.06 t ha$^{-1}$ yr$^{-1}$ (Figure 5(g)). The yield gap in 98-year-old Shiraz that had recently been reworked averaged 8.3 ± 0.70 t ha$^{-1}$ (solid symbols in Figure 5(g)); this compares with a projected gap from the fitted regression of 31 t ha$^{-1}$.

The yield gap correlated with all four yield components; the strength of the correlation ranked bunch weight ≈ berries per bunch > bunch number > berry weight (Figures 6(a)–6(d)). The minimum to close the yield gap was 185,000 bunches ha$^{-1}$, 105 g bunch$^{-1}$, 108 berries bunch$^{-1}$, and 1.1 g berry$^{-1}$ (arrow heads in Figures 6(a)–6(d)). The yield gap declined with increasing pruning weight, and the minimum pruning weight to close the gap was 3.2 t ha$^{-1}$.

Pearson's correlation coefficients were calculated between the yield gap and weather factors in four periods, from late August to budburst, budburst to flowering, flowering to veraison, and veraison to maturity (Figure 7). The association between yield gap and both maximum and minimum temperature shifted from positive before budburst to negative after flowering. The association between yield gap and

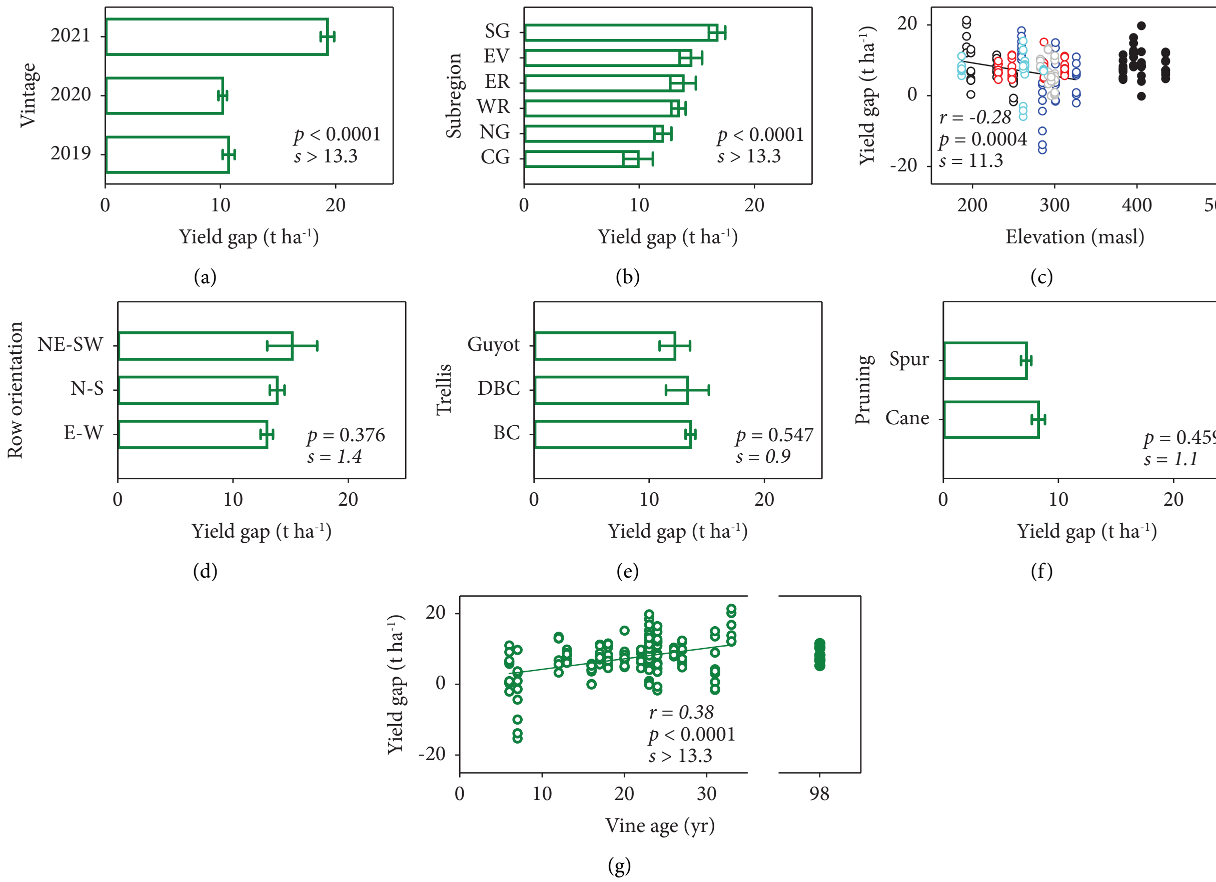



FIGURE 5: Variation in the yield gap of Shiraz in the Barossa zone (GI) with (a) vintage, (b) subregion, (c) elevation, (d) row orientation, (e) trellising system, (f) pruning method, and (g) vine age. In (a–f), error bars are two standard errors of the mean, and $p$ and $s$ from ANOVA. Subregions are Southern Grounds, shown as SG in (b) and open black symbols in (c), Eastern Edge (EE, blue symbols), Western Ridge (WR, red symbols), Northern Grounds (NG, gray), Central Grounds (CG, cyan), and Eden Valley (EV, closed black symbols). In (c), the line is the least squares regression fitted to all sub-regions but Eden Valley. In(f), the line is the least squares regression fitted to age between 6 and 33 years (open symbols); solid symbols (not included in the regression) are the yield gap of reworked vines on 98-year old rootstock.

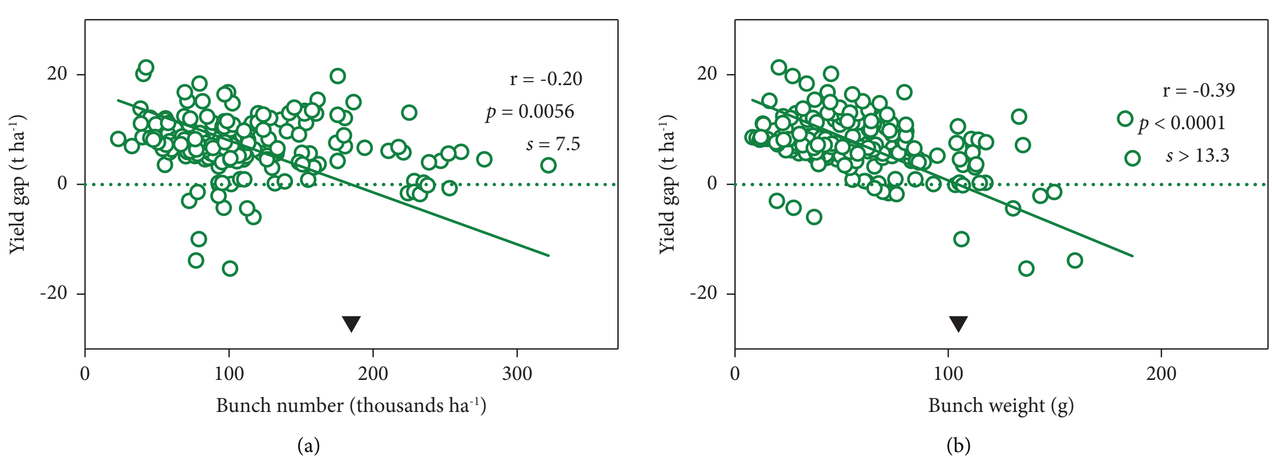



FIGURE 6: Continued.

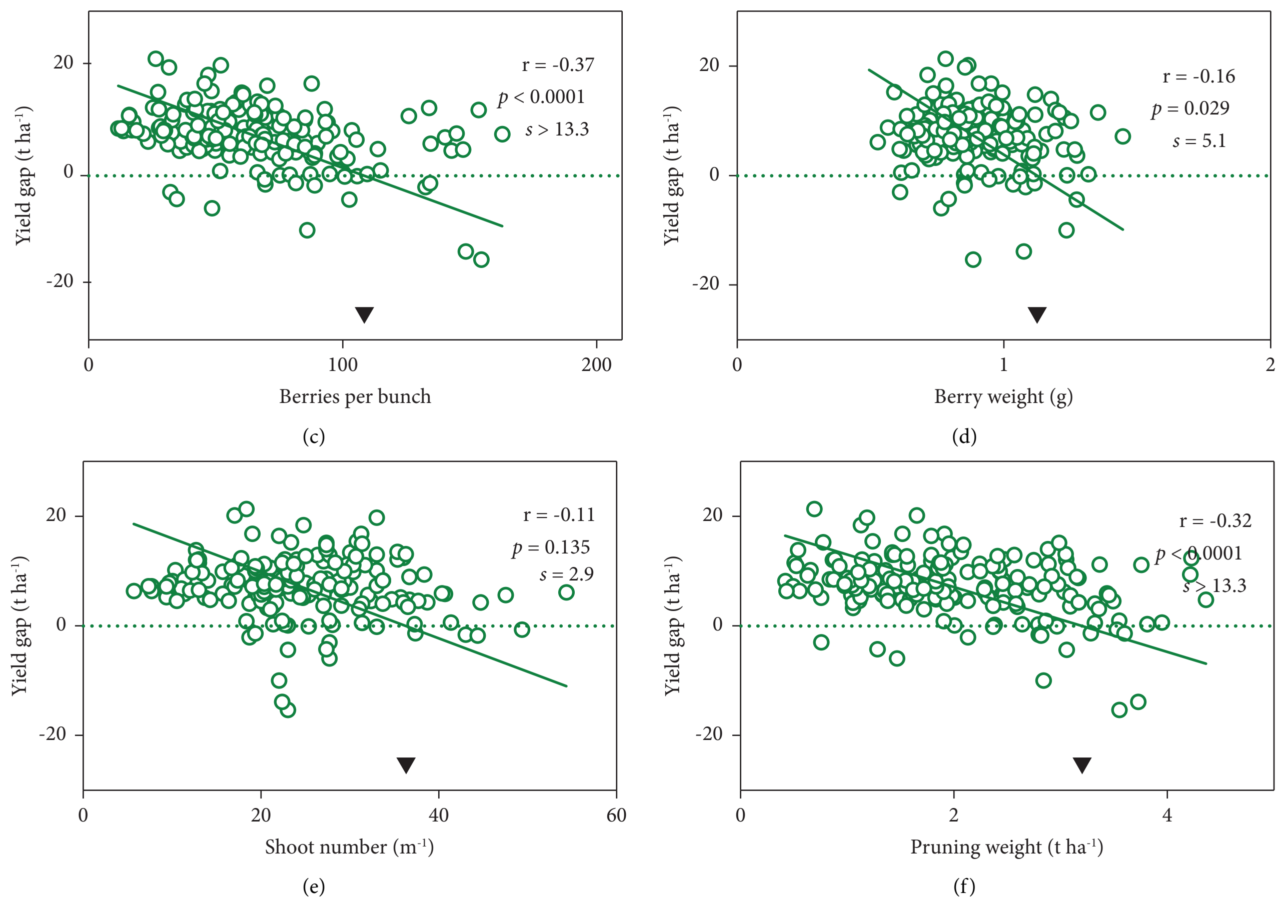



FIGURE 6: Relationship between yield gap of Shiraz in the Barossa zone (GI) and (a) bunch number, (b) bunch weight, (c) berries per bunch, (d) berry weight, (e) shoot number, and (f) pruning weight. Lines are reduced maximum axis regressions. Arrowheads show the trait value for yield gap = 0.

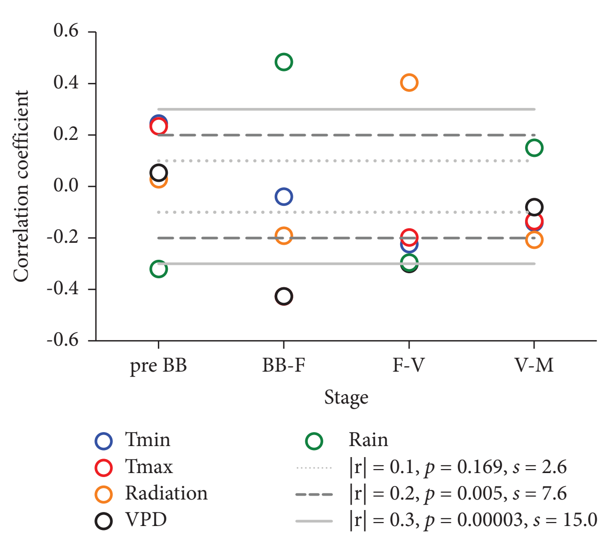



FIGURE 7: Correlation coefficient for the association between yield gap and meteorological variables from 29 August to budburst to budburst (pre-BB), from budburst to flowering (BB-F), from flowering to veraison (F-V), and from veraison to maturity (V-M).

radiation was negative from budburst to flowering and from veraison to maturity, and positive in the intervening period from flowering to veraison. Larger yield gaps were associated with smaller VPD between budburst and maturity, and the association was stronger at earlier stages. The association between yield gap and rainfall was negative before budburst, between flowering and veraison, and positive between budburst and flowering. The larger yield gap with higher rainfall between budburst and flowering was partially associated with the strong negative correlation between rainfall and VPD (Figure 7). The yield gap increased with increasing vine water stress, as quantified by the carbon isotope composition of must (Figure 2(c)).

## 4. Discussion

Climate change is placing increased stress on water resources and supports revisions of water management strategies and how they relate to vineyard productivity. This will help account for the direct (i.e., shifts in amount and seasonality of rainfall, reduced availability of water for irrigation, and higher temperature and vapour pressure deficit) and indirect effects of climate change including the use of irrigation to manage heat stress. In this context, we benchmarked the relation between yield and water use, calculated yield gaps, and explored their underlying environmental and management causes. Our focus was on Shiraz in the Barossa Zone. Irrigation management in this region is similar to other Mediterranean-like grape-growing regions with reduced rainfall and limited water for irrigation during the growing season. Water for supplementary irrigation is limited, historically around 1 ML $ha^{-1}$, and is mostly constrained to the period of ripening, aiming to allow for some level of water stress in the period pre-veraison that increase the concentration of phenolic substances [4] and to maintain functional canopies during the hottest and driest months to support the fruit ripening [52]. Irrigation in this region contrasts with management strategies aimed at maximising yield by matching irrigation with crop evapotranspiration demand during the cycle and by applying irrigation from the start of the season [53].

*4.1. Relationship between Yield and Applied Water.* The reduced maximum axis regression between yield and ETc returned a slope of 0.065 t $ha^{-1}$ $mm^{-1}$ and an $x$-intercept of 216 mm (Table 2). This compares with slopes from 0.061 to 0.123 t $ha^{-1}$ $mm^{-1}$ and x-intercepts from 136 to 175 mm in a sample of vineyards in Spain, the US, and China (Table 3). Parameters from least squares regressions, the default in most software packages, are included in Table 3 to highlight the flatter slopes and lower x-intercepts from this approach that assumes error in $x$ is negligible in relation to error in $y$ [48, 57]. The assumption is unjustified because error in ETc is not negligible. Indeed, yield correlated more strongly with seasonal rainfall than with ETc (Figure 4; Table 2). This was partially related to the uncertainty in the quantification of both soil water content and irrigation used in the calculation of ETc [58, 59]. Likewise, ETc estimation is influenced by canopy size and other management-related factors, which are either ignored or assumed to be uniform in the analyses of French and Schultz [15] as well as Rockström [16]. These models have been developed for rainfed crops where yield is contingent on rainfall and other management variables are less impactful for the potential yield. It is therefore expected that there is a skewed correlation between yield and ETc in both of these analyses for highly managed crops such as winegrapes in premium production regions such as the Barossa zone, where irrigation is reduced for the sake of attaining a regional wine style. We thus favoured a rainfall-based benchmark for water-limited yield potential and yield gap analysis. The model of French and Schultz [15] has several other assumptions, including a single $x$-intercept representing soil evaporation. The model developed by Rockström [16] explicitly accounts for the reduction in soil evaporation associated with larger canopies and higher yield (equation (2)). Our data conformed to this model, but statistical and biophysical criteria supported the conclusion that it is unsuitable for our analysis: the relationship ETc: yield vs yield is spurious [18] and inconsistent with the small variation in Es: ET with increasing yield (Figure 3).

In contrast to annual crops where canopy size is a large source of variation in energy partitioning, the wide-row structure dampens the variation in Es: ETc of vineyards, particularly in low-rainfall environments and under drip irrigation that wets a limited soil area [60–63]. In a furrow-irrigated Sultana vineyard in the arid Victorian Mallee, Australia, Es: ETc was 0.46–0.51 for a yield range between 7 and 22 t $ha^{-1}$ [64]. In a drip-irrigated Sultana vineyard in the same region, with a yield range from 6 to 20 t $ha^{-1}$, the RMA rate of decline in Es: ETc with increasing yield was $0.011 \pm 0.003$ $(t\,ha^{-1})^{-1}$ [61] compared with the rate of $0.018 \pm 0.002$ $(t\,ha^{-1})^{-1}$ in our data set (Figure 3(b)). These two studies [61, 64] are thus consistent with both the flat relation between Es: ETc and yield in vineyards and the lower Es: ETc at high yield under drip irrigation compared to furrow irrigation.

*4.2. Benchmarking Yield and Identifying Causes of Yield Constraints.* Yield gap is the difference between yield defined at two levels; here we define the yield gap as the difference between the water-limited yield potential (Yw) and the actual yield (Ya), as the most relevant for the production system in the Barossa where vineyards are grown primarily on rainfall, with only limited supplementary irrigation, where a proportion of the yield may be purposely sacrificed to achieve a desired grape/wine style.

The spatial coherence of seasonal and annual rainfall in the Barossa regions [35] and the biophysical and viticultural meaningful yield gaps derived from a rainfall-based benchmark reinforce the robustness of our approach. The yield gap was larger in the season with the highest yield and varied with location (Figures 5(a) and 5(b)). Elevation, a major factor in the clustering of locations in the Barossa regions [35], accounted for part of the variation with smaller gaps with increasing elevation (Figure 5(c)). Historically, the name Barossa Valley was used to describe the area below 400 masl, and the name Eden Valley, rather than Barossa Ranges, has been favoured for higher elevations since the 1950s [65]. The Eden Valley locations departed from this trend, with larger yield gaps than expected from their elevation (Figure 5(c)). This larger-than-expected yield gaps can be related to management of shallow soil and limited access to

Table 3: Range of crop evapotranspiration (ETc) and yield, and slopes and x-intercepts from regressions between yield and ETc in a sample of vineyards from the literature. Regression methods are reduced maximum axis (RMA, model II) and least squares (LS, model I) for comparison. Calculated from data reported by Intrigliolo and Castel [54] (Spain), Williams [55] (US), and Du et al. [56] (China).

| Variety | Location | ETc range (mm) | Yield range ($t\ ha^{-1}$) | RMA | | LS | |
|---|---|---|---|---|---|---|---|
| | | | | Slope ($t\ ha^{-1}\ mm^{-1}$) | *x*-int (mm) | Slope ($t\ ha^{-1}\ mm^{-1}$) | *x*-int (mm) |
| Tempranillo | Requena, Spain | 225–482 | 2.3–18.3 | 0.061 | 175 | 0.044 | 124 |
| Cab. sauvignon | California, US | 307–432 | 8.6–19.2 | 0.068 | 170 | 0.042 | 46 |
| Rizamat | Shiyang, China | 157–305 | 2.7–17.3 | 0.123 | 136 | 0.102 | 118 |

irrigation water [35], according to the Department of Environment and Water [66]. Unlike the Barossa Valley region that relies largely on irrigation water from the River Murray, the Eden Valley region is heavily reliant on native sources, i.e., groundwater and surface water (Department of Environment and Water [66].

The yield gap did not vary with row orientation, trellis system, or pruning method (Figure 5). Water use of vertically trained, potted vines was approximately 18% lower in east-west-orientated vines compared to north-south vines in the northern hemisphere [67]. Row orientation did not affect carbon assimilation; hence, the water use efficiency (based on both carbon assimilation and yield) was higher for the east-west vines than the vines orientate north-south [67]. Modelled intercepted radiation is higher in north-south than east-west-orientated rows [68]. However, the impact of row orientation is complicated by its interactions with and between canopy configuration, time of year, and row spacing [69] as well as vine water status, crop load, and the other practices discussed above. Shiraz vines in the Barossa and Eden Valley regions are traditionally managed using spur pruning and a single cordon, with some vineyards maintaining a second cordon approximately 0.4 m above the first [2]. More recently, occasional vineyards have been changed to Guyot, locally described as rod or cane pruning, often to improve trunk disease management [70]. Multiple cordons increase the number of buds retained on the vine, and canes favour bud fertility, hence, both systems have the potential to increase bunch number and yield relative to the single cordon spur pruned system [71].

The yield gap increased linearly with vine age, and this can be related to at least three factors: time to peak production and decrease in yield with age, disease progression, and vine management. Crop evapotranspiration and yield increase with vine age from establishment until the canopy and root system reach their full capacity to capture radiation and water, around 6 to 10 years after planting, depending on management, variety, and growing conditions [6, 72, 73]. Hence, age-related variation in vine capacity to capture water and radiation was a minor factor for the range from 6- to 33-year-old vines in which the yield gap related to vine age. Likewise, 93–168 year old Shiraz vines growing in Barossa [74] and 40–60 year old Zinfandel vines in California [75] yielded higher than younger vines (5–12 years old in California and 6–28 years old in Barossa), reducing the likelihood that vine age per se was the reason decreasing vineyard productivity in vineyards between 6 and 33 years old. Eutypa dieback, caused by the fungus *Eutypa lata*, is a severe, widespread trunk disease of grapevines [73, 76, 77]. The fungus grows slowly in the plant, and the onset of foliar symptoms occurs 3–8 years after infection. In south-eastern Australian vineyards, the incidence of trunk disease increased with vine age [78], reducing vineyard longevity and productivity [79]. The yield of Chenin blanc vineyards in California varied nonlinearly with age, increasing up to a peak over 20 $t\ ha^{-1}$ in 12-year-old vines, and declining dramatically after this peak in association with the period of rapid increase in Eutypa dieback [73]. The putative effects of disease can be partially confounded with management; arm wrapping into the cordon wire is a practice commonly used during the establishment of a new vineyard, which may have a devigorating effect and a potential drop in production as cordon strangulates over the years [80]. Irrespective of the causes, the costs of dealing with older, less productive vines (vine redevelopment, new planting, and delay of productivity of young vines) need to be weighed against the rate of increase in yield gap of $0.3 \pm 0.06\ t\ ha^{-1}\ yr^{-1}$ (Figure 5(g)) and the potential increase in quality and selling price of fruit, frequently associated with older vineyards [75]. Plant water deficit was neutral or slightly improved the tolerance of grapevine to infection and colonisation by *E. lata* [81]. Once established in the plant, Eutypa dieback fungi invade bark tissues and xylem, resulting in the death of a portion of the vascular cambium whereby infected structures are no longer able to produce newly functional xylem and phloem, and cankers develop [82]. Eutypa dieback reduced the water content and disrupted the dynamics of free abscisic acid (ABA) and its glucose esters (ABA-GE) in the diseased organs of Cabernet sauvignon [76]. Consistent with the disruption in the vascular system and altered water relations, the yield gap increased with water stress, as quantified with the carbon isotope composition (Figure 2(c)). Other factors that contribute to water stress and the yield gap include soil plant availability of water, primarily related to soil depth [35, 83].

Yield is correlated with all four yield components, particularly bunch number (Table 1); bunch number is usually the largest source of variation in grapevine yield [84]. The yield gap was correlated with all four yield components, particularly bunch weight and berries per bunch, highlighting the incidence of berry set. The causes of the shift from bunch number as the main source of variation in yield to bunch size as the main source of variation in yield gap are unclear. Irrespective of the causes, the minimum bunch size (105 g $bunch^{-1}$, 108 berries $bunch^{-1}$) to close yield gaps may be used as a rule-of-thumb to benchmark vineyard performance but requires independent testing (Figure 6). The yield gap was smaller with higher rainfall before budburst, putatively favouring early-season vegetative growth and allocation to reproduction, and with higher rainfall between flowering and veraison, putatively favouring fruit set and early berry growth [85, 86]. Consistent with our correlative findings, experimental evidence led to the conclusion that winter irrigation is required to maintain yield in the context of drier winters with climate change in production regions relying in winter and spring rainfall as the main source of water [41]. Across the three seasons, vineyards received an average of 48 mm (less than 15% of the regional average seasonal water requirement) before fruit set, which emphasises the approach to irrigation in this region, where limited water allocation justifies saving water for the hotter summer months. Likewise, the lower yield gap with more rainfall before budburst highlights the potential reductions in yield associated with the projected reduction in winter and spring rainfall with climate change in the region and other Mediterranean-like regions and the need to revise irrigation practices under these scenarios [41]. The gap was larger with high rainfall, and associated low radiation, between budburst and flowering (Figure 7). For Godello in the Ribero Designation of Origin, the production of pollen spanned 2-3 weeks in May and June, and yield correlated negatively with rainfall in May [87]. Three successive rainy days in late May (53 mm), just after the seasonal pollen peak, promoted a fast decrease in the airborne pollen concentration [87]. The association between yield gap and temperature shifted from positive early in the season to negative at later stages, particularly between flowering and veraison. This agrees with evidence that indicates differential sensitivity to temperature between phenological stages [88–91]. Consistent with the positive correlation observed between the yield gap and temperature early in the season, artificially elevated temperature two weeks before budburst decreased the number of flowers at a rate of −7.3 flowers per °C for the lower inflorescence and −5.5 flowers per °C for the upper inflorescence, with no impact of temperature two weeks after budburst [90]. Temperature sensitivity increases again during anthesis; the damage, however, depends on the threshold temperature. Temperatures over 35°C at flowering reduce fruit set and the number of berries per bunch [89], whereas temperatures around 28°C favour pollen germination and ovule fertilization [91]. Therefore, we hypothesise that higher temperature from flowering to veraison during the mild seasons of this analysis may have contributed to reducing cold damage during flowering, contributing to increase in fruit set and closing the yield gap.

## 5. Conclusion

With a focus on irrigated Shiraz vineyards in the Barossa GI, we benchmarked yield and quantified yield gaps. A total of 48 sites were assessed during three vintages, and plant, weather, and management practices were characterised at each site and used to explain gaps between current and water-limited yield. We found typical variations in yield with vintage and a spatial pattern of yield variation across the region that was consistent over the three years of this study. Yield gaps between sites were partly explained by elevation, but mainly by the differences in soil water availability and meso-climate that impacted vine water status. As indicated by the carbon isotope composition in the fruit at harvest, the yield gap increased with a higher vine water deficit. Despite the use of irrigation that could potentially buffer vintage-to-vintage variations in yield, productivity in this region seems to be strongly influenced by seasonal variations in rainfall. The yield gap was smaller with higher rainfall before budburst and from flowering to veraison, opening an opportunity for the improvement in productivity by changing irrigation management that modulates seasonal variation in water availability during this period. These findings also highlight the vulnerability of these regions and other Mediterranean-like regions with limited water for supplementary irrigation to climate change and anticipate the decrease in productivity that may be expected in a drier future if water availability is not sustained. The trellising system, row orientation, or pruning method did not impact the yield gaps. The yield gap increased with vine age, possibly due to prevalent trunk diseases. This study provides a useful benchmarking analysis of yield and its drivers that can improve the productivity of Shiraz in the Barossa. The causes of the yield gap are specific to the system under study, but the approach may be useful to other varieties and regions with little or no irrigation.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Disclosure

An earlier version of this paper has been submitted as preprint [92, 93].

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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