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Wine Australia

Managing Wine pH in a Changing Climate



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Principal Investigator: **Suzy Y Rogiers**

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Managing Wine pH in a Changing Climate

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Suzy Rogiers, Tintu Baby, Zeyu Xiao, Bruno Holzapfel, Leigh Schmidtke, Rob Walker

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Abstract

The role of potassium in berry acidity was investigated in six cultivars in the Riverina and Orange wine regions of NSW. It was found that a high magnesium to potassium ratio ([Mg]/[K]) in the soil and in the grapevine was associated with lower berry pH and higher titratable acidity. The monitoring of the [Mg]/[K] ratio should become part of an integrated soil management strategy that is focused not only on productivity, but also on berry composition. A questionnaire and interviews highlighted drivers and barriers to the implementation of sustainable grapegrowing and formed the basis of an adoption strategy specific to addressing berry composition.

Executive Summary

Warmer climates are associated with higher evaporative demand, accelerating plant transpiration and the associated uptake of nutrients through the vascular streams. Potassium (K^+) is the dominant cation of the grape berry. This nutrient regulates berry sugar accumulation and has a strong influence on wine microbiological stability and fermentation processes. Past research has demonstrated that high berry K^+ concentration [K], is associated with high total soluble solids (TSS), however links with juice pH and titratable acidity (TA) requires substantiation for Australian warm grape growing regions.

Soil, leaves and berries were sampled at several phenological stages in a survey of vineyards in the Riverina and Orange wine regions of NSW to better understand the role of nutrition on berry composition. Juice pH was positively correlated with juice [K], while juice TA was negatively correlated with juice [K] in several cultivars. Grapevine [Mg] and [Ca] status, assessed using petiole or laminae samples, had an influence on vine and juice [K] and on juice pH and TA. Higher concentrations of the potassium cation antagonists, Mg^{2+} and Ca^{2+}, in the juice were associated with lower pH and higher TA. The vine [Mg]/[K] ratio was particularly important to grape berry composition suggesting that targeted vine nutrition management offers an avenue to ameliorate climate driven losses in wine acidity.

Subsequently, potted-vine and field-vine trials were implemented to test the effectiveness of the potassium cation antagonists at manipulating berry composition. In the second season of the potted-vine study, high cation concentrations in the petioles were associated with high levels of the corresponding cation in the juice. Notably, juice [K] was inversely correlated with petiole [Mg]. Furthermore, the petiole and blade [Mg]/[K] ratios were inversely correlated to juice pH. Juice [K] was positively correlated with pH, but there was no association with TA. Despite this, the fertiliser treatments of the potted and field vines did not alter berry pH or TA. Only minor changes in vine nutrient levels, unseasonably wet conditions and the characteristics of the soils may all have contributed to the absence of treatment effects. Overall, these findings indicate that the application of cation antagonist fertilisers could be utilised to alter juice characteristics, but this would require further refinement and investigation. It is expected that several seasons of nutrient application would be required to alter vine nutrient levels to the extent that they will have an impact on berry composition.

Based on the extensive regional survey results and bearing in mind the need for further nutrition trials, we have proposed several sustainable vineyard practices to modify berry composition. These are grounded on reducing excessive K application and increasing Mg application if deficient or marginal. Excessive vine [K] can be addressed by ensuring there is no over-application of K, adoption of K excluding rootstocks, crop manipulation to slow berry ripening and ripening-related K accumulation, reduction in bunch exposure, and curtailing excess irrigation and nutrient uptake through soil and

plant water status monitoring. To address marginal Mg status or deficiency, Mg fertilisers should be applied, and non-acidifying fertilisers used to avoid soil acidification. The pH should be adjusted in acidic soils with soil alkalinity-enhancing fertilisers to increase Mg availability, although this treatment would be most effective prior to planting.

The drivers and barriers to the adoption of sustainable vineyard practices were investigated through an online questionnaire and interviews. The main drivers for implementing these practices were long-term viability and 'doing the right thing'. The foremost impediments were cost, confidence in region-specific solutions, and complexity. The CSIRO ADOPT tool was used to assess how quickly the adoption of practices that lead to improved berry acidity will spread and what percentage of adoption we could expect. The targeted populations are those growers that are rewarded for berry quality or those that process their own fruit into wine. The modelling predicts that the peak adoption rate will be 46% and that this will occur in seven years. The monitoring of the [Mg]/[K] ratio can become part of an integrated soil management strategy that is focused not only on growth or yield, but also on berry composition.

This work was the result of collaboration between NSW Department of Primary Industries, the Gulbali Institute of Charles Sturt University, and CSIRO with strong support from the NSW Wine Industry.

Background

It is well known that over recent decades, wine alcohol levels have risen as a result of rising berry sugar levels. Similarly, over this same period, TA has decreased and pH has increased (Ganichot, 2002; Neething et al. 2012; Gaiotti et al. 2020). High temperature accelerates the loss of berry acidity through malic acid degradation during ripening (Kliewer 1964, Gladstones 1992, Sadras et al. 2013). Past research has also demonstrated that high berry [K] is associated with high pH and low acidity (Somers 1975, Hale 1977, Morris et al. 1983, Rühl 1989, Walker et al. 1998). This is because K binds with the free tartaric acid in the juice, forming potassium bitartrate crystals.

Potassium is an essential macronutrient important to numerous biochemical and physiological processes in the vine and the berry. This element accumulates once the ovary is fertilised, however transport into the berry accelerates after veraison. Given that K^+ is important to phloem functioning, K^+ transport through the vine and into the berry is tightly linked with both sugar and water transport. The accumulation of this cation ceases once berry growth reaches a plateau and mesocarp cell death and other senescence processes within the grapevine begin.

K^+ accumulation can be linked to climate change for the following reasons:

1. Warm temperatures initiate earlier ripening, which stimulates the linked sugar-K-water transport into the berry (Coetzee et al. 2017 and 2019).
2. Warmer climates are associated with higher evaporative demand and higher vapour pressure deficit, which accelerates transpiration and the associated uptake of nutrients through the vascular streams (Masle et al. 1992, Polley et al. 1999).
3. Increasing atmospheric carbon dioxide stimulates photosynthetic rates, leading to more vigorous vines (Kizildeniz et al. 2018). This is well known to be linked to greater K uptake, possibly because of a more extensive root system (Mpelasoka 2003).

Low natural acidity and copious berry K^+ may result in the requirement for interventions such as acid additions in the winery. Natural berry acidity negates the requirement for expensive tartaric acid

additions. Some winemakers also consider that fruit low in acid may lack desirable flavour and aroma characters.

There are several potential approaches to manipulating berry composition that are focussed on ameliorating excess berry [K]. These include rootstocks, vine balance, bunch microclimate, irrigation, soil temperature and cation antagonism. Cation antagonism refers to the competition between nutrients for uptake by the roots. Cations such as Mg^{2+} and Ca^{2+} have been shown to reduce K^{+} uptake in other species but the evidence for this in grapevines is unclear.

Project Aims

The objectives of this project were to:

1. Characterise the relationships between soil [K], petiole and lamina [K], berry [K], berry pH and berry TA
2. Assess cation antagonism as a potential method to manipulate berry [K], pH and TA.

The overall aim was to find sustainable vineyard-based methods to maintain juice pH and TA within desirable ranges in warm growing regions that are becoming warmer.

Methods/Results/Discussion

2018-19 Orange/Riverina survey: a multi-cultivar comparison

Objective: to better understand the relationship between K^{+} and juice pH & TA in a number of cultivars.

Method: Soil at 10 and 30 cm depths, petioles and berries were sampled during late ripening (approx. 20 °Brix), ahead of harvest, in Orange and Riverina wine regions across several cultivars and several vineyard blocks per region (Table 1). The vineyard blocks varied in soil type, altitude and grapevine age in order to capture a wide range of growing conditions. Three representative rows were chosen across each block, with sampling of ten vines per row. One basal bunch and one petiole opposite the bunch were sampled from each vine. Nutrients were assessed in dried petioles and juice by Inductively Coupled Plasma Mass Spectrometry (i.e. ICP).

The late sampling of petioles and soil prior to harvest (as opposed to early in the season) was in response to the timing of the advice that this project may receive funding. This survey was undertaken to gain some preliminary data to help guide future potential treatments.

Table 1: Sampling across two wine regions in the 2018-19 growing season.

	Number of blocks sampled	
Cultivar	**Riverina**	**Orange**
Shiraz	3	3
Cabernet Sauvignon	3	3
Chardonnay	4	4

Semillon	3	1
Pinot Gris	2	3
Durif	3	0

Background petiole and soil [K]

Table 2: Regional and cultivar differences in petiole and soil K concentration:

	Petiole [K] (mg/kg) Cultivar x region P<0.001		**$Soil_{10\,cm}$ [K] (mg/kg)** Cultivar P<0.01	**$Soil_{30\,cm}$ [K] (mg/kg)** Cultivar P<0.01
Cultivar	**Orange**	**Riverina**	**Mean of 2 regions**	**Mean of 2 regions**
Semillon	22522	28178	612	516
Chardonnay	19057	31164	586	531
Pinot Gris	34789	18849	700	587
Shiraz	17056	20411	435	365
Cabernet Sauv.	23653	24688	448	378
Durif	-	17654	484	407

Petiole [K] was generally higher in the Riverina than in Orange wine region except for Pinot Gris where the reverse was apparent. Soil [K] was not different between regions (P=ns) and averaged 530 mg/kg at 10 cm and 450 mg/kg at 30 cm depths.

Hypothesis 1: Juice pH is positively correlated with juice [K].

*Hypothesis confirmed for all cultivars.

The relationship was strong for Chardonnay, Semillon, Pinot Gris and Shiraz. In Cabernet Sauvignon the relationship was not as strong but still positive. Juice pH was also positively correlated with whole berry homogenate (composite of skin, flesh and seeds) [K] but not as tightly as juice [K] (data not shown).

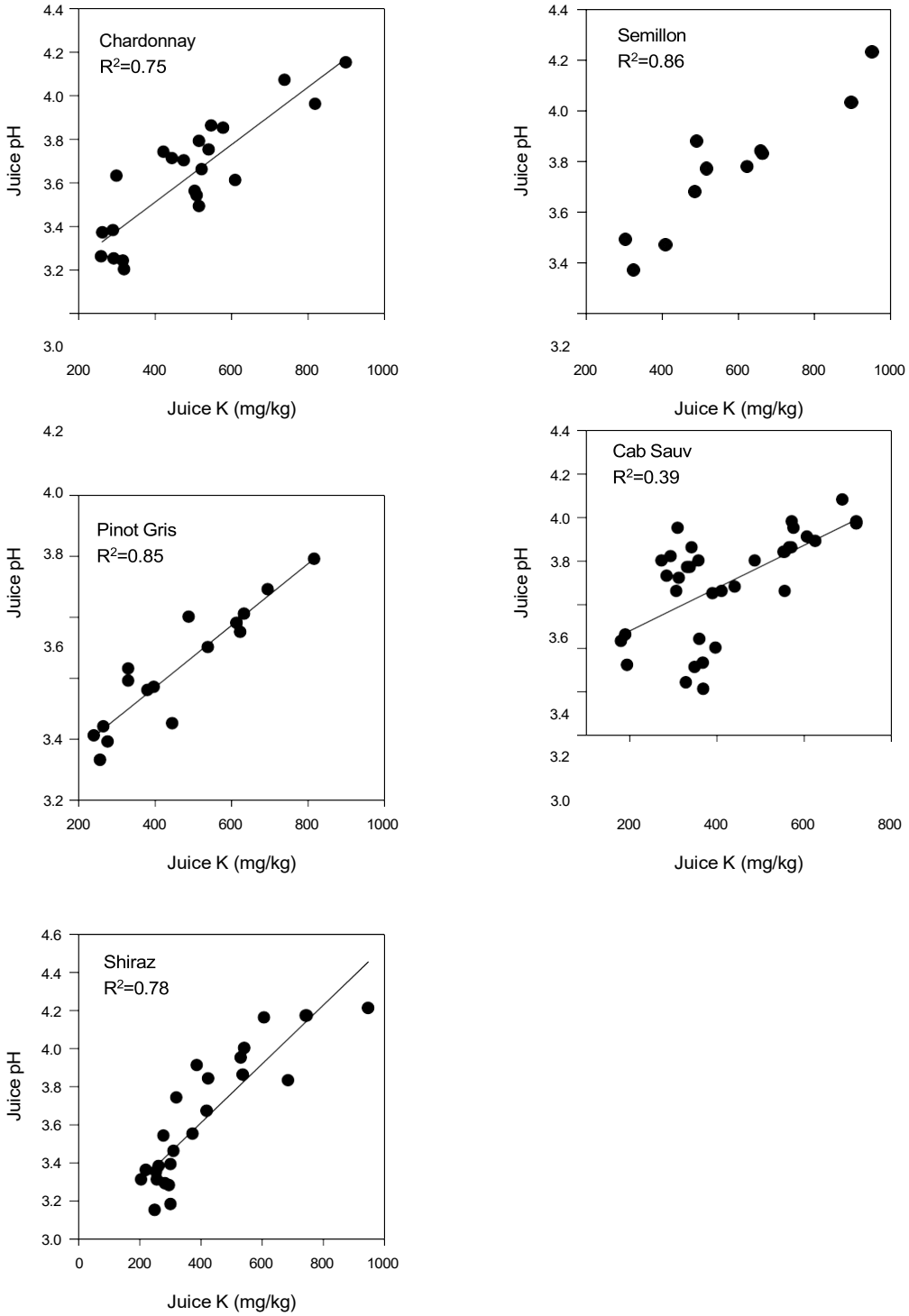


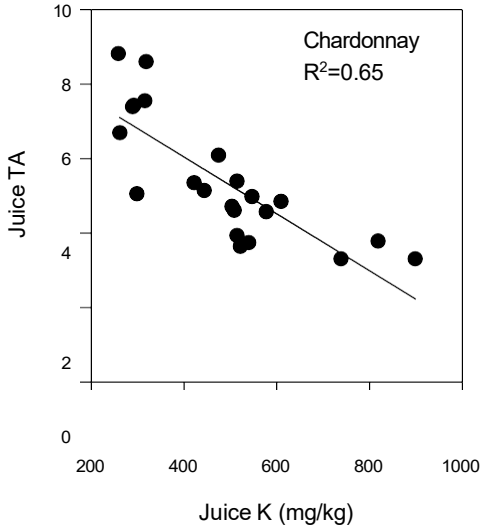
Figure 1. Juice pH as a function of juice [K] in five cultivars. Each data point on the graph represents the average of a pooled 10-vine replicate. Data include both regions. Each

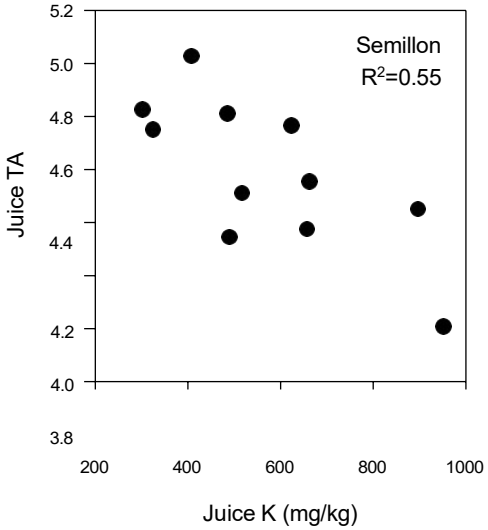
correlation shown was significant ($P < 0.001$).

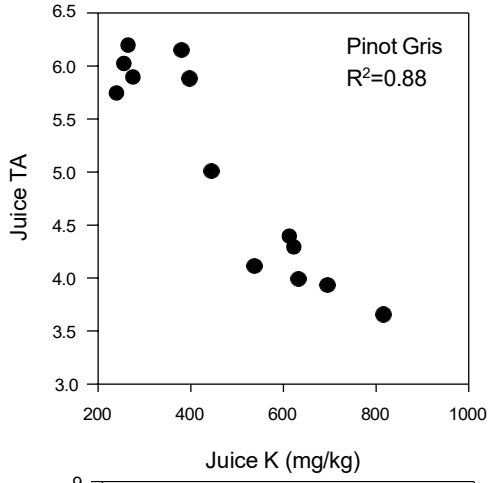
Hypothesis 2. Juice TA is negatively correlated with juice [K].

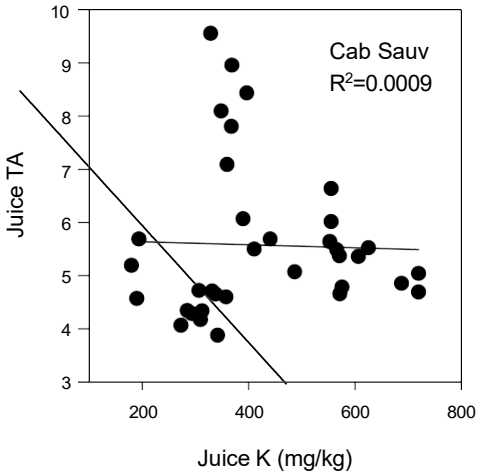
*Hypothesis confirmed for all cultivars except Cabernet Sauvignon.

The relationship between juice TA and juice [K] was negative for most of the cultivars (P <0.001), but not quite as strong as the one between juice pH and juice [K]. Correlations in Cabernet Sauvignon were poor (ns).









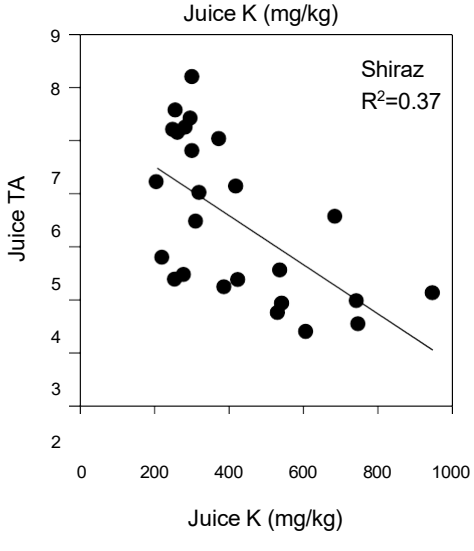


Figure 2. Juice TA as a function of juice [K] in five cultivars. TA is in g/L.

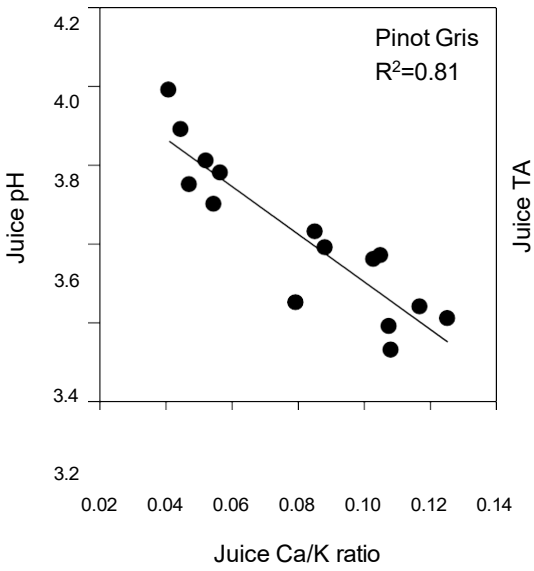
Hypothesis 3: High juice [Mg] and [Ca] relative to [K] can lower pH and increase TA

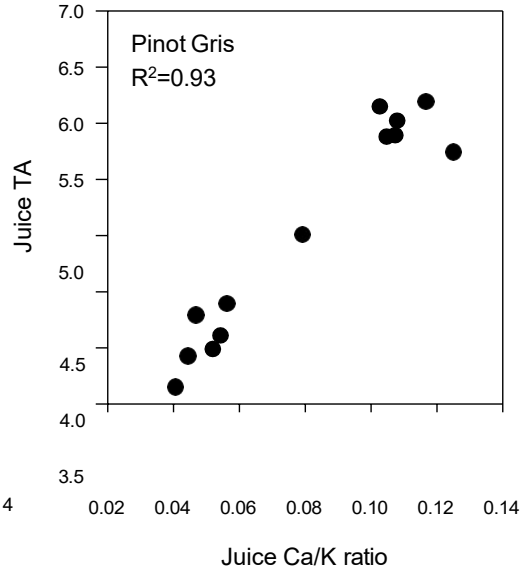
*Hypothesis confirmed for all cultivars except for Cabernet Sauvignon.

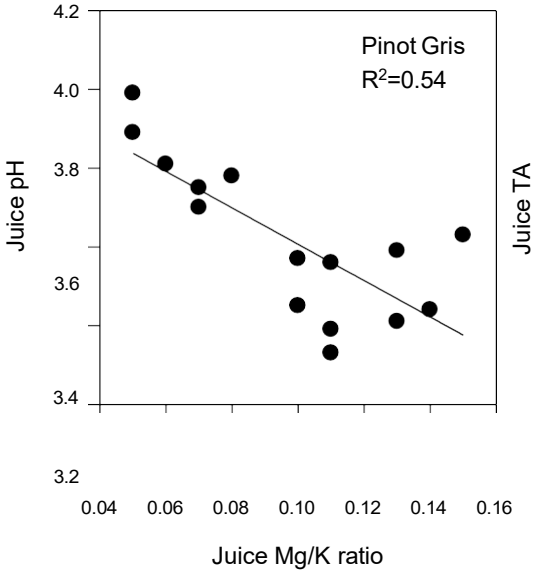
Table 3: Correlations (R^2) between juice pH or TA with juice [Mg]/[K], [Ca]/[K] and ([Mg]+[Ca])/[K] ratios for several cultivars. Grey highlight indicates significant correlations (P<0.05).

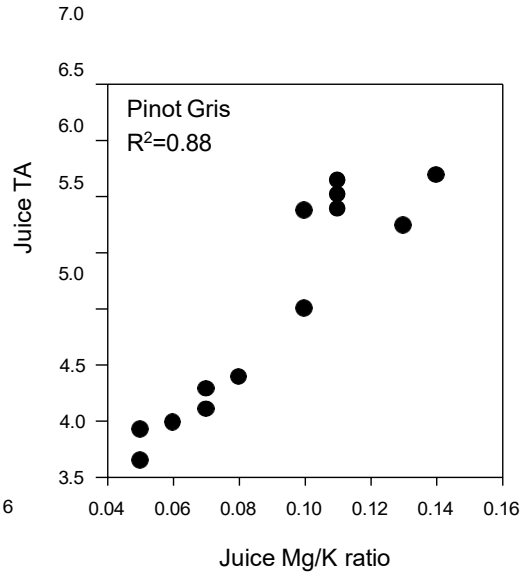
Cultivar	Juice pH			Juice TA		
	Juice [Mg]/[K]	Juice [Ca]/[K]	Juice ([Mg]+[Ca])/[K]	Juice [Mg]/[K]	Juice [Ca]/[K]	Juice ([Mg]+[Ca])/[K]
Semillon	0.53	0.69	0.64	0.47	0.70	0.62
Chardonnay	0.46	0.45	0.49	0.65	0.59	0.68
Pinot Gris	0.54	0.81	0.72	0.88	0.93	0.92
Shiraz	0.69	0.58	0.65	0.61	0.56	0.62
Cab. Sauv.	0.19	0.41	0.28	0.040	0.025	0.007
Durif	0.92	0.69	0.85	0.72	0.84	0.80

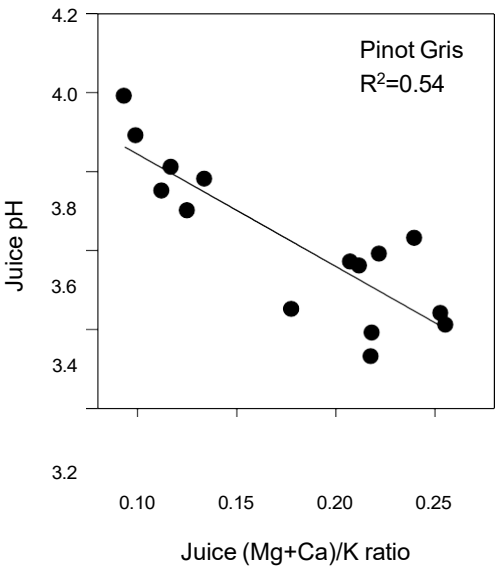
When juice [Ca] and [Mg] are assessed relative to [K], individually and in combination, strong relationships were apparent. These results indicate that both cations (Mg and Ca) are important to juice pH and TA. When the [Mg]:[K] ratio is high then pH is likely to be lower and the TA is likely to be higher. Similarly, when the [Ca]:[K] ratio is high, the pH is likely to be lower and the TA is likely to be higher. An example for Pinot Gris is shown below in Fig. 3. The other cultivars also demonstrated this trend except for Cabernet Sauvignon. In some cultivars the relationship is stronger for [Mg]/[K] while in others it is stronger for [Ca]/[K] despite the much smaller concentrations of Ca relative to that of Mg. This suggests that both cations may be important candidates for manipulating pH and TA.


Pinot Gris
R2=0.81
Juice pH
Juice Ca/K ratio
4.2
4.0
3.8
3.6
3.4
3.2
0.02
0.04
0.06
0.08
0.10
0.12
0.14


Pinot Gris
R2=0.93
Juice TA
Juice Ca/K ratio
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0.02
0.04
0.06
0.08
0.10
0.12
0.14


Pinot Gris
R2=0.54
Juice pH
Juice Mg/K ratio
4.2
4.0
3.8
3.6
3.4
3.2
0.04
0.06
0.08
0.10
0.12
0.14
0.16


Pinot Gris
R2=0.88
Juice TA
Juice Mg/K ratio
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0.04
0.06
0.08
0.10
0.12
0.14
0.16


Pinot Gris
R2=0.54
Juice pH
Juice (Mg+Ca)/K ratio
4.2
4.0
3.8
3.6
3.4
3.2
0.10
0.15
0.20
0.25

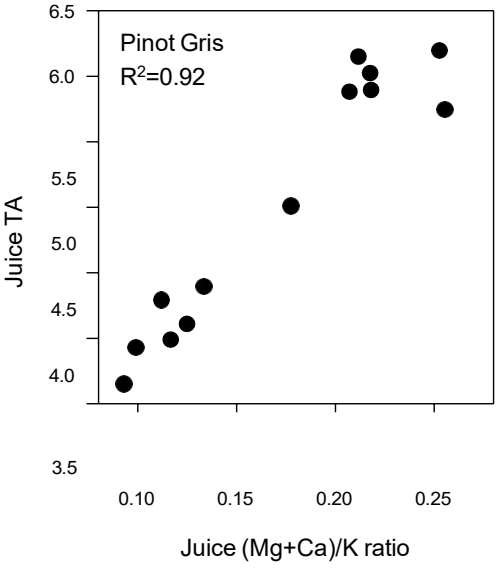

Pinot Gris
R2=0.92
Juice TA
Juice (Mg+Ca)/K ratio
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0.10
0.15
0.20
0.25

Fig 3: Juice pH and TA (g/L) relative to juice cations ($P < 0.001$ for each regression).

Juice [Ca] showed a positive relationship with juice [tartaric acid] in three of the cultivars (Table 4) with the relationship for Semillon shown below in Fig. 4. Juice titratable acidity (TA) was positively correlated with [tartaric acid] and negatively correlated with pH for all cultivars (Table 4), as shown for Shiraz in Fig. 5. There were no strong correlations between juice [tartaric acid] and juice [Mg] (data not shown). TSS correlated positively with juice pH and negatively with juice TA in only three of the cultivars (Table 4).

Table 4: R^2 of relationships between various juice parameters. Grey highlight indicates significant correlations (P<0.05).

Cultivar	Juice [Ca] vs [tartaric acid] (+ve)	Juice TA vs [tartaric acid] (+ve)	Juice TA vs juice pH (-ve)	TSS vs juice pH (+ve)	TSS vs juice TA (-ve)
Semillon	0.51	0.25	0.75	0.34	0.24
Chardonnay	0.05	0.63	0.76	0.12	0.09
Pinot Gris	0.34	0.59	0.79	0.72	0.48
Shiraz	0.01	0.70	0.87	0.28	0.28
Cab. Sauv.	0.18	0.73	0.55	0.12	0.01
Durif	0.57	0.44	0.63	0.06	0.08

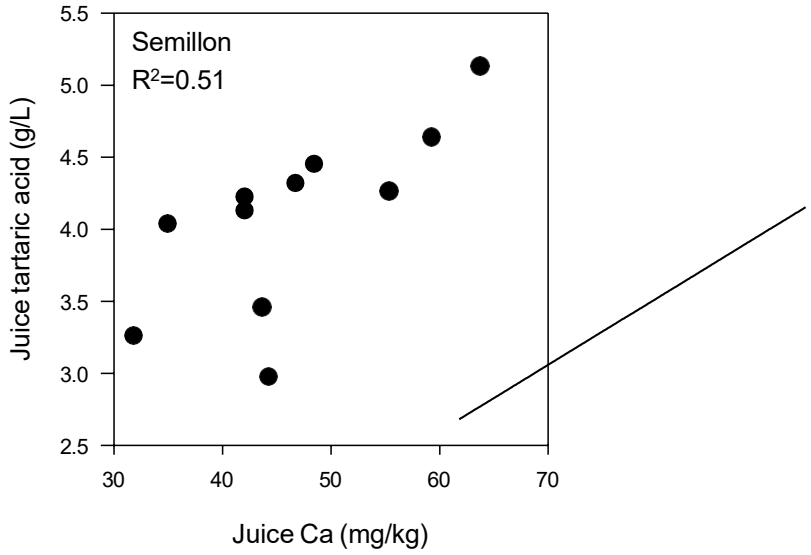


Fig 4. Juice [tartaric acid] as a function of juice [Ca] (P <0.05).

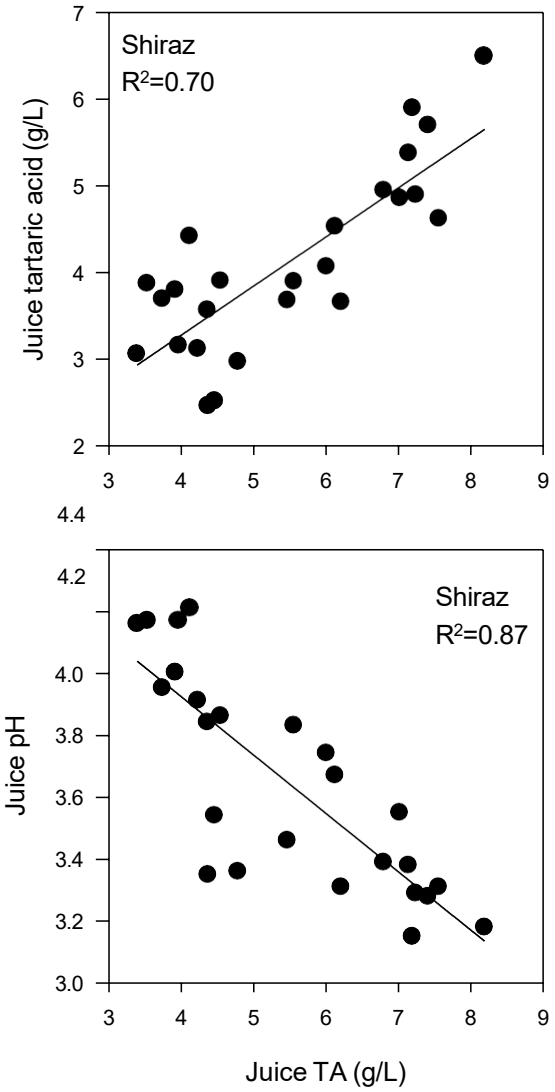


Fig 5. Juice pH and [tartaric acid] as a function of juice TA (P <0.001).

Hypothesis 4: There are positive correlations between juice and berry [K], and between berry and petiole [K]

* Hypothesis supported for some cultivars.

Table 5: Correlations (R^2) of relationships between juice and berry [K] and between berry and petiole [K] for several cultivars. Berry [K] refers to the homogenised berry and includes skin, flesh and seeds. Significant correlations are marked in grey (P<0.05).

Cultivar	Juice [K] vs Berry [K]	Berry [K] vs Petiole [K]
Semillon	0.73	0.07
Chardonnay	0.055	0.065
Pinot Gris	0.003	0.17
Shiraz	0.24	0.32
Cab. Sauv.	0.11	0.38
Durif	0.45	-ve slope

In Semillon, there was a strong positive correlation between juice [K] and berry [K] (R^2=0.73). Shiraz and Durif also showed significant correlations (Table 5). The poor correlation between juice [K] and berry [K] in some cultivars may be related to seed number and size as well as the skin: flesh ratio as the skin harbours a substantial amount of berry K.

Berry [K] was positively correlated to petiole [K] in Shiraz and Cabernet Sauvignon. Partitioning and reserve mobilisation play a large role in the amount of K moved to the berry and this may explain the cultivar differences in the relationship between petiole [K] and berry [K].

Hypothesis 5: [Mg] and [Ca] in the petiole are inversely related to petiole [K].

*Hypothesis confirmed for Mg for all cultivars except Pinot Gris (Table 6) and shown for Cabernet Sauvignon (Fig. 6) but not confirmed for Ca (Table 6).

Table 6: R^2 of negative relationships between petiole [K] and petiole [Mg] or [Ca]. Grey highlight indicates significant correlations (P<0.05)

Cultivar	Petiole [K] vs Petiole [Mg]	Petiole [K] vs Petiole [Ca]
Semillon	0.35	0.04
Chardonnay	0.21	0.08
Pinot Gris	0.09	0.21
Shiraz	0.35	0.031
Cab. Sauv.	0.53	0.06
Durif	0.67	0.004

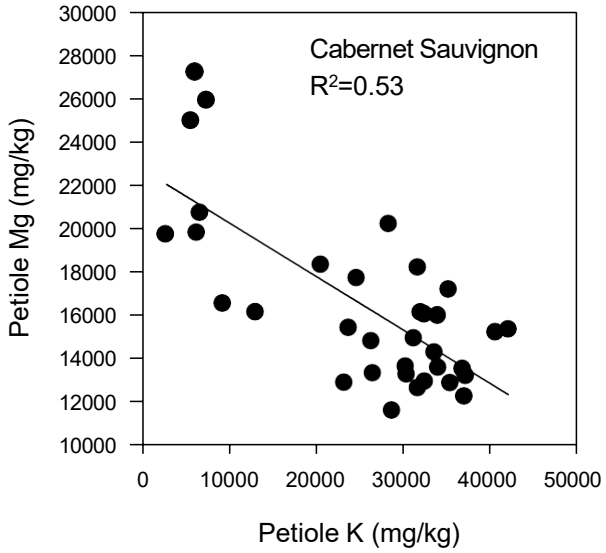


Fig 6. Petiole [Mg] as a function of petiole [K] for Cabernet Sauvignon (P <0.001).

These data suggest that Mg might be an important cation antagonist to K, but it is unlikely that Ca is as well.

Petiole [Mg] less than 0.2% DW (2000 mg/kg) is considered deficient and 0.2-0.3% DW is considered marginal, so none of these vines were deficient or marginal.

Petiole [K] at flowering is used to determine the nutrient standard for K, with concentrations less than 0.6 % DW considered deficient and concentrations in the range 0.6-0.9% DW considered low. Similarly, when sampled at veraison, concentrations <0.6% DW are considered deficient. We may have a few samples in this range (Table 7), however because our sampling was undertaken during late ripening, when most of the nutrients had already been exported from the leaves opposite the bunch, it is difficult to draw any conclusions as to vine nutrient status earlier in the season.

Table 7. Petiole [K] as sampled during late ripening for the cultivars from several locations in the Riverina and Orange wine regions.

Cultivar	Petiole [K] (mg/kg)	Petiole [K] (% DW)
Semillon	12000-25000	1.2-2.5
Chardonnay	4000-38000	0.4-3.8
Pinot Gris	7000-31000	0.7-3.1
Shiraz	5000-45000	0.5-4.5
Cab. Sauv.	3000-42000	0.3-4.2
Durif	9000-27000	0.9-2.7

Hypothesis 6: Berry [K] is inversely related to petiole [Mg] or [Mg]/[K] ratio

*Hypothesis confirmed for two cultivars for the relationship between berry [K] and petiole [Mg] (Figure 7 and Table 8) and for three cultivars for berry [K] and petiole [Mg]/[K] ratio (Table 8).

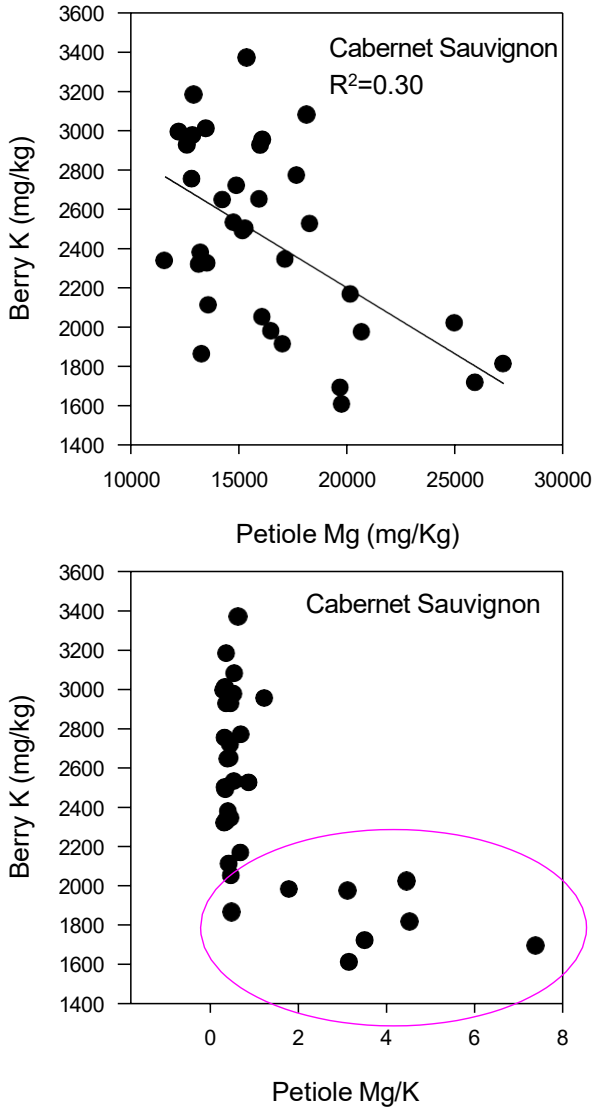


Figure 7. Negative correlation between berry [K] and petiole [Mg] in Cabernet Sauvignon, and relationship between berry [K] and the petiole [Mg]/[K] ratio.

The bottom figure (Fig. 7) shows that at a low petiole [Mg]/[K] ratio, berry [K] varied widely, however as the [Mg]/[K] increased beyond one berry, [K] remained low.

Table 8: R^2 of negative relationships (with Durif the exception, which has a positive relationship) between berry [K] and petiole cations. Grey highlight indicates significant at $P<0.05$.

Cultivar	Berry [K] vs Petiole [Mg]	Berry [K] vs Petiole [Mg]/[K]	Berry [K] vs Petiole ([Mg]+[Ca])/[K]
Semillon	0.44	0.29	0.15
Chardonnay	0.01	0.03	0.05
Pinot Gris	0.03	0.09	0.11
Shiraz	0.04	0.31	0.28
Cab. Sauv.	0.30	0.41	0.38
Durif	+ve slope	+ve slope	+ve slope

The inverse correlations between berry [K] and petiole [Mg] are notable for Semillon and Cabernet Sauvignon. Thus, when the vine contained greater amounts of Mg (as indicated by the petiole concentration), berry [K] was lower. In Shiraz, the negative correlation became apparent when berry [K] was plotted against petiole [Mg]/[K] and ([Mg]+[Ca])/[K]. In Cabernet Sauvignon the relationship became stronger when plotted as a ratio, but not in Semillon.

The correlation did not improve by adding Ca to relative cation proportions (Table 8).

Summary

- Juice pH was positively correlated with juice [K] in all cultivars
- Juice TA was negatively correlated with juice [K] in most cultivars
- Juice [Mg]/[K] and [Ca]/[K] have an influence on juice pH and TA in most cultivars
- Juice [K] was correlated with berry [K] in only some cultivars
- Berry [K] was correlated with petiole [K] (close to harvest) in some cultivars
- Petiole [K] was inversely correlated with petiole [Mg] in most cultivars
- Berry [K] was inversely correlated with petiole [Mg]/[K] in some cultivars

These results suggest that cation antagonism (in particular, by Mg) to reduce berry [K] might be a feasible experimental treatment, based on results from the season of investigation.

2019-20 Riverina/Orange Survey: a focus on Chardonnay and Shiraz

Objective: To better understand the relationship between [K] (in the soil, petioles and berries) and juice pH and TA, with a focus on Chardonnay and Shiraz.

Method: Soil at 10 and 30 cm depths, petioles and berries of own rooted Chardonnay and Shiraz were sampled at various phenological stages during the growing season in Orange and Riverina. Three rows, each as one replicate and consisting of 10 vines, were sampled across each block. One basal bunch and one petiole opposite the bunch were sampled from each vine. The 10 vine samples from each row were pooled to make three replicates for each block. Cation concentrations in dried petioles, homogenised whole berries and juice were assessed by ICP.

Table 1: Petiole, soil and berry sampling across two wine regions in 2019-20 growing season.

Cultivar	Number of blocks sampled	
	Riverina	Orange
Chardonnay	5	5
Shiraz	6	6

Parameter	Time of sampling
Soil at 10 and 30 cm depth	Budburst
Petioles and laminae	Flowering, veraison and harvest
Berries	Veraison and harvest

Background- berry parameters at harvest

Table 2: Regional and cultivar differences in basic berry parameters close to harvest.

	Chardonnay		Shiraz		Significance	LSD
	Orange	Riverina	Orange	Riverina		
Bunch wt (g)	83.6	93.5	77.2	112.9	Region x CV, P<0.05	14.7
Berry fresh wt (g)	0.91	1.06	0.86	1.30	Region x CV, P <0.001	0.09
Berry dry wt (g)	0.226	0.245	0.227	0.331	Region x CV, P <0.001	0.02
TSS (°Brix)	20.7	19.1	21.5	22.4	Region x CV, P <0.05	1.20
pH	3.49	3.45	3.43	3.78	Region x CV, P <0.001	0.089
TA (g/L)	6.32	8.01	6.82	4.02	Region x CV, P <0.001	0.77
Anthocyanins (mg/g fwt)			1.00	0.67	Region, P<0.001	0.11
Phenolics (abs units/g fwt)			1.02	0.72	Region, P <0.001	0.09

Shiraz and Chardonnay bunch weight, berry fresh weight and dry weight were higher in the Riverina than in the Orange wine region.

TSS of Chardonnay was greater in Orange relative to the Riverina. There were no differences in TSS for Shiraz between the two regions. Juice pH of Chardonnay did not differ between Orange and the Riverina. In Shiraz however, pH was higher in the Riverina than in Orange. TA of Chardonnay juice was lower in Orange than in the Riverina but the reverse was apparent in Shiraz with higher TA in Orange relative to the Riverina. Anthocyanins and phenolics of Shiraz berries were higher in Orange relative to the Riverina.

Table 3: Correlations (R^2) between pH, TA and TSS at harvest. Negative and positive refer to the direction of the slope.

Cultivar	pH vs TA	pH vs TSS	TA vs TSS
Chardonnay	0.44 (negative)	0.41 (positive)	0.64 (negative)
Shiraz	0.81 (negative)	0.42 (positive)	0.47 (negative)

pH and TA were more tightly correlated in Shiraz than in Chardonnay. There was a good association between TSS levels and TA or pH in both cultivars.

Table 4: Correlations (R^2) between pH, TA, TSS and berry dry weight at harvest.

Cultivar	TA vs berry dwt	pH vs berry dwt	TSS vs berry dwt
Chardonnay	0.05 (ns)	0.00 (ns)	0.02 (ns)
Shiraz	0.57 (negative)	0.49 (positive)	0.28 (positive)

For Shiraz, smaller berries tended to have higher TA, lower pH and lower Brix. In Chardonnay there were no relationships between berry size and these parameters (Table 4).

Background- leaf and soil parameters

Table 5: Regional and cultivar differences in extractable soil and tissue [K]:

	Chardonnay		Shiraz		Significance	LSD
	Orange	Riverina	Orange	Riverina		
$Soil_{10\,cm}$ [K] (mg/kg)	393.9	550.0	223.9	512	Region <0.001 CV ns Region x CV ns	167.1
$Soil_{30\,cm}$ [K] (mg/kg)	320.4	439.6	182.8	357.2	Region <0.01 CV <0.01 Region x CV ns	150.3
Petiole [K] (mg/kg) at flowering	35246	34635	29676	49666	Region <0.01 CV <0.05 Region x CV <0.001	6283
Petiole [K] (mg/kg) at veraison	59776	37125	46737	49736	Region ns CV ns Region x CV ns	7338
Petiole [K] (mg/kg) at harvest	42316	28394	34365	25876	Region <0.001 CV ns Region x CV ns	7244
Lamina [K] (mg/kg) at flowering	14337	15648	13327	14690	Region <0.05 CV ns Region x CV ns	1598
Lamina [K] (mg/kg) at veraison	17666	13352	15012	14045	Region <0.001 CV ns	2387

					Region x CV ns	
Lamina [K] (mg/kg) at harvest	15035	14735	10779	11005	Region ns CV 0.001 Region x CV ns	2184

Soil extractable [K] (mg/kg) tended to be lower in Orange than the Riverina.

Petiole [K] tended to be higher in Orange for Chardonnay but higher in the Riverina for Shiraz with the exception of the harvest sampling time. Lamina and petiole [K] tended to decline by harvest, possibly due to leaf senescence since they were sampled opposite the basal bunch.

According to the petiole nutrient analysis, petiole [K] and [Mg] at flowering were in the adequate range for all the Chardonnay and Shiraz blocks sampled (Table 6), while petiole [Ca] at flowering was adequate for Chardonnay but low-adequate for Shiraz. Petiole [K], as sampled at flowering, at less than 0.62% DW (6,200 mg/kg) is considered deficient and 0.6-0.9% DW is considered low. Petiole [Mg] at less than 0.2% DW (2000 mg/kg) is considered deficient and 0.2-0.3% DW is considered low, therefore none of these vines were deficient or marginal. Petiole [Ca] at less than 1.2% DW is considered less than adequate. There were a few Shiraz vines in both the Riverina and Orange that fell into this range. These ranges are based on the AWRI Viti-Notes Research to Practice fact sheet (2010).

Table 6: Petiole [K], [Mg] and [Ca] at flowering in reference to the recommended concentrations in two wine regions and two cultivars.

	Chardonnay		**Shiraz**	
Range (%)	**Orange**	**Riverina**	**Orange**	**Riverina**
Petiole K at flowering	1.5-6.9%	2.2 to 5.8%	2.0-3.9%	2.9-5.9%
Recommended range	Adequate	Adequate	Adequate	Adequate
Petiole Mg at flowering	0.4-1.4%	0.4-1.1%	0.4-1.2%	0.3-1.1%
Recommended range	Adequate	Adequate	Adequate	Adequate
Petiole Ca at flowering	1.3-1.9%	1.1-1.7%	1.0-1.7%	0.9-2.0%
Recommended range	Adequate	Adequate	Low-Adequate	Low-Adequate

Both petioles and laminae were sampled to gain a better understanding of which tissue is a better indicator for berry nutrients (see hypothesis 4).

Table 7: Regression (R^2) of lamina [K] vs petiole [K] at different sampling times in the season. The correlation was significant at all three sampling times, and all were positive associations.

Sampling time	**Lamina [K] vs Petiole [K]**
Flowering	0.32
Veraison	0.46
Harvest	0.44

Hypothesis 1: Juice pH is positively correlated with juice [K], and juice TA is negatively correlated with juice [K].

*Hypothesis supported for Shiraz, but not Chardonnay.

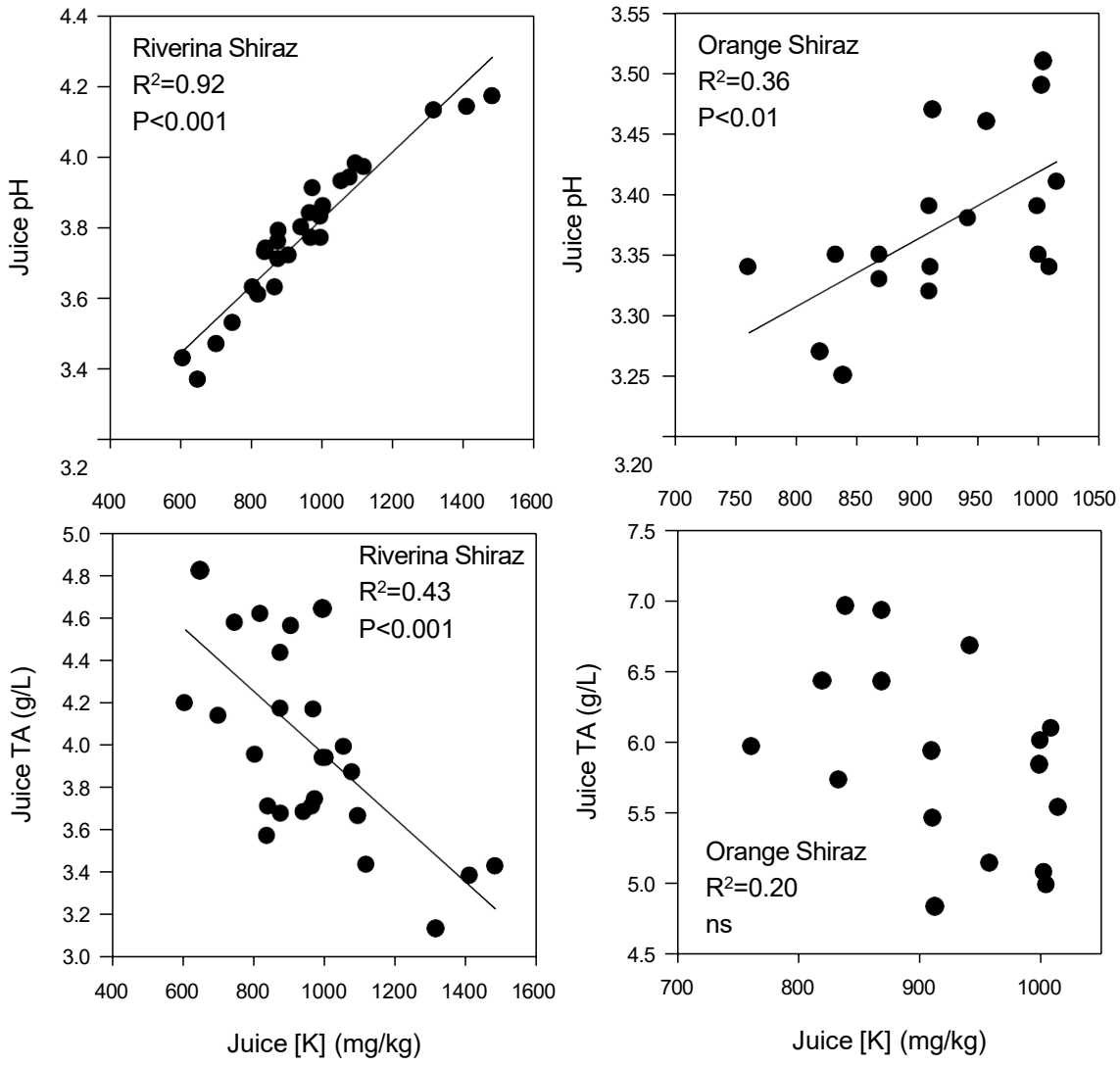


Figure 1. Correlations between juice [K] and juice pH or TA for Riverina and Orange Shiraz. Each data point on the graph represents the average of a pooled ten-vine replicate, with one bunch per vine.

Juice [K] of Shiraz berries from the Riverina varied to a greater extent (600-1500 mg/kg) than juice [K] from Orange (750 to 1000 mg/kg). Juice pH, however, was positively correlated with juice [K] in both regions. TA was significantly negatively correlated with juice [K] in the Riverina only, however there was a tendency for the same trend in Orange. The correlations were not significant for Chardonnay in the Riverina or Orange (data not shown).

Hypothesis 2: Higher juice [Mg] and [Ca] is associated with lower pH and higher TA

*Hypothesis supported for Shiraz in both regions, but not for Chardonnay.

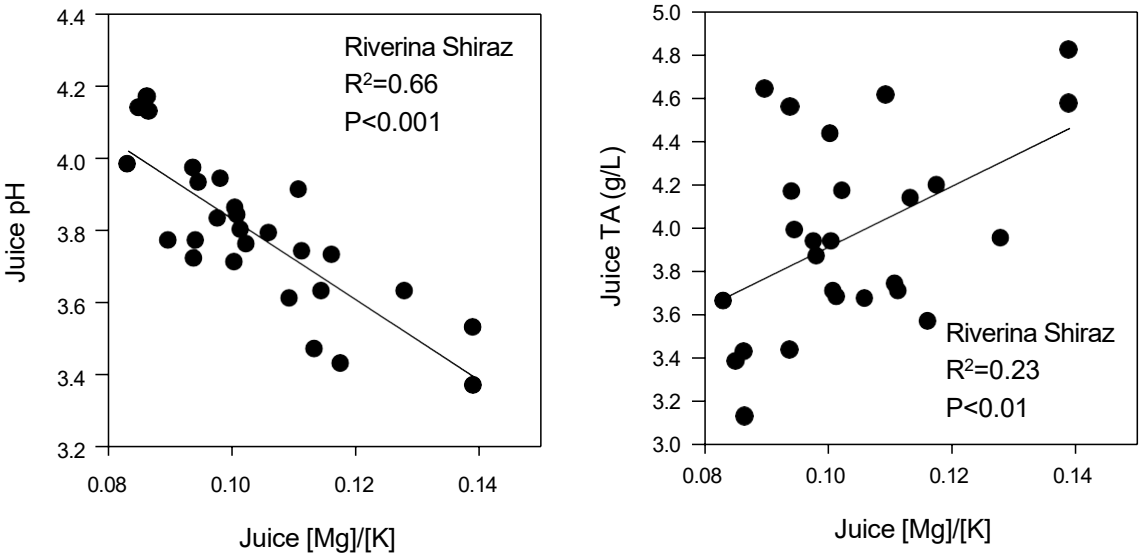


Figure 2. Juice pH and TA plotted against juice [Mg]/[K] ratio for Riverina Shiraz.

As the proportion of [Mg] relative to [K] increases the pH declines and the TA increases (Figure 2). The [Ca]/[K] was also important to Shiraz juice TA in Orange (Table 8).

Table 8: Correlations (R^2) between juice pH (negative slope) or TA (positive slope) with juice [Mg]/[K], [Ca]/[K] and ([Mg]+[Ca])/[K] ratios for Shiraz and Chardonnay. Grey highlight indicates significant at P<0.05 or greater.

Region x Cultivar	**Juice pH**			**Juice TA**		
	Juice [Mg]/[K]	Juice [Ca]/[K]	Juice ([Mg]+[Ca])/[K]	Juice [Mg]/[K]	Juice [Ca]/[K]	Juice ([Mg]+[Ca])/[K]
Riverina Shiraz	0.66	0.55	0.62	0.23	0.13	0.18
Orange Shiraz	0.29	0.20	0.31	0.42	0.44	0.58
Riverina Chardonnay	0.11	0.03	0.07	0.01	0.00	0.00
Orange Chardonnay	0.02	0.02	0.02	0.00	0.00	0.00

There were no significant correlations between juice pH or TA and juice [Mg]/[Ca].

Hypothesis 3: There are positive correlations between soil [K] and leaf (petiole or lamina) [K]

*Hypothesis supported for Chardonnay and Shiraz.

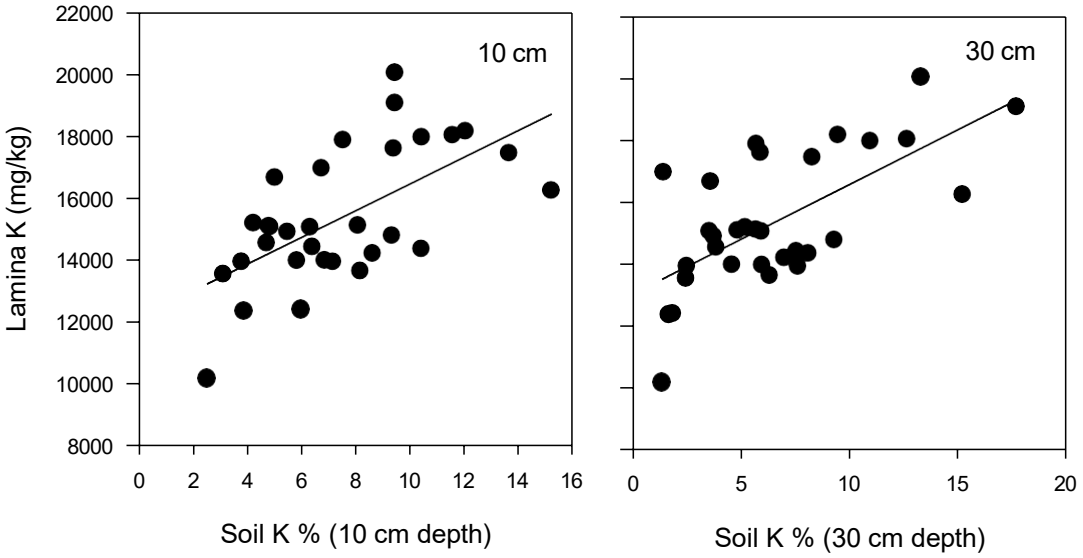


Figure 3. Chardonnay lamina [K] at flowering as a function of soil exchangeable K (% of CEC) at 10 or 30 cm depth. P<0.001 for both correlations.

Table 9: Correlations (R^2) between leaf (petiole or lamina) [K] and soil exchangeable K (% of CEC) for Shiraz and Chardonnay. Grey highlight indicates significant at P<0.05 or better. Petioles and laminae were sampled at flowering, veraison and harvest.

Leaf sampling time		**Chardonnay**	**Shiraz**	**Slope**
Flowering	Petiole $K_{flowering}$ vs Soil $_{10\,cm}$ K%	0.17	0.35	pos
	Petiole $K_{flowering}$ vs Soil $_{30\,cm}$ K%	0.18	0.14	pos
	Lamina $K_{flowering}$ vs Soil $_{10\,cm}$ K%	0.37	0.08	pos
	Lamina $K_{flowering}$ vs Soil $_{30\,cm}$ K%	0.44	0.03	pos
Veraison	Petiole $K_{veraison}$ vs Soil $_{10\,cm}$ K%	0.06	0.32	pos
	Petiole $K_{veraison}$ vs Soil $_{30\,cm}$ K%	0.02	0.42	pos
	Lamina $K_{veraison}$ vs Soil $_{10\,cm}$ K%	0.26	0.02	pos
	Lamina $K_{veraison}$ vs Soil $_{30\,cm}$ K%	0.37	0.06	pos
Harvest	Petiole $K_{harvest}$ vs Soil $_{10\,cm}$ K%	0.04	0.05	pos
	Petiole $K_{harvest}$ vs Soil $_{30\,cm}$ K%	0.15	0.05	pos
	Lamina $K_{harvest}$ vs Soil $_{10\,cm}$ K%	0.16	0.05	pos
	Lamina $K_{harvest}$ vs Soil $_{30\,cm}$ K%	0.18	0.01	pos

Petiole [K] of Shiraz at flowering and veraison were positively correlated with soil exchangeable K %. For Shiraz, lamina [K] was not a good indicator of soil [K] at any sampling stage. For Chardonnay, however, the lamina was a better indicator than the petiole. Harvest sampling was not a good indicator of soil nutrient levels.

Hypothesis 4: There are positive correlations between juice [K] and berry [K]

*Hypothesis supported for Chardonnay (Fig. 4).

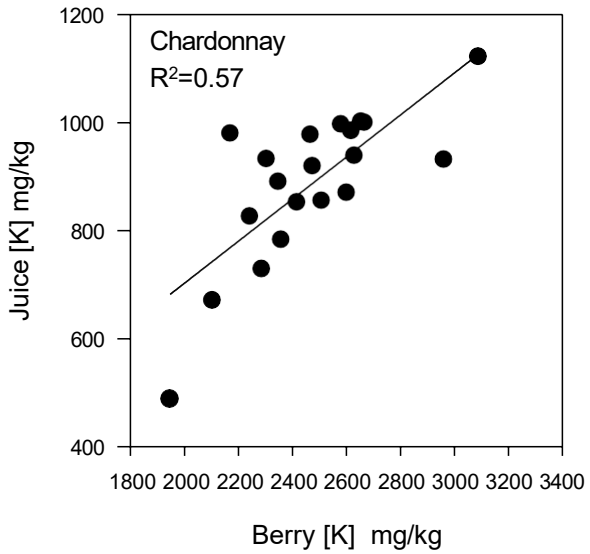


Figure 4. Correlation between berry [K] and juice [K] in Chardonnay.

In Chardonnay there were non-significant correlations between petiole or lamina [K] and berry [K] (data not shown).

Hypothesis 5: Soil [Mg] and [Ca] have an influence on petiole [K] concentrations

*Hypothesis supported for both cultivars

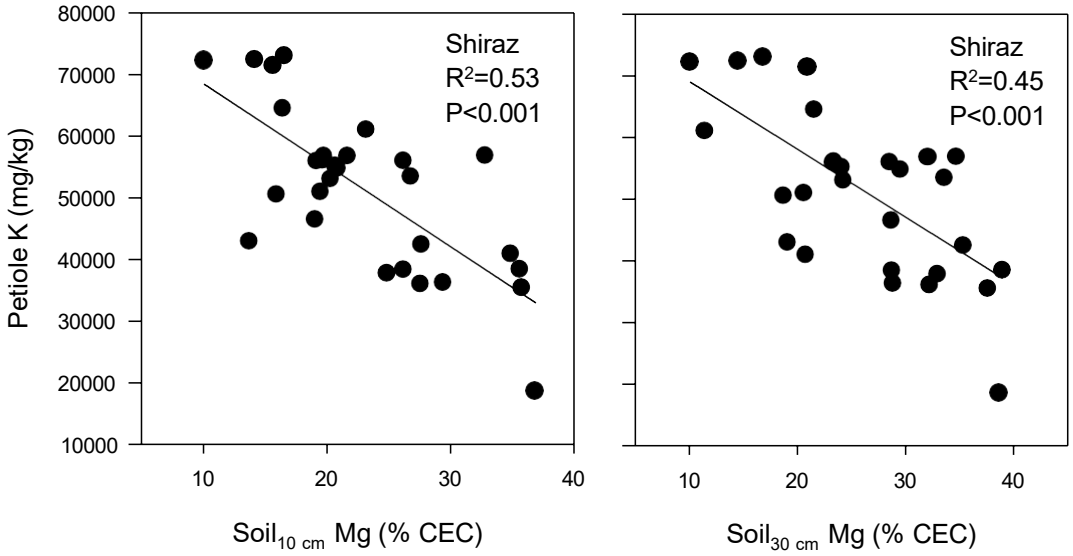


Figure 5. Shiraz petiole [K] at veraison as a function of soil exchangeable Mg (% of CEC) at 10 and 30 cm depths (combined data from both regions).

The leaf (lamina or petiole) [K] at flowering and veraison was inversely correlated with soil exchangeable Mg %, [Mg]/[K] and [Ca]/[K] (Table 10, and Fig.5, for petiole [K] at veraison). For Shiraz at flowering, the correlations with [Mg]/[K] and [Ca]/[K] were significant for petiole (not for laminae) at 10 cm, while at veraison they were significant for petiole and laminae at both soil depths. For Chardonnay at flowering, the correlations with [Mg]/[K] and [Ca]/[K] were significant for laminae (not for petioles) at both soil depths, while at veraison they were significant for lamina [Mg]/[K] at both soil depths but for [Ca]/[K] it was evident for laminae (not for petioles) at 30 cm depth (Table 10). This suggests that the soil cation ratio influences vine [K] levels. This is particularly apparent at the veraison leaf sampling date in Shiraz, but also at flowering for laminae of Chardonnay.

Table 10. Correlations (R^2) between petiole and lamina [K] and soil [Mg]/[K]. Petiole and laminae [K] are in mg/kg, while for soil, K% refers to the K cmol(+) kg/ECEC cmol(+) kg X100. Blue highlight indicates correlation significance P<0.05 or better.

Soil nutrient	Leaf sampling time		**Chardonnay**	**Shiraz**	**Slope**
Mg/K	Flowering	Petiole $K_{flowering}$ vs Soil $_{10\ cm}$ Mg/K	0.22	0.34	neg
		Petiole $K_{flowering}$ vs Soil $_{30\ cm}$ Mg/K	0.13	0.18	neg
		Lamina $K_{flowering}$ vs Soil $_{10\ cm}$ Mg/K	0.39	0.14	neg
		Lamina $K_{flowering}$ vs Soil $_{30\ cm}$ Mg/K	0.23	0.06	neg
	Veraison	Petiole $K_{veraison}$ vs Soil $_{10\ cm}$ Mg/K	0.16	0.45	neg
		Petiole $K_{veraison}$ vs Soil $_{30\ cm}$ Mg/K	0.09	0.38	neg

		Lamina $K_{veraison}$ vs Soil $_{10\ cm}$ Mg/K	0.27	0.46	neg
		Lamina $K_{veraison}$ vs Soil $_{30\ cm}$ Mg/K	0.29	0.39	neg
Ca/K	Flowering	Petiole $K_{flowering}$ vs Soil $_{10\ cm}$ Ca/K	0.21	0.37	neg
		Petiole $K_{flowering}$ vs Soil $_{30\ cm}$ Ca/K	0.23	0.23	neg
		Lamina $K_{flowering}$ vs Soil $_{10\ cm}$ Ca/K	0.33	0.09	neg
		Lamina $K_{flowering}$ vs Soil $_{30\ cm}$ Ca/K	0.33	0.03	neg
	Veraison	Petiole $K_{veraison}$ vs Soil $_{10\ cm}$ Ca/K	0.03	0.35	neg
		Petiole $K_{veraison}$ vs Soil $_{30\ cm}$ Ca/K	0.18	0.32	neg
		Lamina $K_{veraison}$ vs Soil $_{10\ cm}$ Ca/K	0.18	0.35	neg
		Lamina $K_{veraison}$ vs Soil $_{30\ cm}$ Ca/K	0.30	0.33	neg

Several of the Orange vineyards that had relatively low petiole [Mg] (5000 mg/kg or 0.5%) showed higher petiole [K] (with very good correlation). Therefore, K may have been compensating for the low Mg.

Hypothesis 6: Lamina [K] has an influence on juice [K]

*Hypothesis supported for Riverina Shiraz

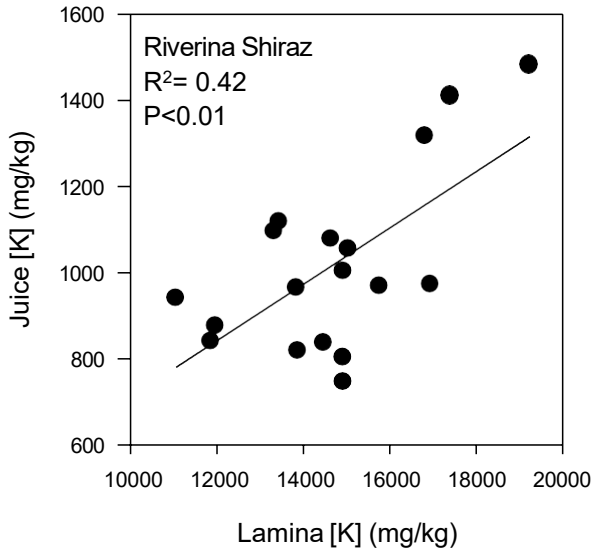


Figure 6. Juice [K] as a function of lamina [K] in Riverina Shiraz

Juice [K] and lamina [K] were positively correlated in Riverina Shiraz indicating that the lamina [K] has an influence on juice [K].

This relationship was not significant for Chardonnay in the Riverina or Orange.

Hypothesis 7: Soil cations have an influence on juice [K]

*Hypothesis supported for Riverina Shiraz

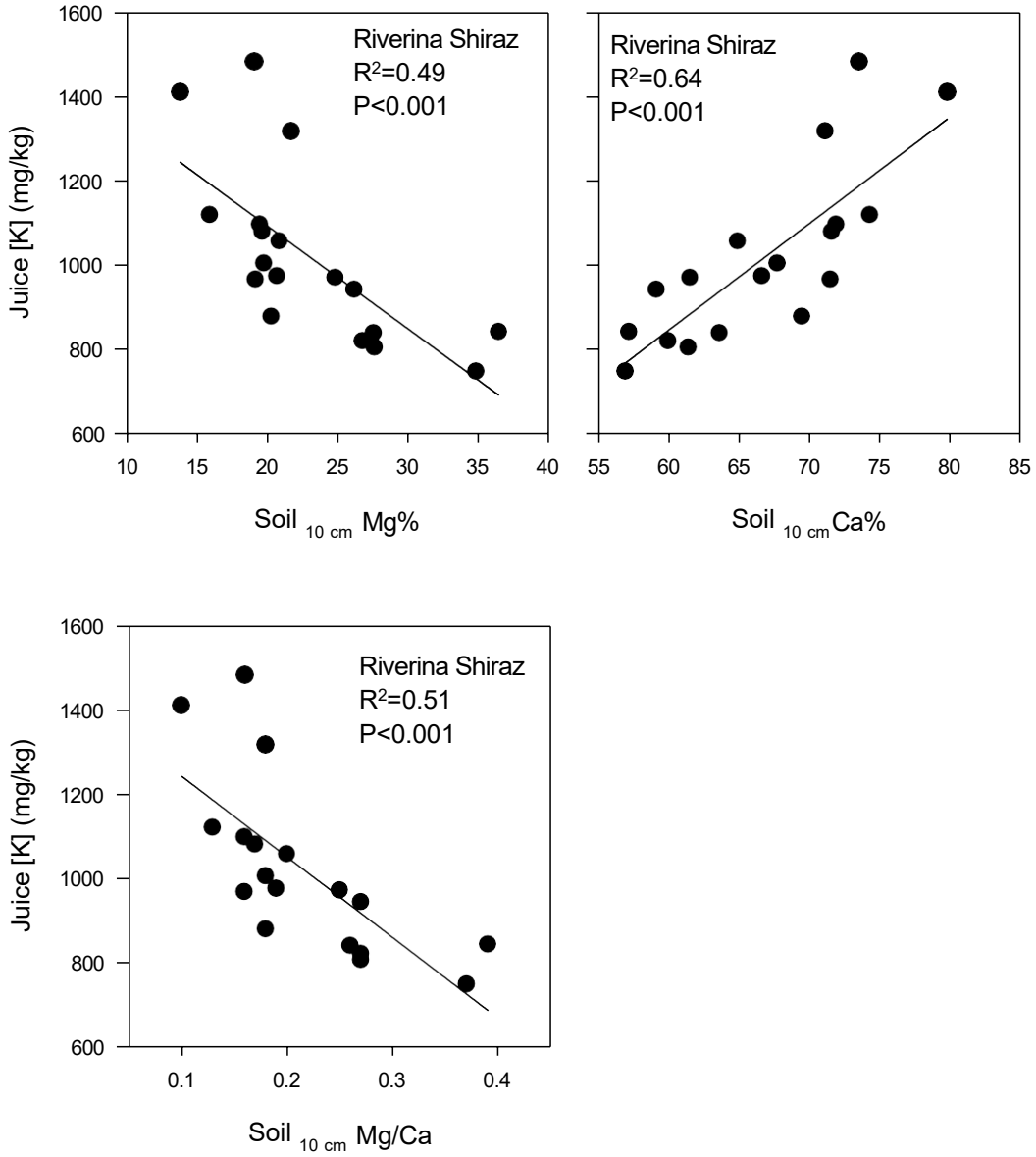


Figure 7. Riverina Shiraz juice [K] as a function of soil exchangeable Mg (% of CEC), soil exchangeable Ca (% of CEC) and soil [Mg]/[Ca] at a 10 cm depth.

As soil exchangeable Mg % increased juice [K] declined in Riverina Shiraz (Fig. 7). An unexpected result, however, was the positive relationship between soil exchangeable Ca % and juice [K]. In this instance Ca appears to promote berry K uptake. Notably, the [Mg]/[Ca] ratio has a slightly stronger influence on juice [K] than soil exchangeable Mg %.

(Ca may have been applied as a form of N fertiliser or during liming. We do not have soil N values, however correlations between leaf [N] and soil [Ca] were strong (R^2=0.62) and so may partly explain this trend. Increased vine vigour has been associated with higher N and higher K.)

There was no relationship between soil pH and juice [K].

These relationships were not significant for the Riverina Chardonnay.

Hypothesis 8: Soil cations have an influence on juice pH and TA

*Hypothesis supported for Riverina Shiraz and Riverina Chardonnay.

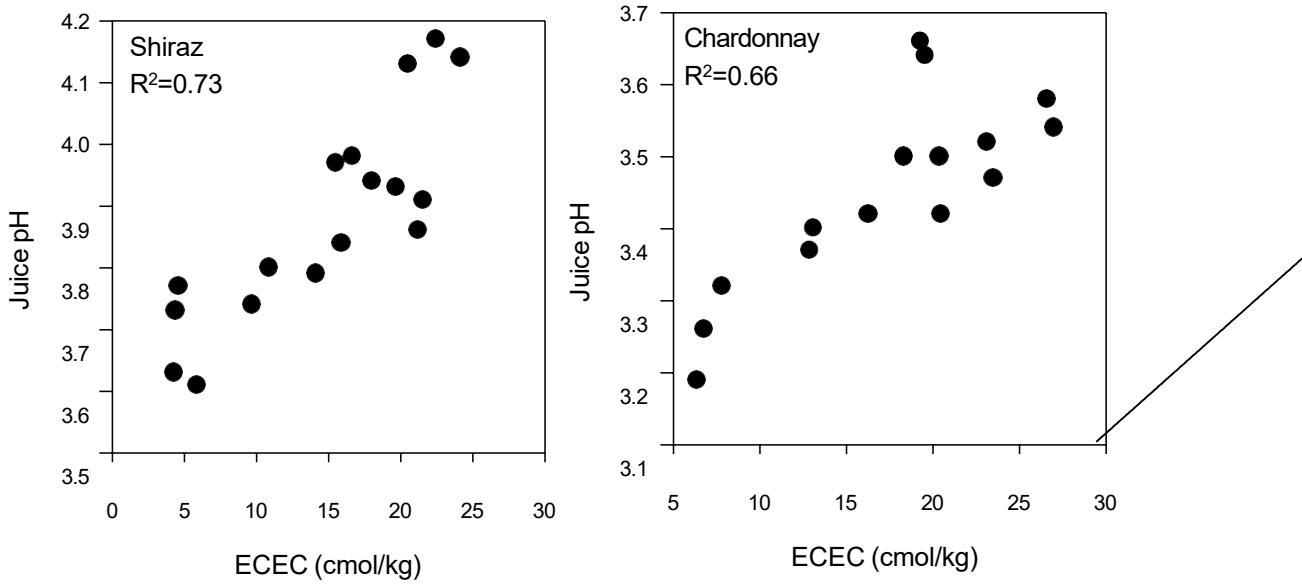


Figure 8. Juice pH as a function of soil effective cation exchange capacity (ECEC) as measured at 30 cm depth.

In both Shiraz and Chardonnay there were strong positive correlations between soil effective cation exchange capacity (ECEC) and juice pH (Fig. 8). This relationship may be the direct result of greater availability of nutrients resulting in more rapid ripening. This is supported by the observation that the relationships were also apparent for TSS and TA in Chardonnay (data not shown). However, TSS and TA were not related to ECEC for Shiraz, indicating there are other factors driving this relationship.

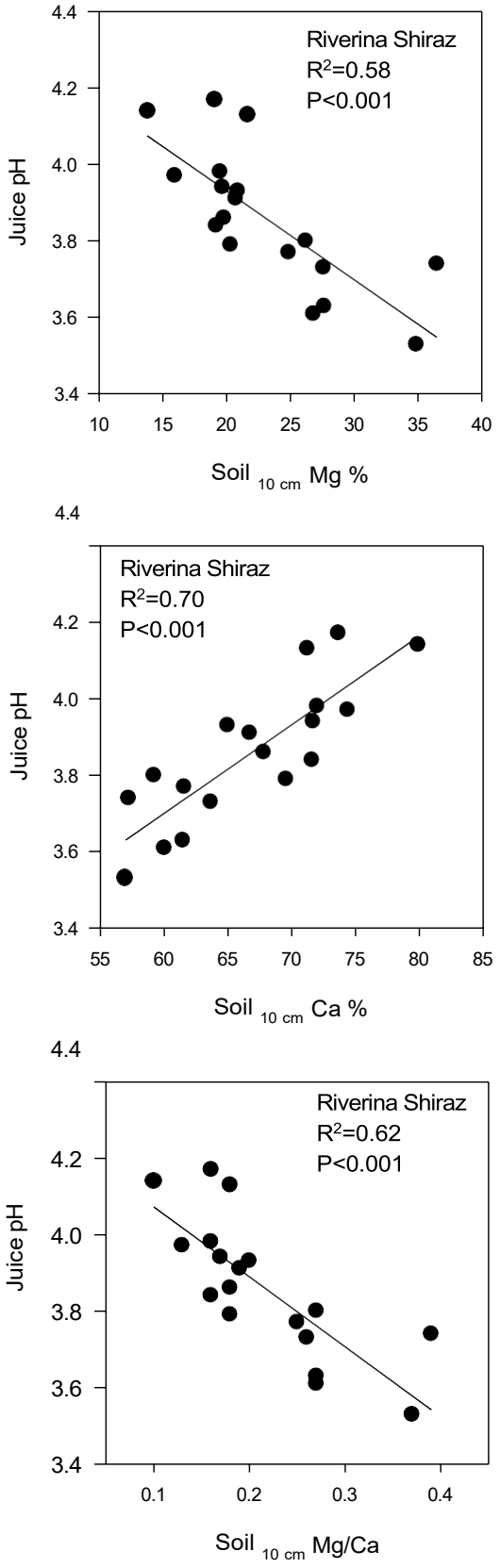


Figure 9. Juice pH of Riverina Shiraz in response to soil exchangeable Mg (% of CEC) and Ca (% of CEC) at 10 cm depth and soil [Mg]/[Ca] also at 10 cm depth.

Riverina Shiraz juice pH declined as soil exchangeable Mg % increased but there was an upward trend with exchangeable Ca % (Fig. 9). The soil [Mg]/[Ca] ratio has a slightly stronger influence on juice pH than [Mg] or Mg %. As the ratio increases the pH declines.

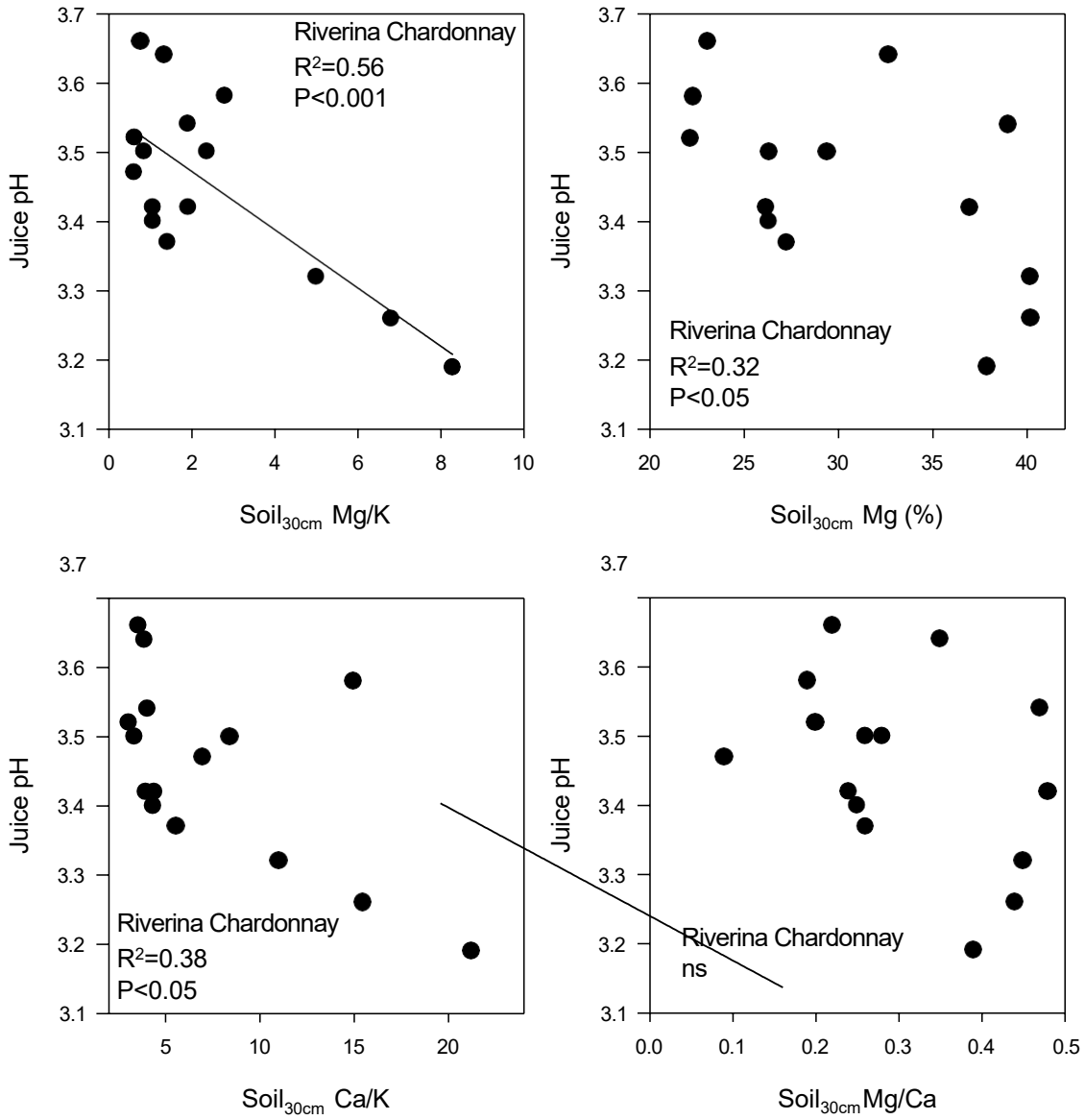


Figure 10. Riverina Chardonnay juice pH as a function of soil [Mg]/[K], soil exchangeable Mg (% of CEC), soil [Ca]/[K], and soil [Mg]/[Ca] at a 30 cm depth.

Similar to the Riverina Shiraz, Riverina Chardonnay juice pH was also influenced by the soil cations, notably negative correlations with soil exchangeable Mg (% of CEC), [Mg]/[K], and [Ca]/[K] at 30 cm (Fig. 10). Unlike Shiraz, soil [Mg]/[Ca] did not have an influence on juice pH of Chardonnay.

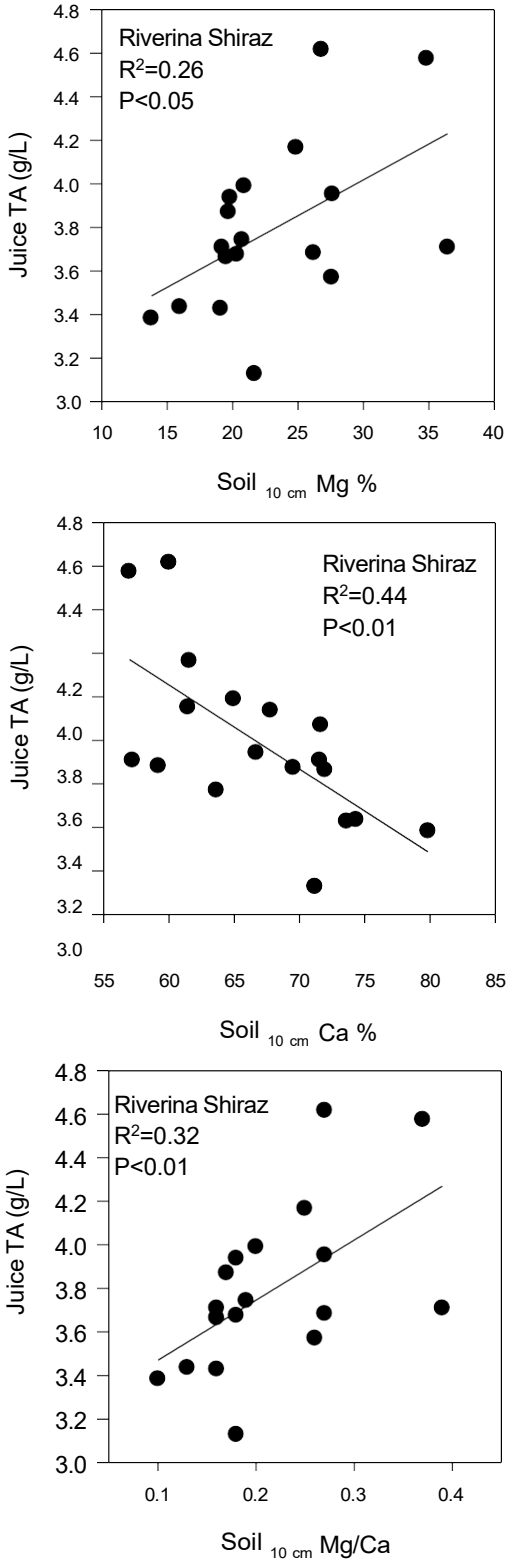


Figure 11. Juice TA of Riverina Shiraz in response to soil exchangeable Mg (% of CEC) and Ca (% of CEC) at 10 cm depth and soil [Mg]/[Ca] also at 10 cm depth.

The relationships are not as significant for TA (Fig. 11) as they are for pH in the Riverina Shiraz (Fig. 9). However, as soil % Mg increased, juice TA increased. Soil [Mg]/[Ca] ratio at 10 cm has a stronger influence on juice TA than [Mg] or Mg %. These relationships were not apparent in the Orange sites. These soil parameters did not have an influence on Chardonnay TA in the Riverina or in Orange.

Hypothesis 9: Vine (petiole and lamina) cations have an influence on juice pH and TA

*Hypothesis supported for Riverina Shiraz and Riverina Chardonnay.

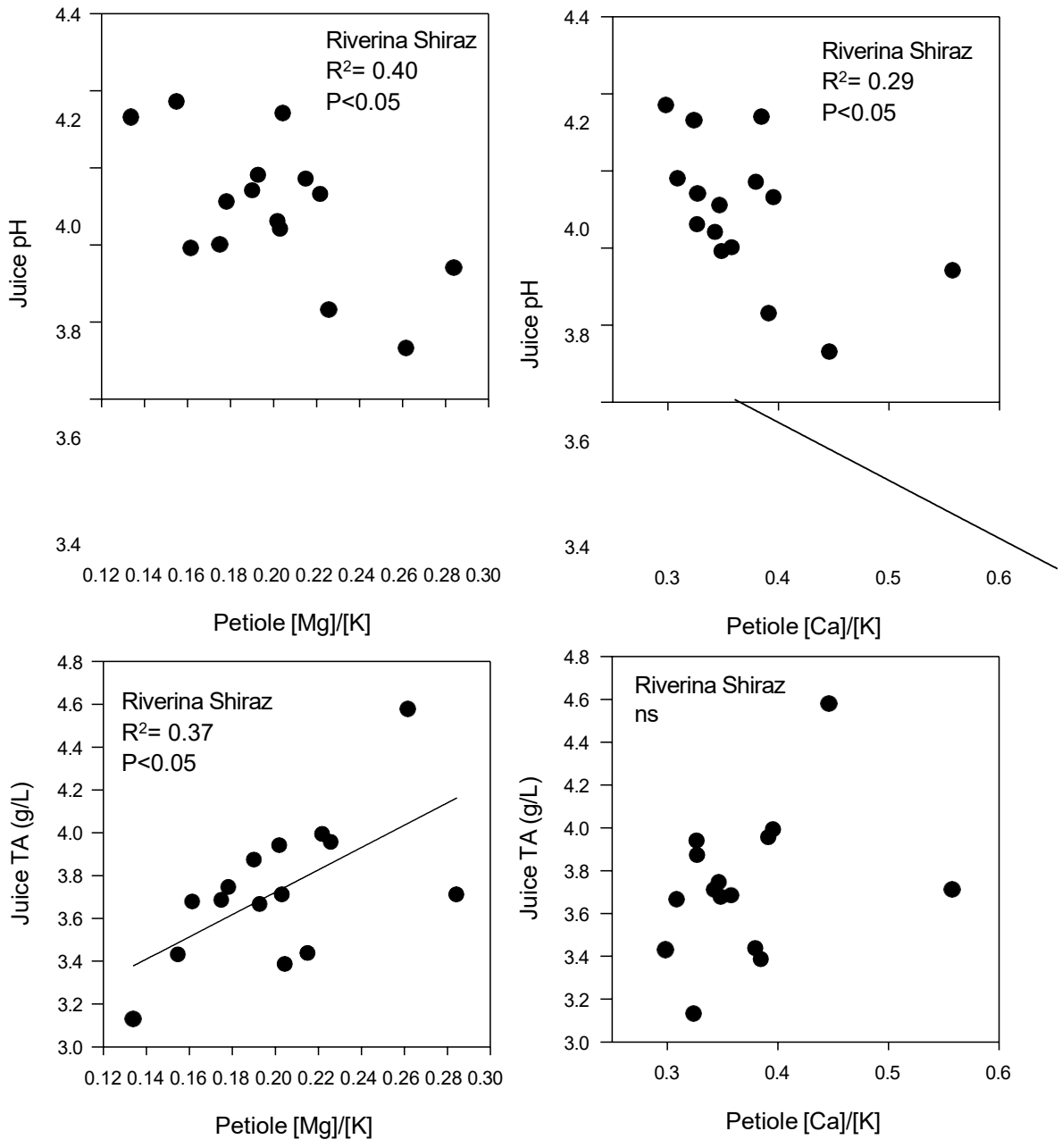


Figure 12. Juice pH and TA as a function of petiole [Mg]/[K] and [Ca]/[K] for Shiraz sampled at flowering in the Riverina.

Petiole [Mg]/[K] had a stronger influence than petiole [Ca]/[K] on both pH and TA (Fig. 12). As the proportion of Mg increases the pH declines and the TA increases. The [Ca]/[K] relationship was significant for pH only.

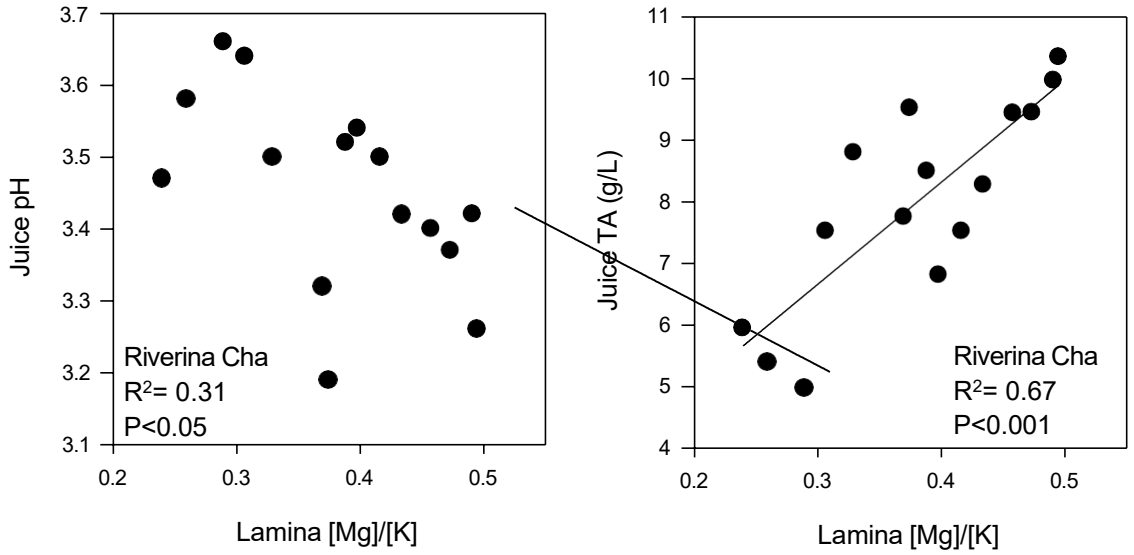


Figure 13. Juice pH and TA as a function of lamina [Mg]/[K] for Chardonnay sampled at flowering in the Riverina. Cha = Chardonnay.

Riverina Chardonnay lamina [Mg]/[K] was negatively correlated with juice pH and positively correlated with TA (Fig. 13). The correlations were slightly tighter for the lamina than for the petiole (data not shown). Lamina [Ca]/[K] did not have an influence on pH and TA (data not shown).

Summary

- Juice pH was positively correlated with juice [K] for Shiraz in both regions, but not for Chardonnay in either region.
- Juice TA was negatively correlated with juice [K] for Shiraz in both regions, but not for Chardonnay.
- Juice pH was negatively correlated with juice [Mg]/[K] while juice TA was positively correlated with this parameter for Shiraz in both regions, but not for Chardonnay in either region.
- Soil K% was positively correlated with lamina or petiole [K] for both cultivars across both regions
- Juice [K] was positively correlated with berry [K] in Chardonnay. It was not assessed in Shiraz.
- Soil Mg %, [Mg]/[K] and [Ca]/[K] were all inversely correlated with leaf [K] in both cultivars
- Lamina [K] was positively correlated with juice [K] in Riverina Shiraz, but not for Orange Shiraz or Chardonnay in either region
- Juice [K] was negatively correlated with soil Mg % and soil [Mg]/[Ca] in Riverina Shiraz but not for Orange Shiraz, or Chardonnay in either region
- Juice pH was inversely correlated with soil Mg % and soil [Mg]/[Ca] in Riverina Shiraz but not for Orange Shiraz. Juice TA was positively correlated with these two parameters. Riverina Chardonnay juice pH was inversely correlated with soil Mg %, [Mg]/[K] as well as soil [Ca]/[K]. These parameters did not have an influence on TA, however, for this cultivar.
- Riverina Shiraz juice pH was inversely correlated with petiole [Mg]/[K] and [Ca]/[K]. TA was positively correlated with petiole [Mg]/[K]. Riverina Chardonnay juice pH was similarly negatively correlated with lamina [Mg]/[K], while TA was positively correlated with this parameter.

Table 11. Direction of significant slopes between various juice, leaf and soil parameters for Riverina Shiraz and Riverina Chardonnay. 'X' means the correlation was not significant.

Riverina Shiraz		**Juice [K]**	**Juice [Mg/[K]**	**Leaf [Mg/[K]**	**Leaf [Ca]/[K]**	**Soil Mg%**	**Soil [Mg/[K]**	**Soil [Ca]/[K]**	**Soil [Mg]/[Ca]**
Juice pH		+ve	-ve	-ve	-ve	-ve	X	X	-ve
Juice TA		-ve	+ve	+ve	X	+ve	X	X	+ve
Juice K				-ve	-ve	-ve	X	X	-ve
Riverina Chardonnay		**Juice [K]**	**Juice [Mg/[K]**	**Leaf [Mg/[K]**	**Leaf [Ca]/[K]**	**Soil Mg%**	**Soil [Mg/[K]**	**Soil [Ca]/[K]**	**Soil [Mg]/[Ca]**
Juice pH		X	X	-ve	X	-ve	-ve	-ve	-ve
Juice TA		X	X	+ve	X	X	X	X	X
Juice K				X	-ve	X	X	X	X

Take home message: When leaf (petiole or lamina) [Mg]/[K] is high the juice pH is more likely to be lower and TA is more likely to be higher in both Shiraz and Chardonnay.

Potted-Vine Nutrition Trial

Abstract

Potassium (K^+) is the most predominant cation in grape berries and is integral to many of the physiological functions of grapevines. At the same time, the negative consequences of high [K] in grape berries on wine pH and quality are well established. This study aimed to understand whether high [Mg] in the growing medium has an antagonistic effect on the uptake of K by the vine and if this would have consequent effects on [K] in the berry. Three-year-old Shiraz vines grown in sand culture were root fertilised fortnightly from budburst to berry maturity with a complete nutrient formulation based on a modified Hoagland's solution (control), high Mg, or high K. Nutrient levels in the leaves, berries and juice were assessed and juice TSS, pH, TA, malic acid, tartaric acid and YAN were also analysed. The high K treatment increased [K] in the petioles, and the high Mg treatment increased petiole [Mg]. Petiole [K] was inversely correlated with [Mg] so that high [Mg] was associated with low [K], thus suggesting the presence of cation antagonism at the vine level. The high Mg treatment also significantly increased [Mg] in the berries and juice, however the high K treatment did not increase [K] in these reproductive components. Notably, juice [K] was inversely correlated with petiole [Mg]. Despite no direct treatment effects on juice pH or TA, the combined data showed a significant positive correlation between juice [K] and juice pH. The petiole and lamina [Mg]/[K] ratios were inversely correlated to juice pH. However, there was no association with TA, possibly because TA levels were very high. The results of this potted-vine study suggest that at least juice pH may respond to Mg antagonism, but it is likely that longer-term applications of Mg may be required to have a strong influence on berry composition.

Introduction

K has a number of essential roles in the growth and development of the grapevine. This cation maintains cellular function, berry growth and long distance transport of sugars, amino acids and organic acids to the berry (Rogiers et al. 2017) That said, the negative consequences of high K on wine pH are fairly well established (Mattick et al. 1972; Somers, 1977; Mpelasoka et al. 2003; Walker and Blackmore, 2012; Walker and Clingeleffer, 2016). High [K] in the grapes can contribute to increased wine pH because it binds with tartaric acid once the berry is crushed, forming potassium bitartrate crystals. The relatively high pH requires expensive additions of tartaric acid, significantly elevating winery costs. Also, many reports suggest that wines with natural acidity are preferred over wines that have had acid additions (Howard 2015). K affects wine colour (Boulton, 1980), can alter microbiological stability and fermentation processes, increases oxidative processes and potentially alters taste and mouthfeel in both red and white wines. It is an issue that affects warm growing regions globally (De Orduna, 2010).

The balance between maintaining optimum levels of K to ensure physiological functioning while restricting excessive accumulation of K in grape berries is a challenge to the wine industry, especially in warmer regions. The relationship between soil cations, vine (petiole or lamina) [K], berry [K] and juice quality parameters is not clearly understood. We tested the hypothesis that vine K uptake can be reduced by soil application of competing cations such as Mg. The partial substitution of these ions by the vine during root uptake may satisfy the plant's essential requirements without entering into the excess zone. The objective of this trial was to provide new insights into the potential of soil application of Mg to reduce K uptake through the root system of grapevines. The specific aims of this study were to:

- Apply K and Mg to the growing medium of potted vines and assess for treatment effects on vine nutrient status and berry/ juice cation concentrations.
- Assess the impact of K and Mg fertilisation on berry [K] and juice quality parameters such as pH, TA and organic acids.

Materials and Methods

Plant growth conditions and nutrient treatments

Three-year-old Shiraz vines were grown in 20 L pots containing washed river sand and established in greenhouse conditions under natural light with an average air temperature of 25 °C during the day and 16 °C during the night. Eight shoots with two bunches on each shoot were retained on each plant, and the shoots were staked vertically. Each shoot was pruned back to 15 leaves. A drip irrigation system was set up with an output of 2 L/hr water. From budburst to fruit set (until all the 15 leaves developed), all vines were irrigated with 1 L water/vine every day, followed by 2 L/vine from fruit set to harvest. The vines were placed in a randomised block design across five rows, with each row consisting of two vines of each treatment. The treatments consisted of three different nutrient regimes: Control (a complete nutrition made based on Hoagland's solution), high Mg and high K (Table 1). The nutrient solutions were applied (200 mL per vine) fortnightly starting from budburst until harvest, once berries were mature. This trial was carried out over two growing seasons with the same treatments in the second year.

Table 1. Ion concentrations of the treatment nutrient solutions formulated based on a modified Hoagland's solution, and in the run-off soil solution after passage through the root zone.

Ions	Concentration of ions in the nutrient solutions (mM)			Concentration of ions in the run-off soil solution (mM)*		
	Control	High K	High Mg	Control	High K	High Mg
K^+	39.45	123.90	39.45	3.95	12.39	3.95
Ca^{2+}	46.20	46.20	46.20	4.62	4.62	4.62
Mg^{2+}	25.74	25.14	78.24	2.57	2.51	7.82
NH_4^+	42.60	42.60	42.60	4.26	4.26	4.26
Cl^-	31.80	42.00	40.80	3.18	4.20	4.08
NO_3^-	128.69	127.49	128.69	12.87	12.75	12.87
SO_4^{2-}	24.00	40.20	72.00	2.40	4.02	7.20
$H_2PO_4^-$	63.30	63.30	63.30	6.33	6.33	6.33
Fe EDTA$^-$	0.56	0.56	0.56	0.056	0.056	0.056
Mn^{2+}	0.11	0.11	0.11	0.011	0.011	0.011
Zn^{2+}	0.09	0.09	0.09	0.009	0.009	0.009
Cu^{2+}	0.05	0.05	0.05	0.005	0.005	0.005
MoO_4^{2-}	0.03	0.03	0.03	0.003	0.003	0.003
B^{2+}	1.09	1.09	1.09	0.109	0.109	0.109

Plant tissue sampling

At flowering (80% cap fall), veraison (50% berries soft) and harvest, leaves opposite inflorescences/bunches were sampled from the basal bunch node position, with an inflorescence/bunch opposite each sampled leaf. Those inflorescences/bunches were also sampled. Each leaf was separated into petiole and lamina. Whole flowers and whole berries were separated from the rachis.

Nutrient analysis

Laminae, petioles and flowers were dried at 60 °C for one week and ground using a tissue lyser (TissueLyser II, Qiagen, Chadstone, Victoria). 100 mg of the ground tissue was analysed for [K], [Ca] and [Mg] by inductively coupled plasma atomic emission spectroscopy (ICP-AES) at the Environmental and Analytical Laboratories at Charles Sturt University, Wagga Wagga. Intact berries were separated from one bunch of each replicate and 50 berry sub-samples were frozen for future analysis. Berry samples were defrosted, homogenised and 500 mg of the homogenate was used for [K], [Ca] and [Mg] analysis by ICP-AES.

Juice TSS, pH, TA and Tartaric acid

After subsampling, the rest of the grape samples were juiced. Fresh juice samples were analysed for TSS with a digital refractometer (Pocket PAL-1, Atago, Japan). Juice pH and TA were assessed using an autotitrator (Metrohm Fully Automated 59 place Titrando System, Switzerland).

Statistical methods.

A one-way ANOVA, followed by Tukey's multiple comparison test was applied to nutrients in the petioles, laminae, berries and juice, and to the juice maturity parameters to compare the main effects of treatments. *P* values <0.05 were considered significant. All analyses were performed using GraphPad Prism 8 (GraphPad Software, San Diego, California, USA).

Results and Discussion

There were few treatment effects in the 2020/21 growing season. This may be partially attributed to difficulties in maintaining equal plant water status across all the vines. Additionally, the second season was particularly short as a result of sooty mold that developed under the extremely wet conditions that occurred in 2021/22. Despite these difficulties, the results of the second season point towards a potential role for Mg antagonism in manipulating berry composition.

Leaf cation concentrations in response to nutrient treatments

High K treatment

In both the 2020/21 season (Table 1) and the 2021/22 season (Table 2), the high K application resulted in greater [K] in the leaf petiole at veraison, however this was not apparent at flowering or harvest. There was no impact of the high K treatment on [K] in the lamina, with the exception at harvest in 2022. The high K treatment did not have an effect on the [Mg] or [Ca] in either leaf tissue in 2020/21. In 2021/22, however, high K did decrease [Mg] in the petiole at flowering.

Table 1. Cation concentration in the vegetative organs after treatment with high K or Mg in the 2020/21 growing season

Growth stage	Tissue	Nutrient (mg/kg)	Treatments			*P-value*
			High K	High Mg	Control	
Flowering	Petiole	Ca	11123	10933	10433	ns
		K	43771	38158	41184	ns
		Mg	3330[b]	5502[a]	3324[b]	0.0006
	Lamina	Ca	16141	14307	13580	ns
		K	20380	16394	17271	ns
		Mg	4910	5316	3951	ns
Veraison	Petiole	Ca	14961	14368	13472	ns
		K	33395[a]	23830[b]	26701[b]	0.0042
		Mg	8020[b]	14762[a]	9096[b]	0.001
	Lamina	Ca	16301	18501	18362	ns
		K	16708	13832	16549	ns
		Mg	5240[b]	7561[a]	5958[ab]	0.0096
Harvest	Petiole	Ca	14133	13323	12315	ns
		K	26304	18480	18652	ns
		Mg	9573[b]	13118[a]	8995[b]	0.0269
	Lamina	Ca	18168	17043	20276	ns
		K	16669[a]	13518[b]	14111[ab]	0.0308
		Mg	6035	6863	6333	ns

One – way ANOVA table showing the treatment effects on leaf (petiole or lamina) cations at flowering, veraison and harvest in 2020/21. Values are mean of ten replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

High Mg treatment

In 2020/21, the high Mg application increased [Mg] in the petiole at flowering, veraison and harvest. There were few effects of this treatment on [Mg] in the lamina though there was an increase relative to the control at flowering and veraison in 2021/22 (Table 2). The high Mg treatment did not reduce [K] in the petiole or lamina in 2020/21. In 2021/22, this treatment decreased the [K] in the leaf petiole at veraison and harvest, however this was not statistically different from the control (Table 2). Despite this, an assessment of the entire 2021/22 data set, across all treatments, revealed that petiole [Mg] and petiole [K] were inversely correlated (R^2=0.46, P<0.001). The high Mg treatment also decreased the petiole [Ca] at flowering in 2021/22.

Table 2. Cation concentration in the vegetative organs after treatment with high K or Mg in the 2021/22 growing season

Growth stage	Tissue	Nutrient (mg/kg)	Treatments			*P-value*
			High K	High Mg	Control	
Flowering	Petiole	Ca	20547^{ab}	15992^{b}	21670^{a}	0.0209
		K	4102	5940	5374	ns
		Mg	1716^{b}	2826^{a}	2557^{a}	<0.0001
	Lamina	Ca	20196	15809	19358	ns
		K	4736^{ab}	6041^{a}	4144^{b}	0.0117
		Mg	2344^{ab}	2579^{a}	1885^{b}	0.0224
Veraison	Petiole	Ca	17577	14590	16993	ns
		K	17982^{b}	9862^{a}	13739^{ab}	0.0058
		Mg	4429^{b}	8926^{a}	5557^{b}	0.0005
	Lamina	Ca	20799	21303	20837	ns
		K	7521	6030	6756	ns
		Mg	2049^{b}	2930^{a}	2125^{b}	0.0015
Harvest	Petiole	Ca	15936^{b}	16085^{b}	20210^{a}	0.0072
		K	11899^{a}	6936^{b}	9999^{ab}	0.0406
		Mg	4589^{b}	10191^{a}	6797^{b}	0.0009
	Lamina	Ca	8799^{a}	1947^{b}	1564^{b}	0.0221
		K	1899^{a}	1460^{b}	1464^{b}	0.0257
		Mg	1668	2335	1237	ns

One – way ANOVA table showing the treatment effects on leaf (petiole or lamina) cations at flowering, veraison and harvest in 2021/22. Values are mean of ten replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Cation concentrations in the flowers, berries, and juice in response to the high nutrient treatments

Flowers

The high nutrient treatments had no impact on the cation concentrations in the flowers in 2020/21 (Table 3), however in 2021/22 the high K treatment reduced flower [Ca] (Table 4).

Berries and Juice

At harvest in 2021, berry [Mg] concentrations were higher in response to the high Mg treatment and the high K treatment (Table 3). However, [K] was not altered in the berries or juice at veraison or harvest by either the high K or high Mg treatment. In 2021/22 there were more treatment effects (Table 4). The high K treatment increased [K] in the berry and juice at veraison, though this was no longer significant at harvest. Despite this, petiole [K] was strongly correlated with juice [K] at harvest ($P<0.001$, $R^2=0.72$).

Additionally, in 2021/22, the high Mg treatment increased [Mg] in the berries and juice at veraison and in berries at harvest (Table 4). Petiole [Mg] was positively correlated with juice [Mg] at harvest ($P<0.001$, $R^2=0.70$) (Table 7). The high Mg treatment reduced the [K] in the berries and juice at harvest but this was not statistically significant from the control (Table 4). Despite the absence of a treatment effect, when all the data across the treatments were combined, there was a significant inverse correlation between petiole [Mg] at harvest and juice [K] ($P<0.001$, $R^2=0.36$) (Table 7).

Table 3. Cation concentration in flowers, berries and juice after treatment with high K or Mg in the 2020/21 growing season

Tissue	Nutrient	Treatments			*P-value*
		High K	High Mg	Control	
Flowers	Ca (mg/kg)	6427	5896	7051	ns
	K (mg/kg)	19157	16783	17092	ns
	Mg (mg/kg)	3266	3415	3593	ns
Berries at veraison	Ca (mg/kg)	216	197	208	ns
	K (mg/kg)	1531	1508	1599	ns
	Mg (mg/kg)	106^{b}	120^{a}	112^{ab}	0.0439
Juice at veraison	Ca (mg/L)	54^{a}	38^{b}	46^{ab}	0.0455
	K (mg/L)	1116	1150	1202	ns
	Mg (mg/L)	86	95	83	ns
Berries at harvest	Ca (mg/kg)	197	181	169	ns
	K (mg/kg)	2167	2588	2859	ns
	Mg (mg/kg)	106^{a}	106^{a}	87^{b}	0.0249

One – way ANOVA table showing the treatment effects on the concentration of cations in flowers, berries and juice at veraison and in berries at harvest in 2020/21. Values are mean of ten replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Table 4. Cation concentration in flowers, berries and juice after treatment with high K or Mg in the 2021/22 growing season

Tissue	Nutrient	Treatments			*P-value*
		High K	High Mg	Control	
Flowers	Ca (mg/kg)	15628[b]	23898[a]	22708[a]	0.0013
	K (mg/kg)	5776	5171	6832	ns
	Mg (mg/kg)	2709	2270	2142	ns
Berries at veraison	Ca (mg/kg)	139	142	141	ns
	K (mg/kg)	849[a]	760[ab]	759[b]	0.029
	Mg (mg/kg)	42[b]	50[a]	43[b]	0.0063
Juice at veraison	Ca (mg/L)	40	36	45	ns
	K (mg/L)	576[a]	497[b]	510[b]	0.0049
	Mg (mg/L)	35[b]	44[a]	37[b]	0.0039
Berries at harvest	Ca (mg/kg)	136	144	146	ns
	K (mg/kg)	1014[a]	855[b]	919[ab]	0.0016
	Mg (mg/kg)	49[b]	56[a]	49[b]	0.0247
Juice at harvest	Ca (mg/kg)	39	36	37	ns
	K (mg/kg)	709[a]	600[b]	650[ab]	0.0087
	Mg (mg/kg)	42[b]	49[a]	44[ab]	0.0348

One – way ANOVA table showing the treatment effects on the concentration of cations in flowers, berries and juice at veraison and harvest in 2021/22. Values are mean of ten replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Influence of nutrient treatments on juice TSS, pH, TA, malic acid and tartaric acid

There were no significant treatment effects on juice TSS, pH, TA, malic acid or tartaric acid in the 2021 season (Table 5). In the second season, the grapes were harvested earlier (17-18 °Brix) than the first season (21 °Brix) due to the onset of fungal disease in the vines, and again there were no treatment effects apart from that on [tartaric acid] (Table 6).

A correlation analysis of the entire data set found an inverse relationship between the juice [Mg]/[K] ratio and juice pH at veraison (Table 7). More notable were the correlations between the mid-ripening petiole [Mg]/[K] ratio (R^2 of 0.33) and blade [Mg]/[K] ratio (R^2 of 0.51) on mid-ripening juice pH. As expected, [tartaric acid] was positively correlated with TA. Petiole [Mg] was strongly correlated with berry and juice [Mg]. The same positive relationships between the vegetative and reproductive components were apparent for K.

Table 5. Juice chemical parameters at veraison and harvest in 2021

		Treatments			*P-value*
	Variables	High K	High Mg	Control	
Veraison	TSS (°Brix)	18.2	18.3	17.8	ns
	pH	3.2	3.2	3.2	ns
	TA (g/L)	12	11.1	13	ns
	Malic acid (g/L)	5.0	4.6	7.5	ns
	Tartaric acid (g/L)	5.3	5.2	5.4	ns
Harvest	TSS (°Brix)	21.9	21.8	21.6	ns
	pH	3.6	3.6	3.6	ns
	TA (g/L)	6.3	6.2	6.6	ns
	Tartaric acid (g/L)	2.9	2.9	3	ns
	Malic acid (g/L)	3.0	3.0	3.2	ns

One – way ANOVA table showing the treatment effects on the concentration of cations in flowers, berries and juice at veraison and harvest in 2021. Values are mean of ten replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Table 6. Juice chemical parameters at veraison and harvest in 2022

		Treatments			*P-value*
	Variables	High K	High Mg	Control	
Veraison	TSS (°Brix)	13.6	14.4	14.3	ns
	pH	3.2	3.2	3.2	ns
	TA (g/L)	15.1	13.8	13.6	ns
	Malic acid (g/L)	8.4	6.9	6.6	ns
	Tartaric acid (g/L)	5.5	5.2	5	ns
Harvest	TSS (°Brix)	17.2	17.5	18	ns
	pH	3.3	3.3	3.3	ns
	TA (g/L)	13.2	12.2	12.1	ns
	Tartaric acid (g/L)	5.5^{a}	5.3^{ab}	4.8^{b}	0.0231
	Malic acid (g/L)	4.8	4.4	4.4	ns

One – way ANOVA table showing the treatment effects on the concentration of cations in flowers, berries and juice at veraison and harvest in 2022. Values are mean of ten replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Table 7. Regression coefficients between two parameters as assessed across the entire 2022 data set, including all treatments.

Phenological stage of Parameter 1	Parameter 1	Phenological stage of Parameter 2	Parameter 2	Regression R^2 Negative slope refers to inverse correlation
Veraison	Petiole Mg	Veraison	Juice K	ns
Veraison	Petiole Mg	Veraison	Berry K	ns
Mid-ripening	Petiole Mg	Mid-ripening	Juice K	0.36 (-ve slope)
Mid-ripening	Petiole Mg	Mid-ripening	Berry K	0.16 (-ve slope)
Veraison	Petiole Mg	Mid-ripening	Juice K	0.29 (-ve slope)
Veraison	Petiole Mg	Mid-ripening	Berry K	0.19 (-ve slope)
Veraison	Petiole Mg	Veraison	Juice Mg	0.54
Veraison	Petiole Mg	Veraison	Berry Mg	0.60
Mid-ripening	Petiole Mg	Mid-ripening	Juice Mg	0.70
Mid-ripening	Petiole Mg	Mid-ripening	Berry Mg	0.47
Veraison	Petiole Mg	Mid-ripening	Juice Mg	0.64
Veraison	Petiole Mg	Mid-ripening	Berry Mg	0.59
Veraison	Petiole K	Veraison	Juice Mg	0.30 (-ve slope)
Veraison	Petiole K	Veraison	Berry Mg	0.32 (-ve slope)
Mid-ripening	Petiole K	Mid-ripening	Juice Mg	0.14 (-ve slope)
Mid-ripening	Petiole K	Mid-ripening	Berry Mg	ns
Veraison	Petiole K	Mid-ripening	Juice Mg	0.30 (-ve slope)
Veraison	Petiole K	Mid-ripening	Berry Mg	0.18 (-ve slope)
Veraison	Petiole K	Veraison	Juice K	ns
Veraison	Petiole K	Veraison	Berry K	ns
Mid-ripening	Petiole K	Mid-ripening	Juice K	0.72
Mid-ripening	Petiole K	Mid-ripening	Berry K	0.45
Veraison	Petiole K	Mid-ripening	Juice K	0.41
Veraison	Petiole K	Mid-ripening	Berry K	0.32
Veraison	Juice K	Veraison	pH	0.32

Veraison	Berry K	Veraison	pH	0.26
Veraison	Juice K	Veraison	TA	0.32
Veraison	Berry K	Veraison	TA	0.19
Mid-ripening	Juice K	Mid-ripening	pH	0.34
Mid-ripening	Berry K	Mid-ripening	pH	0.15
Mid-ripening	Juice K	Mid-ripening	TA	0.14
Mid-ripening	Berry K	Mid-ripening	TA	0.33
Veraison	Juice Mg	Veraison	pH	ns
Veraison	Berry Mg	Veraison	pH	ns
Veraison	Juice Mg	Veraison	TA	ns
Veraison	Berry Mg	Veraison	TA	0.12
Mid-ripening	Juice Mg	Mid-ripening	pH	ns
Mid-ripening	Berry Mg	Mid-ripening	pH	ns
Mid-ripening	Juice Mg	Mid-ripening	TA	ns
Mid-ripening	Berry Mg	Mid-ripening	TA	ns
Veraison	Juice Mg/K	Veraison	pH	0.29 (-ve slope)
Veraison	Berry Mg/K	Veraison	pH	ns
Veraison	Juice Mg/K	Veraison	TA	ns
Veraison	Berry Mg/K	Veraison	TA	0.18
Mid-ripening	Juice Mg/K	Mid-ripening	pH	0.17 (-ve slope)
Mid-ripening	Berry Mg/K	Mid-ripening	pH	0.19 (-ve slope)
Mid-ripening	Juice Mg/K	Mid-ripening	TA	ns
Mid-ripening	Berry Mg/K	Mid-ripening	TA	ns
Mid-ripening	Juice tartaric acid	Mid-ripening	TA	0.59
Mid-ripening	Juice pH	Mid-ripening	TA	0.12
Veraison	Petiole Mg/K	Veraison	pH	ns
Veraison	Blade Mg/K	Veraison	pH	ns
Veraison	Petiole Mg/K	Veraison	TA	ns
Veraison	Blade Mg/K	Veraison	TA	ns
Mid-ripening	Petiole Mg/K	Mid-ripening	pH	0.33 (-ve slope)
Mid-ripening	Blade Mg/K	Mid-ripening	pH	0.51 (-ve slope)
Mid-ripening	Petiole Mg/K	Mid-ripening	TA	ns
Mid-ripening	Blade Mg/K	Mid-ripening	TA	ns

Conclusions

The high Mg treatment reduced the [K] in the berries and juice at mid-ripening in the 2022 season, but this was not statistically significant from the control. As a result, there were no significant treatment effects on berry pH, TA or TSS. However, a further in-depth analysis revealed that high petiole [Mg] was correlated with lower juice [K]. Moreover, significant inverse correlations between mid-ripening juice pH and the mid-ripening petiole or blade [Mg]/[K] ratios were apparent. Given the challenging experimental conditions in both growing seasons, we recommend that the pot trial be repeated. Certainly, the indicative data of the 2021/22 growing season suggests that further research is required to better understand the impact of cation antagonism on berry composition.

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Field-Vine Nutrition Trial

Abstract

Global warming impacts key factors of vineyard profitability, namely the yield and quality of grape berries. Loss of berry and wine acidity due to increasing temperatures has been widely reported in warm climatic regions. High concentration of potassium (K) in grape juice can also contribute to increased wine pH, requiring expensive additions of tartaric acid during winemaking, significantly elevating winery costs. This study aimed to devise a K management strategy in vineyards, specific to warm regions, so that the appropriate sugar-acid balance can be achieved in berries to elevate wine quality. We hypothesised that K uptake by grapevine roots may be reduced by soil application of competing elements, such as Ca or Mg, both potential cation antagonists to K. A fertiliser trial was conducted on 20-year-old own-rooted *Vitis vinifera* cv. Shiraz vines in a commercial vineyard of the Gundagai growing region, NSW. Fertiliser treatments included $CaNO_3$, KNO_3, $MgNO_3$, UAN (urea ammonium nitrate) and an untreated control. UAN treated vines had significantly higher pruning weight compared to untreated vines. All the nitrate treatments increased juice yeast assimilable nitrogen (YAN), and decreased berry and wine colour. However, none of the berry cation concentrations were affected by the treatments and consequently pH and TA were also not affected. This study suggested that long term field trials including several seasons are required to gain a better understanding of the potential for cation antagonism, as the substantial perennial nutrient reserves in field grown mature vines can buffer against any sudden nutrient supply changes.

Introduction

Global warming is exerting a significant impact on vine phenology and grape composition, mainly elevating grape sugar concentrations and leading to high wine alcohol levels, lower acidity and changes in sensory attributes (De Orduna, 2010). Riverina wines tend to be low in acidity and this can at least be partially attributed to the temperature driven respiratory decline in malate (Sweetman et al. 2014). At the same time, high concentration of potassium (K) in grape berries can result in increased must pH, leading to difficulty in wine making and low wine quality (Chan and Fahey 2011).

One of the overall aims of this project is to devise a K management strategy that is specific to a warm growing region so that the appropriate sugar-acid balance is achieved/maintained. Viticultural practices that may reduce K accumulation in grape berries include rootstock selection (Mpelasoka et al. 2003; Walker and Clingeleffer 2009; Xiao et al. 2020), opening the canopy by shoot thinning or leaf removal (Rojas-Lara and Morrison 2015) or reducing irrigation during the active K uptake period (Freeman and Kliewer 1983, Hepner and Bravdo 1985). However, the impacts of these practices may vary depending on each vineyard situation, especially the climatic conditions of the vineyard. For example, opening the canopy or reducing irrigation during hot weather especially in warm climate regions may cause other issues like sunburn or water stress. Similarly, during vineyard establishment, K excluding rootstocks can offer the potential to reduce berry K, however this option is not applicable for established vineyards.

The influence of soil cation composition on wine grape quality has received considerable research attention (Mpelasoka et al. 2003; Treeby et al. 2004; Mackenzie and Christy 2005; Chan and Fahey 2011). Likewise, the antagonistic effect of Ca and Mg on the uptake of K is well established (Omar and Kobbia 1966; Kirkby, 1979; Jakobsen, 1993). An oversupply of K to the rootzone is suggested to lower the concentration of Ca and Mg in the tissues and to increase grape juice pH (Morris et al. 1982; Kudo et al. 1998; Mpelasoka et al. 2003; Treeby et al. 2004). Early studies involving pot trials with different levels of K fertilisation showed a positive relationship between K addition to the soil and berry K. However, field trials on mature grapevines demonstrated conflicting results (Morris et al. 1982; Ruhl 1989). The objective of this project was to provide new insights into the potential of soil application of Ca and/or Mg fertilisers to reduce K uptake by the vines and reduce the accumulation of K in grape berries. This project tested the hypothesis that the addition of cations antagonistic to K can reduce the uptake of K by vines. As the outcomes of field trials are dependent on the overall soil characteristics (including its cation exchange capacity), a vineyard with the most common Riverina soil type was selected for this project.

Project aims

- In a Riverina field trial, assess the impact of K, Mg and Ca fertilisation on the K concentration and pH of the must, and the chemical components of the wine.
- Apply K, Mg and Ca using fertigation to the same vineyard in Riverina and assess the cumulative effect of treatments on berry composition and must properties.
- Make wine using miniature ferments and assess for links between soil, berry and wine chemical composition. If differences in wine chemical composition are apparent, carry out wine tasting assessment with industry members.

Research questions:

- Can we manipulate the amount of K taken up by the berry from the soil?
- Can berry K uptake be reduced by encouraging berry Ca or Mg uptake from the soil?
- Can we encourage Ca or Mg uptake by supplying more of these elements to the vines?
- Can we change the pH and TA of grape juice and wine by fertiliser treatments?
- Can we change berry composition and wine composition/quality by fertiliser application?

Materials and Methods

Plant material and experimental design

The trial was conducted in Gundagai vineyards (35.0541°S, 147.8698°E), on 20-year-old *Vitis vinifera*, cv. Shiraz vines on own roots. The vines received a total irrigation of 1 ML/ha water, and total

nitrogen of 30 kg/ha per growing season. Fertiliser treatments included $CaNO_3$, KNO_3, $MgNO_3$, UAN and an untreated control. Nitrogen in all the treatments were equalised by the addition of UAN. For each treatment there were four replicates containing nine vines per replicate. The four replicates of each treatment were randomised throughout the trial block. The fertiliser treatments were applied in three equal split applications of the total fertiliser, with first application soon after budburst, the second soon after 100% flowering and the third application at berries at pea size. This trial was repeated for two consecutive seasons.

Soil analysis: Soil samples were collected at flowering and veraison in both growing seasons. Soil cores were collected from between the vines along the dripper lines at 0-10 cm and 10-30 cm depths. The samples were air dried at 60 °C for 5 days, ground and sieved (2 mm mesh size). A 2.5 g soil sample was used to analyse exchangeable cations (Al, Na, K, Ca and Mg) by inductively coupled plasma atomic emission spectroscopy (ICP-AES) at the Environmental and Analytical Laboratories at Charles Sturt University, Wagga Wagga. Soil electrical conductivity (EC1:5) (SevenCompact Conductivity meter, Mettler Toledo, Port Melbourne, Australia) and pH (Hanna precision pH meter Model pH 211, Hanna instruments, Melbourne, Australia) were also determined.

Tissue nutrient analysis: Samples of 20 leaves per replicate were taken at flowering, veraison and harvest. Along with the leaves inflorescences/bunches were also collected for nutrient analysis. Laminae, petioles and inflorescences were washed, dried and ground, and 100 mg of the ground tissue was analysed for nutrients. K, Ca and Mg analyses were performed using ICP-AES at the Environmental and Analytical Laboratories at Charles Sturt University, Wagga Wagga. Intact berries were separated from 20 bunches of each replicate and 100 berry sub-samples were frozen for future analysis. Berry samples were defrosted, homogenised and 500 mg of the homogenate was used for K, Ca and Mg analysis by ICP-AES.

Vine growth and yield parameters assessment

At dormancy, pruning weight was determined from three individual vines in each replicate and the average value from the three vines was calculated. Bunch number per vine was counted from three vines within each replicate, average bunch weight was taken from ten bunches from each replicate, and the yield per vine was calculated from the total number of bunches per vine and average bunch weight.

Juice TSS, pH, TA and tartaric acid and cations

After sub-sampling the grapes, the rest of the grape samples were juiced. Fresh juice samples were analysed for TSS with a digital refractometer (Pocket PAL-1, Atago, Japan). Juice pH and TA were assessed using an autotitrator (Metrohm Fully Automated 59 place Titrando System, Switzerland). One mL of juice sample was analysed for K, Ca and Mg using ICP-AES at the Environmental and Analytical Laboratories at Charles Sturt University, Wagga Wagga. Berry colour analysis was performed by using a spectroscopic method developed from research of Somers and Evans (1974).

Wine making and wine analysis

Twenty bunches from each replicate were sampled at harvest and micro ferments were made at the Charles Sturt University winery. Grapes were destemmed, crushed, and transferred into 2 L glass bottles for fermentation. Fermentation was performed by yeast *Saccharomyces cerevisiae* and maintained at 25−26°C. Malolactic fermentation was carried out using a co-inoculation procedure, with Enoferm alpha LAB (*Oenococcus oeni*) added two days post yeast inoculation. Ferments were pressed when the residual sugar decreased to <0.5 g/L and transferred to 1 L glass bottles. These were maintained at 22°C until the malic acid concentration decreased to <0.05 g/L. The wine was then racked off the gross lees into amber coloured wine bottles, filled with CO_2 prior to filling and then capped with a screwcap, and transferred to a -4°C cool room. Wines were sampled at the time of bottling, and 1 mL of each wine was analysed for K, Ca and Mg using ICP-. Wine colour intensity was analysed using a spectroscopic method developed from research of Somers and Evans (1974).

Statistical methods.

A one-way ANOVA, followed by Tukey's multiple comparison test was applied to the following data: vine performance; juice and wine parameters; nutrients in the vegetative and reproductive organs, juice and wines, and soil characteristics to compare the main effects of treatments and seasons. *P* values <0.05 were considered significant. All analyses were performed using GraphPad Prism 8 (GraphPad Software, San Diego, California, USA).

Results and Discussion

Effects of treatments on pruning weight and yield parameters

Few treatment effects were apparent on vegetative growth or yield parameters (Table 1). The exception was that the $MgNO_3$ resulted in a lower pruning weight relative to the UAN treatment in the second season.

Table 1. Treatment effects on vine performance

Variables	Season	Treatments					*P-value*
		Control	$CaNO_3$	KNO_3	$MgNO_3$	UAN	
Yield/vine (Kg)	2021	3.1	3.9	3.2	3.4	3.8	ns
	2022	4.5	3.6	3.3	4.5	5.2	ns
Average bunch weight (g)	2021	80	94	88	98	90	ns
	2022	83	98	92	102	93	ns
Bunch number per vine	2021	38	42	36	34	41	ns
	2022	54	36	36	43	55	ns
Average berry wt (g)	2021	1.9	1.9	1.9	1.9	1.9	ns
	2022	2	1.9	2.1	2.0	2.0	ns
Pruning wt per vine (kg)	2021	1.2	1.5	1.4	1.4	1.6	ns
	2022	2.8^{ab}	3.1^{ab}	3^{ab}	2.3^{b}	4.7^{a}	0.0423

One – way ANOVA table showing the treatment effects on vine performance parameters, in two seasons 2021 and 2022. Values are mean of four replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Effects of treatments on juice parameters

In 2022, YAN in juice at veraison and harvest was significantly higher in all nitrate fertiliser treatments compared to untreated vines (Table 2). TSS, pH, TA and tartaric acid in the juice at veraison was not different between treatments in either season. In the harvest juice of 2021, [tartaric acid] was higher in the $CaNO_3$ relative to the UAN treatment, however this did not result in a significant change in TA. In the harvest juice of 2022, however, TA was higher in the $CaNO_3$ and KNO_3 treatments relative to the untreated vines, but not different from the UAN treatment. Malic acid was significantly higher in the KNO_3 compared to untreated vines but not different from the UAN (Table 2). Lastly, TSS was lower in the harvest juice of 2021 for most treatments relative to the untreated control vines, but not different from the UAN.

Table 2. Treatment effects on juice parameters

Sampling time point	Variables	Season	Treatments					
			Untreated	$CaNO_3$	KNO_3	$MgNO_3$	UAN	*P-value*
Veraison	TSS (˚Brix)	2021	14.4	13.8	13.4	13.8	13.7	ns
		2022	11.7	11	11.2	10.9	11.4	ns
	YAN (mg/L)	2021	138	168	187	159	165	ns
		2022	144^{a}	367^{b}	318^{b}	338^{b}	270^{b}	0.0002
	pH	2021	3	3	3	3	3	ns
		2022	2.8	2.9	2.8	2.8	2.8	ns
	TA (g/L)	2021	16.2	16.4	17.6	16.7	17	ns
		2022	21.9	22.5	22.7	22.3	21.7	ns
	Tartaric acid (g/L)	2021	7.3	7.1	7.6	7.3	7.6	ns
		2022	8.4	8.3	8.5	8.5	8.4	ns
Harvest	pH	2021	3.4	3.5	3.4	3.4	3.5	ns
		2022	3.5	3.5	3.6	3.5	3.5	ns
	TA (g/L)	2021	6.3	6.7	6.7	6.6	6.2	ns
		2022	6.6^{b}	9.1^{a}	8.9^{a}	7.7^{ab}	7.3^{ab}	0.005
	Tartaric acid (g/L)	2021	5.1^{ab}	5.6^{a}	5.0^{b}	5.3^{ab}	5.0^{b}	0.0153
		2022	5.6	5.9	6	6.2	5.2	ns
	Malic acid (g/L)	2021	2.3^{b}	2.4^{ab}	2.7^{a}	2.5^{ab}	2.4^{ab}	0.0258
		2022	2.9	3.4	3.3	3.2	3.1	ns
	TSS (˚Brix)	2021	19.6^{a}	18.7^{b}	18.8^{b}	18.9^{b}	19.1^{ab}	0.0131
		2022	19.5	18.2	18.3	18.9	18.7	ns
	YAN (mg/L)	2021	95^{b}	168^{b}	170^{b}	163^{b}	160^{b}	<0.0001
		2022	88^{b}	274^{b}	239^{b}	230^{b}	198^{b}	<0.0001

Cations in the vegetative organs

With the exception of Mg, the treatments had little effect on the nutrient levels within the vine (Table 3 & 4). At flowering in season 2022, lamina [Mg] was significantly higher in the $MgNO_3$ and KNO_3 treatments relative to the untreated vines. At harvest of that season, lamina [Mg] was highest in the $MgNO_3$, followed by $CaNO_3$ and KNO_3. Similarly, in both growing seasons petiole [Mg] was significantly higher in the $MgNO_3$ treatment relative to the untreated vines and the UAN treatment. There was no

significant effect of the $MgNO_3$ or $CaNO_3$ treatments on the [K] and [Ca] in the leaf tissues at any stage of development.

Table 3. Treatment effects on the concentration of cations in the laminae

Sampling time point	Element (mg/kg)	Season	Treatments					
			Untreated	$CaNO_3$	KNO_3	$MgNO_3$	UAN	P-value
Flowering	Ca	2021	16805	17811	17005	14354	15732	ns
		2022	20229	21826	21717	22031	21647	ns
	K	2021	10575	10896	11306	9463	10583	ns
		2022	4197	3942	4460	3682	3886	ns
	Mg	2021	3688	4093	3919	3210	3478	ns
		2022	1502^{b}	1867^{ab}	1954^{a}	2042^{a}	1845^{ab}	0.0234
Veraison	Ca	2021	13496	14328	14618	14797	14113	ns
		2022	24174	23737	24224	22767	24725	ns
	Mg	2021	2529	2957	3186	3055	2860	ns
		2022	3149	3559	3779	4000	3653	ns
	K	2021	8661	7976	8106	8073	8260	ns
		2022	9564	8498	8807	9063	8489	ns
Harvest	Ca	2021	17406	18107	17162	17590	16389	ns
		2022	27555	31235	28544	29430	27476	ns
	K	2021	9246	8852	9233	9281	8522	ns
		2022	8947	7861	9028	8052	8862	ns
	Mg	2021	3230	3432	3503	3832	3335	ns
		2022	3159^{c}	4372^{a}	3987^{b}	4708^{a}	3773^{b}	0.002

Table 4. Treatment effects on the concentration of cations in the petioles

Sampling time point	Element (mg/kg)	Season	Treatments					*P-value*
			Untreated	$CaNO_3$	KNO_3	$MgNO_3$	UAN	
Flowering	Ca	2021	13833	12812	11467	13773	14306	ns
		2022	15164	14017	13760	13830	14446	ns
	Mg	2021	6980	6245	6859	7617	7099	ns
		2022	2543	2467	2275	2634	2890	ns
	K	2021	21620	23127	21480	23990	22349	ns
		2022	6657	4399	5549	4308	6010	ns
Veraison	Ca	2021	14645	13890	12961	13952	13964	ns
		2022	18903	20342	20038	18806	19927	ns
	Mg	2021	7246	8784	9715	8958	8857	ns
		2022	9122	10841	11500	12736	10740	ns
	K	2021	25622	21952	24119	23244	24584	ns
		2022	27058	25910	29682	26152	21766	ns
Harvest	Ca	2021	14279	13378	15954	16399	13992	ns
		2022	22772	27306	24925	24434	23194	ns
	K	2021	24153	21068	24280	26552	27850	ns
		2022	23170	22178	26339	23720	21359	ns
	Mg	2021	7302^{b}	9212^{ab}	9311^{ab}	10180^{a}	7373^{b}	0.0073
		2022	10095^{b}	13027^{ab}	11582^{ab}	14592^{a}	10486^{b}	0.0192

Effect of treatments on cation concentration in flowers and berries

The fertiliser treatments did not influence nutrient concentrations in the flowers in either season (Table 5). In season 2021, at veraison, [Mg] in berries was highest in the $MgNO_3$ treatment, though not significantly different from the UAN treatment. In the 2021 harvest, berry [Ca] and [Mg] were higher in all treatments relative to the untreated vines. In the same harvest, berry [K] was highest in the KNO_3 treatment, but not significantly different from the $CaNO_3$ and $MgNO_3$ treatments. Berry [K] was not influenced by the treatments in 2022. In neither season were berry [K] reduced by the $MgNO_3$ or $CaNO_3$ treatments as compared to the UAN or untreated vines.

Table 5. Treatment effects on the concentration of cations in flowers and berries

	Element (mg/kg)	Season	Treatments					*P-value*
			Untreated	$CaNO_3$	KNO_3	$MgNO_3$	UAN	
Flowers	Ca	2021	9777	9144	9764	11388	10732	ns
		2022	18055	17550	16319	19058	19124	ns
	Mg	2021	2730	2670	2778	3210	3022	ns
		2022	1457	1652	2805	1412	1335	ns
	K	2021	18055	17550	16319	19058	19124	ns
		2022	9587	10054	17939	8078	7907	ns
Berries at Veraison	Ca	2021	189	166	172	202	209	ns
		2022	266	241	247	236	248	ns
	K	2021	946^{b}	904^{b}	880^{b}	1242^{a}	1278^{a}	0.0002
		2022	1744	1785	1860	1727	1662	ns
	Mg	2021	68^{b}	65^{b}	67^{b}	86^{a}	80^{ab}	0.0085
		2022	100^{ab}	100^{ab}	104^{a}	105^{a}	95^{b}	0.0269
Berries at Harvest	Ca	2021	85^{b}	221^{a}	213^{a}	196^{a}	216^{a}	<0.0001
		2022	202	201	189	197	199	ns
	K	2021	2220^{c}	5274^{a}	6357^{a}	4742^{ab}	3026^{bc}	0.0001
		2022	1960	2049	2303	2077	2000	ns
	Mg	2021	37^{b}	102^{a}	99^{a}	109^{a}	113^{a}	<0.0001
		2022	96	102	105	107	97	ns

One – way ANOVA table showing the treatment effects on the concentration of cations in the flowers and berries, in two seasons 2021 and 2022. Values are mean of four replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Effect of treatments on cation concentration in juice and wine

Juice [Ca] were increased by all the fertiliser treatments in 2021 but decreased by these treatments in 2022 (Table 6). These effects did not carry over into the wine for this element. In 2021, juice [K] was lowered by all the fertiliser treatments and unexpectedly was lowest in the KNO_3 treatment, though not significantly different from the $CaNO_3$ and $MgNO_3$ treatments. This may have been the result of the formation of K precipitates upon juicing. In the same season, the resultant wine had the highest [K] but this was not statistically significant. There were no treatment effects on juice or wine [K] in

2022. Juice [Mg] was elevated by all the fertiliser treatments in 2021 and were highest in the $MgNO_3$ treatment in 2022. The latter treatment effect was also apparent in the wine of that season.

Table 6. Treatment effect on the concentration of cations in harvest juice and wines

	Element (mg/kg)	Season	Treatments					*P-value*
			Untreated	$CaNO_3$	KNO_3	$MgNO_3$	UAN	
Juice	Ca	2021	31^{b}	44^{a}	43^{a}	40^{a}	41^{a}	0.0011
		2022	55^{a}	49^{b}	49^{b}	47^{b}	50^{b}	0.0011
	K	2021	1384^{a}	$877b^{c}$	800^{c}	907^{oc}	974^{o}	<0.0001
		2022	1800	2063	2175	1950	1838	ns
	Mg	2021	32^{b}	50^{a}	51^{a}	50^{a}	46^{a}	<0.0001
		2022	71^{b}	76^{ab}	78^{ab}	85^{a}	72^{b}	0.0071
Wine	Ca	2021	40	40	42	39	40	ns
		2022	77	65	65	71	71	ns
	K	2021	747	743	822	759	703	ns
		2022	1073	1181	1290	1163	1084	ns
	Mg	2021	62	59	64	65	63	ns
		2022	73^{b}	76^{ab}	78^{ab}	87^{a}	71^{b}	0.0112

One – way ANOVA table showing the treatment effects on the concentration of cations in the harvest juice and wines, in two seasons 2021 and 2022. Each value is a mean of four replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Influence of treatments in berry colour and wine colour density

In 2021, berry colour was highest in the untreated vines, but this was not statistically significant in 2022 (Table 7). Wine colour density was also significantly higher in the untreated vines compared to the fertilised vines in both seasons. Consistent with our results, previous studies suggest that excessive nitrogen supply can decrease anthocyanins in grape juice and wines (Keller et al. 1999).

Table 7. Treatment effects on berry colour and wine colour density

Variables	Season	Treatments					*P-value*
		Untreated	$CaNO_3$	KNO_3	$MgNO_3$	UAN	
Anthocyanins (mg per berry)	2021	2.24^{a}	1.98^{b}	1.83^{b}	1.95^{b}	1.96^{b}	0.0008
	2022	2.29	2.03	1.88	2	2.01	ns
Wine colour density (a.u)	2021	7.5^{a}	5.4^{b}	5^{b}	5.5^{b}	4.7^{b}	0.0008
	2022	7.9^{a}	5.7^{b}	5.1^{b}	5.9^{b}	5^{b}	0.003

One – way ANOVA table showing the treatment effects on berry colour and wine colour density, in two seasons 2021 and 2022. Each value is a mean of four replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Effect of treatments on N concentration in flowers and leaves

Flower [N] was not influenced by the treatments, nor was N% in laminae at flowering and at veraison in season 2021. However, in season 2022, in laminae at flowering and veraison, [N] was significantly higher in all the nitrate treatments compared to untreated vines (Table 8).

Table 8. N % in flower, laminae and petioles at flowering and veraison

Variable	Season	Treatments					*P-value*
		Untreated	$CaNO_3$	KNO_3	$MgNO_3$	UAN	

N % in flowers	2021	2.3	2.5	2.5	2.5	2.5	ns
	2022	2.5	2.4	2.4	2.5	2.5	ns
N% in laminae (flowering)	2021	2.8	2.9	2.9	2.9	2.9	ns
	2022	2.8^{b}	3.1^{a}	3.2^{a}	3.2^{a}	3.3^{a}	0.0007
N% in petiole (flowering)	2021	0.9^{b}	1.1^{a}	1.0^{ab}	1.0^{ab}	1.0^{ab}	0.0277
	2022	1.3^{b}	1.6^{b}	1.6^{b}	1.6^{b}	1.6^{b}	0.0063
N% in laminae (veraison)	2021	1.7	2	2	1.9	1.9	ns
	2022	1.8^{b}	2.3^{a}	2.4^{a}	2.2^{a}	2.3^{a}	<0.0001
N% leaf petiole (veraison)	2021	0.57^{b}	0.7^{a}	0.70^{a}	0.66^{ab}	0.63^{ab}	0.0031
	2022	0.48^{c}	0.68^{ab}	0.71^{a}	0.68^{ab}	0.60^{b}	<0.0001

One – way ANOVA table showing the treatment effects on the concentration of nitrogen in the flowers, laminae and petioles at flowering and at veraison in the 2020/21 and 2021/22 growing seasons. Each value is a mean of four replicates. P values <0.05 were considered significant. Different superscript letters show significant difference.

Influence of treatments on wine chemical parameters

There was no significant difference in wine pH, [TA] and [tartaric acid] between treatments in either season (Table 9).

Table 9. Treatment effect on wine chemical parameters

Variable	Season	Treatments					*P-value*
		Control	$CaNO_3$	KNO_3	$MgNO_3$	UAN	
pH	2021	3.9	3.9	3.8	3.8	3.7	ns
	2022	3.6	3.7	3.7	3.6	3.6	ns
TA (g/L)	2021	5.3	5.2	5.3	5.3	5.3	ns
	2022	5.4	6.1	6.1	5.3	5.3	ns
Tartaric acid (g/L)	2021	1.9	1.6	1.7	1.7	1.8	ns
	2022	2.7	2.4	2.2	2.5	2.7	ns

One – way ANOVA table showing the treatment effects on wine parameters in the 2021/21 and 2021/22 growing seasons. Each value is a mean of four replicates. *P* values <0.05 were considered significant. Different superscript letters show significant difference.

Treatment effects on soil parameters

Soil pH, EC and ECEC were not affected by the fertiliser treatments (Table 10). Apart from [Mg], no change in the concentration of other cations was observed in the soil by the treatments. At flowering, in season 2022, [Mg] at 0-10 cm and 10-30 cm was significantly higher in $MgNO_3$ and UAN treatments, though not significantly different from the control at 10-30 cm (Table 10). At veraison, [Mg] in the top layer of soil (0-10 cm) was significantly higher in $MgNO_3$ compared to $CaNO_3$ and KNO_3 treatments, while in the lower layer of the soil (10-30 cm) this trend was not apparent. The soil test results indicated that a significant change in the soil cation chemistry was not achieved by the short-term fertilizer treatments in our trial.

Table 10. Soil parameters at flowering and veraison in season 1 (2020/21) and season 2 (2021/22).

Variables	Year	Treatments					*P-value*
		Control	$CaNO_3$	KNO_3	$MgNO_3$	UAN	
FLOWERING							
pH at 0-10 cm	2021	7.2	6.9	6.9	6.9	6.8	ns
	2022	7.2	6.5	6.5	6.6	6.8	ns
pH at 10-30 cm	2021	7.2	7.0	7.0	6.9	6.9	ns

	2022	6.9	6.6	6.7	6.7	6.9	ns
EC (µS/cm) at 0-10 cm	2021	80.0	92.0	122.8	134.8	112.3	ns
	2022	59.3	66.0	62.0	69.3	73.0	ns
EC (µS/cm) at 10-30 cm	2021	75.3	67.8	116.5	155.0	92.8	ns
	2022	53.0	53.8	63.3	90.3	60.3	ns
ECEC (cmol(+)/kg) at 0-10 cm	2021	8.0	7.6	8.5	8.1	8.9	ns
	2022	6.4	6.4	6.0	6.3	8.0	ns
ECEC (cmol(+)/kg) at 10-30 cm	2021	7.4	6.8	8.5	8.5	8.1	ns
	2022	4.9	5.3	6.3	6.4	7.9	ns
K (mg/kg) at 0-10 cm	2021	116	147	243	272	225	ns
	2022	159	265	293	216	231	ns
K (mg/kg) at 10-30 cm	2021	94	95	115	189	160	ns
	2022	99	118	345	124	132	ns
Mg (mg/kg) at 0-10 cm	2021	356	353	392	379	377	ns
	2022	312^{b}	333^{b}	352^{ab}	553^{a}	558^{a}	0.003
Mg (mg/kg) at 10-30 cm	2021	334	352	514	514	409	ns
	2022	324^{b}	379^{b}	404^{b}	550^{ab}	678^{a}	0.0023
Ca (mg/kg) at 0-10 cm	2021	928	832	917	831	1008	ns
	2022	667	590	461	237	562	ns
Ca (mg/kg) at 10-30 cm	2021	833	688	754	721	835	ns
	2022	383	334	386	304	376	
VERAISON							
pH at 0-10 cm	2021	6.3	5.7	5.5	6.1	6.3	ns
	2022	6.5^{a}	6.0^{ab}	5.9^{b}	6.0^{ab}	5.8^{b}	0.0103
pH at 10-30 cm	2021	6	5.9	6.3	6.5	5.9	ns
	2022	6	6	5.8	6.1	5.8	ns
EC (µS/cm) at 0-10 cm	2021	75.0	117.0	97.0	130.3	83.5	ns
	2022	44.3	39.3	37.5	41.5	35.0	ns
EC (µS/cm) at 10-30 cm	2021	73.8	105.3	91.0	133.5	85.0	ns
	2022	34.5	29.0	32.3	34.0	29.5	ns
ECEC (cmol(+)/kg) at 0 -10 cm	2021	7.5	7.3	7.5	8.1	7.7	ns
	2022	5.2	5.1	5.0	5.4	5.4	ns
ECEC (cmol(+)/kg) at 10-30 cm	2021	6.9	7.5	7.8	7.5	8.2	ns
	2022	4.5	3.5	4.4	4.5	4.8	ns
K (mg/kg) at 0-10 cm	2021	102	98	200	172	107	ns
	2022	442	483	436	493	404	ns
K (mg/kg) at 10-30 cm	2021	87	91	118	145	95	ns
	2022	363	390	380	432	388	ns
Mg (mg/kg) at 0-10 cm	2021	322^{b}	266^{b}	288^{b}	469^{a}	315^{b}	0.0009
	2022	281	255	275	270	320	ns
Mg (mg/kg) at 10-30 cm	2021	346	335	373	422	406	ns
	2022	275	169	267	252	308	ns
Ca (mg/kg) at 0-10 cm	2021	898	936	894	736	926	ns
	2022	349	339	320	370	337	ns
Ca (mg/kg) at 10-30 cm	2021	722	845	846	694	875	ns
	2022	264	217	237	271	244	ns

Conclusion and recommendations

Our field trial indicated that short-term fertiliser treatments may not be effective for manipulating soil cation chemistry; and that the amount of K taken up by the berry from soil cannot be manipulated by short term fertiliser treatments. An antagonistic effect of Ca and Mg on the uptake of K by vines was not observed by short term application of Ca and Mg to the soil. As expected, all the nitrate treatments

increased juice YAN, and decreased berry and wine colour, which might be due to excessive shading. However, none of the berry cation concentrations were affected by the fertiliser treatments and consequently pH and TA were also not affected. This study suggests that long term field trials including several seasons are required to gain a better understanding of the potential for cation antagonism because the substantial perennial nutrient reserves in field grown mature vines may buffer against any sudden nutrient supply changes.

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Drivers and Barriers to the Adoption of Sustainable Grapegrowing

Abstract

The Australian wine industry is vulnerable to climate change, soil degradation, water scarcity, rising energy prices and running costs. Stakeholders are applying pressure for the adoption of responsible environmental and social practices, and solutions addressing sustainability are required to maintain viability in both the short and long term. However, new outcomes from RD&E projects are not always readily adopted by the end-users in the industry. An online survey and interviews were conducted with growers and winemakers of the Australian wine industry to better understand the drivers and barriers to adoption of new information, processes and products. The majority of the respondents used integrated pest management. Water efficient strategies, protocols to improve biodiversity, non-synthetic fertilisers, conservative tillage and cover-cropping were also implemented. The main drivers for implementing these practices were long-term viability and 'doing the right thing'. The foremost impediments were cost, confidence in region-specific solutions, and complexity. Involving key stakeholders and end users from the beginning of a project and demonstrating local, practical solutions on farm will likely result in better adoption.

Introduction

The Australian wine industry is comprised of 65 wine regions with diverse climate and terroir. Heat, drought, bushfires oscillating with unrelenting rain, floods and severe storms have resulted in lowered yield and altered berry composition, affecting overall wine quality. New management strategies are required to deal with these immediate short-term climate cycles and long-term climate change. Moreover, the degradation of soils, water and biodiversity resources is hampering long-term viability and sustainability of the grape and wine community. Sustainability can be defined in terms of environmental, social and financial realms. All three of these elements need to be satisfied for long-term viability (Gilinksy et al. 2016). Environmental sustainability refers to the practices that protect the environment including water conservation, limiting losses in biodiversity, reduced carbon footprint and preventing contamination to adverse chemicals. Social sustainability protects those people working within the vineyard/winery and the surrounding communities to ensure minimal exposure to toxins and the conservation of their living and recreational spaces. It also refers to passing on productive farmland to the next generations. Financial sustainability refers to profitability through e.g. better margins and reduced costs.

Barriers to adoption of sustainable practices may include economic limits, social factors, inadequate information or the attribute of the practice itself (Rodriguez et al. 2008). Adoption of sustainable practices such as conservative tillage and integrated pest management may be hindered by lack of knowledge or confidence in the effectiveness of alternative solutions. This may be the result of communication gaps between researchers, extension officers and growers (Lucchi and Benelli, 2018). The non-adoption or even reversion back to conventional practices is often the result of rational decisions (Rodriguez et al. 2008), for instance during extremely wet weather conditions. The uncertainty of profitability or a perceived increase in risk are also cited as barriers to adoption. A long transition period to return to profitability or recoup costs is also an impediment. Growers will also express concern if the practice accompanies an increase in demand for labour. The social context and norms of the farming group can either promote or discourage the adoption of sustainable practices. Finally, government policies and regulations can have a major impact on the widespread adoption of specific practices.

The central question of this study is '**what are the drivers and barriers to the adoption of outcomes from RD&E projects focussed on sustainability in the Australian wine industry**?' This paper summarises the views of grapegrowers and winemakers across several Australian grapegrowing regions, mostly from NSW but also from Victoria, Tasmania and South Australia. Through a questionnaire and follow-up interviews, we have attempted to identify and summarise the factors that influence a grower's decision to adopt or not adopt new practices related to long-term sustainability.

Methods

A mixed method approach for data collection was used involving an on-line cross-sectional survey across several segments of the wine industry and a follow-up qualitative study using semi-structured interview questions to gather more in-depth information.

The target population for the questionnaire and interviews included grapegrowers, technical specialists in the vineyard and winery, vineyard managers and winemakers.

Participation recruitment

Information detailing the purpose of the survey and a call for participation was placed on various sites that reach a broad section of the wine industry (Wine Australia, Vinewatch (NSW DPI monthly Newsletter) and National Wine and Grape Industry Centre. Two media releases calling for participation were also released (The Land Australia and Get Farming Australia).

The questionnaire was delivered online using Survey Monkey, between October 2021 to April 2022. It consisted of 48 questions.

In the second phase, 45-60 min semi-structured interviews were conducted in May 2022 using participants from different sized operations. At the end of the questionnaire participants had the opportunity to nominate their interest in taking part in the interview. They were directed to a new page to provide contact details and answer a few short demographic questions. Participants (10) were chosen from a range of regions and operations.

All research activities were approved by the Human Ethics Committee at Charles Sturt University.

Questionnaire and interview topics

The questionnaire and interview addressed

1. Profile and current role in operation (age, education, experience, day-to-day operations)

2. Goals and motivations (region, yield vs quality, market, obstacles, size, environmental sustainability)

4. Current method for managing vine nutrition (tissue analysis, nutrient sources, method of application, costs involved, skills/consultants, soil health) (Results described elsewhere)

5. Factors that currently drive decisions in vine nutrition/soil and undervine management/rootstock selection. (Results described elsewhere)

6. Sustainable growing practices (current practice, drivers)

7. Barriers to adopting a new practice

8. Enablers (benefits) that would support adoption of new practices

Results

Respondent demographics:

The respondents of the questionnaire traversed a wide age range: 11% fell in the 18-34 years category, 49% in the 24-50 category, 22% in the 51-65 category and 17% were over 66. Of these respondents 51% had been working in the wine industry for more than 20 years, 23% for 11-20 years, 11% for 6-10 years and 11% for 1-5 years, while 3% had worked in the industry for less than 12 months. The majority (71%) of the respondents were from greater NSW and ACT, 11% were from the Riverina, 6% from the Murray Valley, 6% from Greater Victoria excluding Murray Valley, and other regions represented included SA (North, Central, South) and Tasmania.

51% of the respondents grow grapes, 11% made wine and 37% both grow grapes and made wine. 68% of the growers grew Shiraz, 48% grew Chardonnay and 45% grew Cabernet Sauvignon. A number of other varieties were mentioned.

Average yield ranged from 1 to 22 t/ha, but mainly 5-10 t/ha. Most winemakers (47%) worked at wineries that crushed 50-1000 t annually, 23% at <50, 18% at 1001-10,000, and 12% at >10,000 t.

Interview participants (11) were distributed across the NSW grapegrowing regions: two from each of Canberra, Orange, Hunter Valley, Griffith, Hilltops and one from Mudgee. The participants were either vertically integrated from vineyard to winery (8) or growers only (3). The participants ranged from small (5), intermediate (4), or large (2) operations. Their age distribution was from <30 to >55.

<u>Goals and overall challenges:</u>

The more important driver of profitability was yield (17% of responses), berry composition (25%), or equally yield and composition (58%).

Climate and weather were regarded as the most dominant challenges affecting both yield and desired composition in the respondent's operation (Table 1). Pests and diseases, water resources, soil/nutrition factors and vineyard floor factors were also ranked highly.

Table 1. Challenges to achieving high yield or the desired berry composition in the respondent's operation.

Factor	Impact of factor on achieving high yield (% of respondents)	Impact of factor on achieving desired berry composition (% of respondents)
Climate and weather	66.7	83.3
Pests and diseases	62.5	45.8
Water resources	54.2	37.5
Soil/nutrition factors	45.8	54.2
Vineyard floor factors	41.7	33.3
Running costs	29.2	20.8

Labour	20.8	0
Varieties	16.7	12.5
Technical know-how	8.3	8.3
Equipment	8.3	4.2

Perceptions on climate change:

92% of respondents felt that climate change was impacting on grape production in their growing region. In terms of fruit quality specifically, only 13% felt that there was no impact.

When asked which fruit quality parameters were being affected by climate change in Australian vineyards, flavour/aroma, pH and acidity were most highly ranked. TSS and colour were also ranked highly. Other parameters mentioned included phenology, sunburn and smoke taint. When asked about their own region, all respondents said that flavour/aroma was altered, and acidity and pH were also highly ranked (Figure 1).

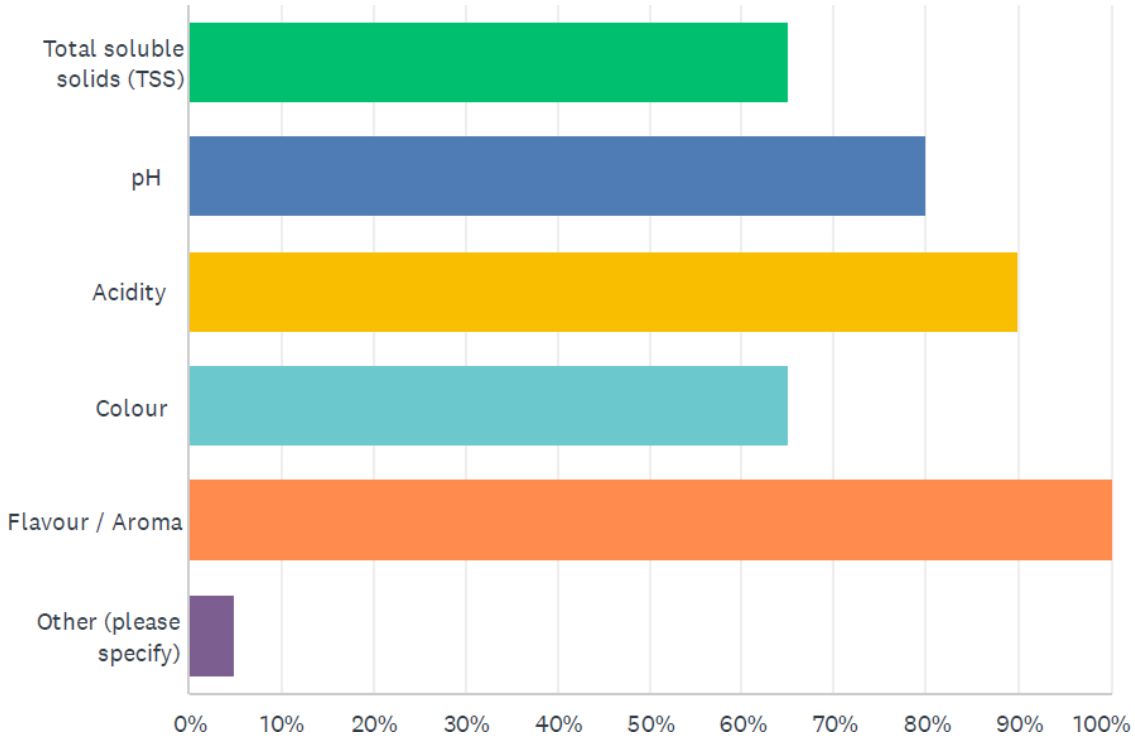


Figure 1. Views on impact of climate change on fruit quality parameters in the respondent's grapegrowing region. X axis refers to percentage of respondents.

Follow up interviews on the role of climate change provided further insights. "These events appear to come more frequently and to greater extremes. This has resulted in higher sugar and alcohol and loss of acid in some years."

A grower and winemaker from the Canberra growing district stated that "We have picking dates for Chardonnay for more than 30 years and it has been advancing at 1.5 days per year. Mind you, there is a change of wine style imposing on that. Now we no longer try to make a red Pinot noir because it doesn't suit our climate. The Pinot of a few decades ago were better than the ones we are making now."

Another operator in Mudgee also commented on the earlier harvest dates; grapes were harvested three weeks earlier relative to 28 years ago, and the grapes had sub-optimal pH.

One grower from Hilltops was more conservative "I don't think we can make any definite claims one way or another", while another one from Orange was more pragmatic, "It is irrelevant whether one believes in climate change or not - the changes are happening, and we have to deal with it."

Views on sustainable growing practices, environmental footprint and GHG emissions

100% of the questionnaire respondents agreed that long-term sustainable growing practices were important to them. 95% agreed that long-term soil health contributes to their decisions about vineyard management protocols. Loss in biodiversity was also of high concern (83% of the respondents).

92% of the respondents said that their environmental footprint was important to their decision-making process. More specifically, 79% of the respondents stated that greenhouse gasses were of a concern to them, while 12% were neutral and 8% were not concerned. Some growers were using solar energy to decrease costs, "You have to look at what is available, and if it is free…". The added benefit of reduced emissions was noted, however reduction in GHG were not the primary driver.

When asked whether GHG contributed to decisions on their fertiliser management protocols, only 43% agreed. Interviews revealed that an organic grower in Orange was very mindful about GHG and that it was a dominant driver for excluding synthetic fertilisers. Another grower from the Riverina stated that the price of fertiliser had tripled and suggested that future application rates will principally be driven by cost. Decreased fertiliser use was also motivated by the desire for reduced vine vigour, improved soil health, and long-term sustainability.

Long-term sustainable methods currently practiced

When asked about sustainable methods implemented in their own operation, 87% of the respondents used IPM, 74% used water efficient strategies, 70% used protocols to improve biodiversity, 65% used non-synthetic fertilisers, 56% practiced no-till, 52% implemented cover-cropping, 35% used waste management strategies and 26% used composting (Figure 3).

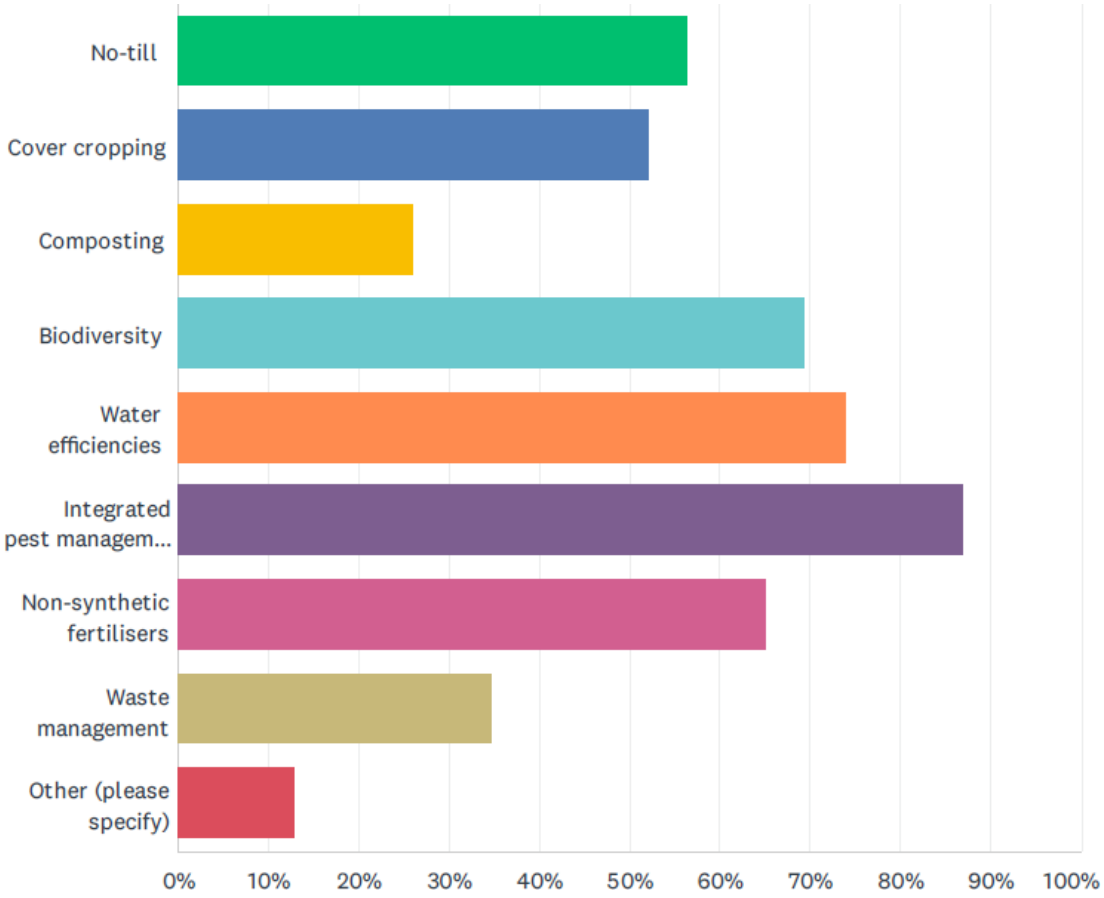


Figure 3. Sustainable farming practices currently implemented by Australian grapegrowers.

In accordance with the questionnaire, interviews revealed the application of mulches for water retention, the adoption of softer chemicals (especially the elimination of broad-spectrum insecticides), the encouragement of biodiversity through revegetation and companion planting, the use of cover crops for weed control and increasing soil C, and the installation of solar power.

However, the interviews also revealed the challenges of implementing particular practices which may not have been more sustainable in the long run. There was the realisation that an advantage in one parameter (softer chemicals for pest and disease control) might mean a cost in another parameter (more tractor passes leading to soil compaction and more diesel usage). A grower applying softer chemicals requiring more frequent application rates stated that, “This last year we were on the tractor all the time spewing out lots of GHG and it was more expensive. Not every season is going to be like that- this one was probably the biggest outlier we will ever experience”. Similar observations were noted for trade-offs in weed control: “Round-up- I don’t like to use it. But for our scale - I can’t control weeds which use a lot of water. So which is more or less sustainable, the chemical or pumping lots of water?”

Drivers for long-term sustainable practices

Benefits to the wider community

Drivers included "doing the right thing" to address climate change: "Maybe my generation is terrified of the world ending. So, we will try new methods." (Hilltops grower)

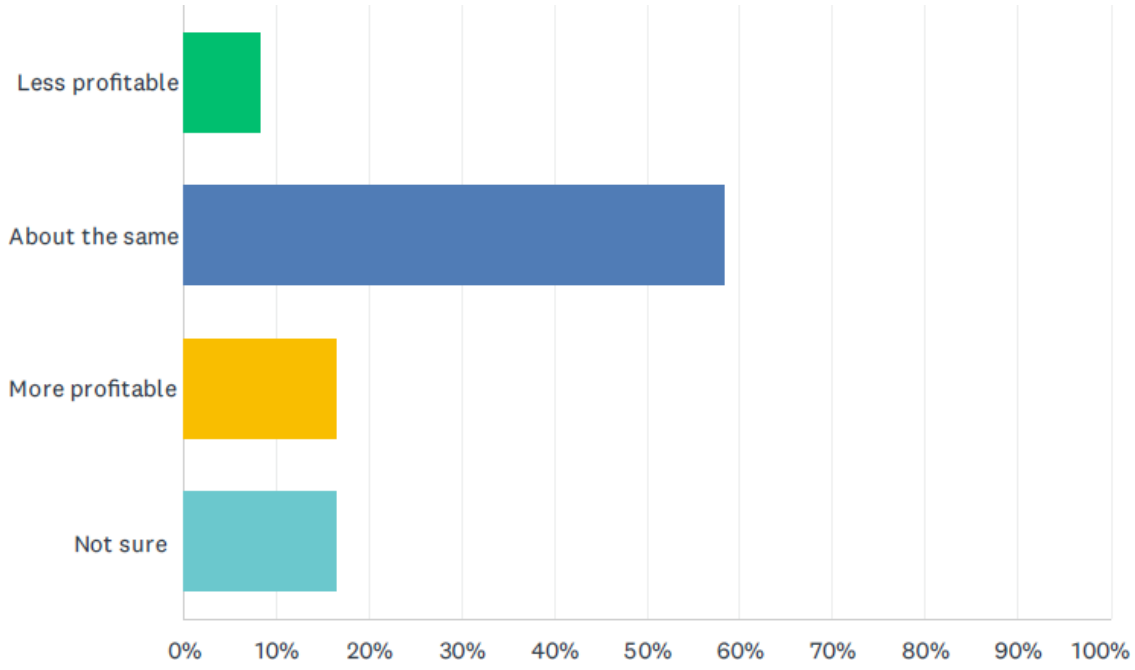
Social responsibility was highlighted by a grower in Hilltops: "I see it as the way of the future - people are concerned about what they are putting on their food. It's also important to have a sustainable, natural system… it is a practice that will still be here in another 50 years' time." (Hilltops grower)

A grower in Mudgee practicing organic viticulture stated, "My previous career was in medicine, and we were concerned about overusing antibiotics, so to put on sprays when you don't need to is akin to using antibiotics. Others would spray in August just in case they got infection - which to me was nonsense."

These viewpoints highlight that members of the wine industry are not only concerned with private benefits but also benefits accruing to wider society.

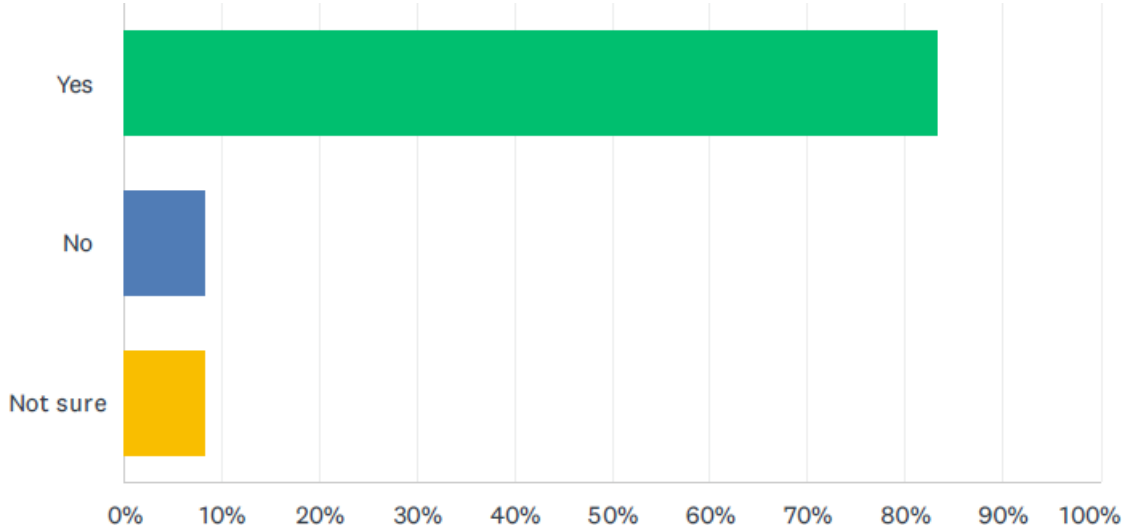
Profitability and long-term viability

When asked to compare the profitability of sustainable farming with conventional farming, 58% considered them to be similar, 17% felt sustainable farming was more profitable, 8% felt it was less profitable and 17% were unsure.



Practices that improved soil health, increased species diversity and beneficial insects were considered to lead to long-term profitability.

Notably, 83% of respondents would consider changing their production practices if there was no immediate economic incentive to do so. 8% were unsure and 8% said they wouldn't.



Long-term viability was highlighted as a major driver for implementing sustainable practices. "There is an understanding that it is not profitable right now, but it will be over a ten-year period. Rather than getting the most profit in the current year but have a reasonable profit over many years. Younger people working in a business are pushing for change so that the farm is future proofed." (Orange grower/ winemaker)

A grower/winemaker from the Canberra region stated that "We define sustainable in environmental, economic and social senses - If you take that view there is no choice but to be sustainable. Usually, people just think environmental. We don't use it as a marketing tool. People who are organic or biodynamic do it because they believe it is best or, more cynically, as a marketing advantage. We are not doing this for a marketing advantage but for what we feel is best for our vineyard and our wines and our long-term future, and so it is more about sustainability from all three perspectives rather than purely environment."

The requirement for profitability was further highlighted in the interviews:

> "We are planting vegetation for encouraging beneficials and biodiversity. At the core, we are doing this as an ethical decision, but it does need to have the extra economic benefit." (Hilltops)
> "Everyone wants to do the right thing, but it needs to make economic sense." (Hunter Valley)
> "We try to be sustainable across the board, but it needs to be profitable." (Riverina)
> "It's no use feeling green if you're not making any money." (Hunter Valley)

In contrast, a grower from Orange had a different viewpoint: "Orange as a region will move together to be a more sustainable industry. We must move that way even though it isn't more profitable."

Profitability in organic viticulture

Organic viticulture is regarded as one form of sustainable viticulture. It was recognised that organic farming may or may not be profitable, and depended on the region and the season, and level of experience with the block. Viewpoints varied widely:

Mudgee grapegrower and winemaker: “Ultimately long-term sustainability is more profitable. For long term sustainability unquestionably, organics is the way to go.”

Orange grower and winemaker: “Organic farming is less profitable. It doesn’t add up. More inputs for similar quality and yields…Big wine companies can sell it amongst the range of labels, but the other labels are supporting the organic ones.”

Canberra grower and winemaker: “We’d rather be sustainable than organic.”

The discord between the grower and winemaker in terms of the value of organically produced crops was also apparent in the interviews:

Orange grapegrower and winemaker: “We increase the price of the endpoint so for us it is more profitable. If you are only a grower, then the winery should pay more for the premium product - but this doesn’t always happen. “

Hilltops grower: “We are pushing towards organic. This is driven by marketing. However, winemakers were not willing to pay extra for organic grapes. There were only a few producers that were interested in it.”

Profitability versus survival

Many operations, especially those in warm regions, are struggling to survive and taking it year by year.

“We are too financially stretched to make the commitment”

“At the moment sustainability is not even a consideration. Viability and surviving are at the forefront - and whether to exit the industry.” (Riverina)

This includes new growers in challenging regions and those that have been growing for years in established regions.

“We put a lot of work in (the vineyard), it cost a lot of money to produce the good fruit, but my wife had to work off the farm to keep us going. It wasn’t sustainable in its own right. So we sold the property because it wasn’t profitable.” (Hunter Valley)

Market saturation and low price of crops was a major issue: “It costs $4000 /ha to maintain your property in the Hunter Valley- it is very high due to high rain and disease management. Often people are happy just to take what they can get for it - rather than nothing at all. The winemaker… didn’t want to compromise.” (Hunter Valley)

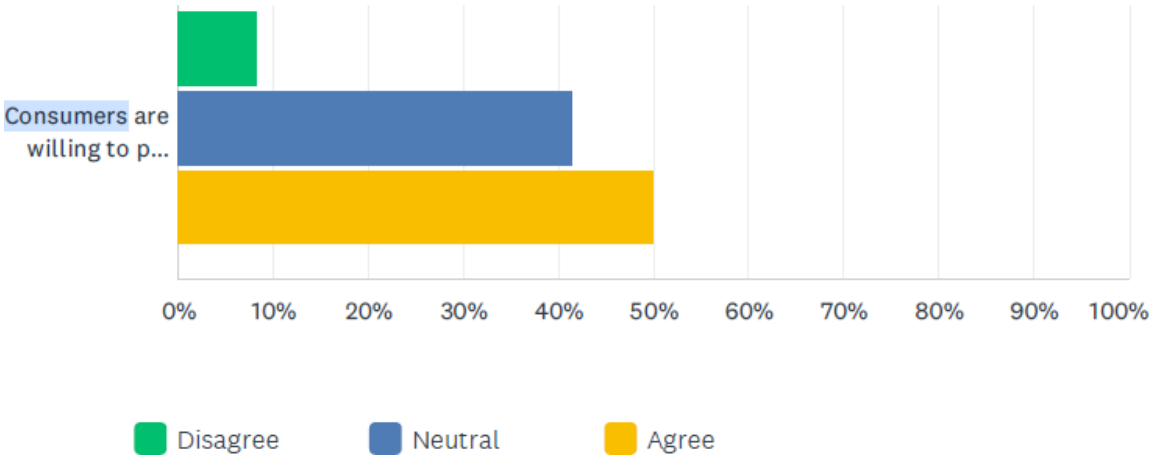
Market drivers

“Change will be driven by market demands. If the market demands that we become more sustainable then we will become more sustainable. Dollars and cents always talk.” (Riverina).

A large operator stated that “It is important to us… we have a sustainability officer. We need to meet the needs of our consumers and overseas markets.” (Riverina).

Despite the increase in market demand this does not seem to lead to direct economic benefits. “At the moment certified organic or sustainable labels do not seem to make more money.” (Riverina).

Only 50% of respondents felt that consumers were willing to pay higher prices for products that are produced in a sustainable manner. 42% were neutral and 8% disagreed.



One optimistic interviewee responded:

> “I’m not making huge amounts of cash, but I think people will spend more on sustainably produced products.” (Organic grower from Mudgee).

Another interviewee felt that there would be an increased market advantage through greater sales at a particular price point.

> “A subset of consumers will target a particular price point and choose the wines they think are more sustainable.” (Canberra District)

In contrast, most other interviewees had more pessimistic attitudes, especially for organic production:

> “Everyone wants to have organic, natural, no pesticide - but not everyone can afford it.” (Riverina)

> “Everyone would buy organic if it was the right price, but it’s not the right price.” (Hunter Valley).

> “Consumers may get a fuzzy good feeling at the dinner table but they don’t want to pay more.” (Orange).

Only a small proportion (10%) at the moment in Australia buy organic products, but this will likely increase (Riverina).

An organic grower in Orange was optimistic, however:

> “Eventually they will. The younger generations are already asking for it. But we still have a long way to go. It is not the norm yet.”

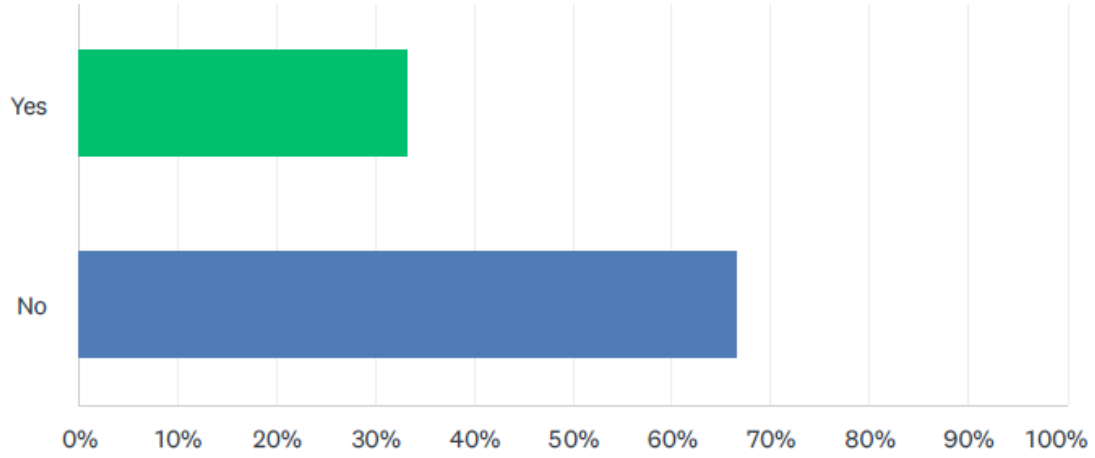
In contrast, international markets may be more willing to pay a premium for organic products:

"Organic operations are often driven by their own passion, and then try to sell it. We implemented the organic operation because we saw a market opportunity (in the Nordic markets) and now also markets opening up in America." (Riverina)

Potential BARRIERS To the adoption of sustainable practices

Resistance to change

Resistance to change can be a significant barrier in the adoption of new agricultural practices. There are a number of reasons for growers and winemakers to continue to do what has worked in the past. The questionnaire revealed, however, that the industry was keen to adopt new methods. 67% of the respondents said that resistance to change was not a significant barrier to adoption in their region.



About half of the respondents said that they knew of other producers who are using new practices to optimise berry quality.

Specific interview responses included:

"If you look at the last 20 years, we've been through a glut, and there is pressure to keep improving and do better." (Canberra)

"People's want to change is there. They will research and try to find the information. They just need the time and money to do it. This is for most of NSW…." (Orange).

"I'm a bit of contrarian. I find it interesting to try new things" (Mudgee)

Region specific attitudes also came through. Some regions, especially young wine growing areas are very responsive.

For Orange, "the region wants to change and be more sustainable."

> A grower from Hilltops was more negative: "Our region is a bad example of adopting new ways. In the 90s there were 20 growers, and now there are 4 big and 3 smaller growers. So that limits the opportunity for new ideas. Age is also important. Growers are over 50 and they are stuck in their ways - they love ploughing and spraying chemicals."

Other interviewees also singled out 'age' as a potential barrier to change:

> "As a general rule, most people are ready to jump onboard and have a go. Younger generations, especially, will adopt new methods and tools, the older ones who are set in their ways will do what they have always done" (Hunter Valley).

> "Average age of most growers, stuck in their ways. Many don't see it (climate change) as an issue, or at least see it as an issue to worry about later. Or, for another generation to worry about."

> "I think with the next generation winemakers like myself they are looking to improve the berry rather than create a higher yield and are more adept to changing their practices to create a better berry flavour."

> "There are more younger people involved. There has been a changing of the guard." (Mudgee)

Social and peer acceptance.

Only 43% of the respondents said that social and peer acceptance was an important driver for adoption in their region.

Time and complexity

The interviews revealed that time restraints, effort and complexity were significant barriers. "Complexity is a big barrier. You need to apply many different practices together. And it is region specific." (Orange)

It was also noted that it is easier for larger companies to invest in R&D and adopt the latest technology. One larger operator stated, "We will try anything new in a heartbeat" (Riverina). Smaller operators were more hesitant to try new things due to the cost involved. They were especially reluctant to invest in replicated trials, and felt they were lacking in resources and skills to do this.

Deficiency of skilled labour in new methods and unavailability of appropriate equipment were listed as other barriers.

Knowledge gaps

It was noted by one interviewee that "Those who don't keep up with the latest developments have trouble adjusting to the new way of doing things" (Riverina).

The on-farm adoption of new recommendations resulting from empirical investigations can be slow and inefficient. The questionnaire revealed that better information transfer could be achieved through on-site demonstrations.

“We need more trials and feedback of successful research with lessons to the growers by bringing this research into the vineyards.” This respondent also highlighted that this would eliminate the cost of implementing inappropriate methods that had not yet been researched and trialled.

“The biggest issue is quantifiable data done scientifically that demonstrates a significant change (50% change season to season)... If the return is better, then the cost is justified”. (Hilltops).

Another interview highlighted the need for follow-up “We also don’t do enough talking about it afterwards to see what the practical outcomes were.” (Hunter Valley)

One of the biggest frustrations was that proposed solutions were often not relevant for a particular region or situation.

> “We’re not adopting it because it isn’t relevant to us. In order to have adoption we need to see it work in our situation. There is variability across the country and the region on what the needs are and what is appropriate. Rootstocks is another good example - this will depend on how much irrigation you apply, water quality, rainfall, soil depth. We are hungry to adopt things that will work for us but it is a matter of filtering out what will work for us in our situation.” (Canberra)

Specific knowledge gaps that were highlighted include:

- Sustainable practices that are cost effective (Specifically vineyard floor management was mentioned)
- Predicting how climate will affect fruit in the future (long term impacts on quality and productivity)
- Better understanding of seasonal variation and weather forecasting
- Methods for dealing with extreme wet or dry seasons
- New varieties that are better matched to a changing climate
- Chemicals for disease control as the number available is declining, particularly required for wet seasons

Discussion

Responsible agriculture focussed on the protection of the environment and the surrounding community is a growing social desire, however its attractiveness to individual growers is highly context dependent. Many growers have strong personal values that encourage the adoption of sustainable solutions. The changes they want to implement, however, must agree with the economics of the vineyard and their time commitment. Implementing practices that are simultaneously environmentally friendly, socially equitable and economically viable is challenging. The application of sustainable practices can be costly in the short-term, with a lag-time in reaping the on-farm benefits. Costs include the acquisition of new knowledge and skills, specialised machinery and tools, on-farm materials, and short-term pest & disease pressures. Most growers are passionate about social responsibility and leaving their land in good condition for the next generation. Better disease management was one of the high priorities. While there may be long-term benefits, these are often outweighed by the more immediate concerns of current farm-finances. The financial hardships that many growers experience is a considerable barrier as new technologies may require considerable investment. Moreover, consumers may not be willing to pay more for environmentally certified wines.

Adoption versus non-adoption is further influenced by non-finance factors such as size of operation, age and growing region.

The obvious wider social benefit can be used as grounds for the development of government programs that support the adoption of sustainable viticulture. Public research institutions can conduct unbiased research programs and extend information through on-farm demonstrations, training and other forms growers can easily use. Governments can supply policies and programs to ensure income protection during transition phase. They can also provide appropriate regulatory frameworks to enable the efficient operation of markets. They may promote change through financial incentives and capacity building.

Summary

Most growers and winemakers are concerned about climate change and are supportive of resource conservation. Many are prepared to implement long term sustainable solutions, even if there is no immediate economic incentive. However, this is not universal, especially in regions where operators are facing severe immediate economic hardship.

Maintaining grape berry acidity in vineyards of warm growing regions - likelihood of new practice adoption

Abstract

Climate change is driving down wine acidity. In many cultivars, berry acid levels decline under warm temperatures through malic acid degradation. This decline can be excessive, resulting in a poor sugar-acid balance. Wine acidity can be improved through the addition of tartaric acid in the winery. We were interested to know if fruit with natural acidity is more desirable by winemakers and, if so, how acid levels may be retained in the vineyard. Vineyard-based manipulation of grape acidity might include alternative cultivars, soil, crop load/canopy management strategies, or alternative rootstocks. We conducted an online questionnaire and interviewed growers and winemakers of NSW to assess the likelihood of adoption of these types of vineyard strategies. The results indicate that the sugar-acid balance was important to winemakers of both warm and cool growing regions. Opinions varied as to the quality of wine made with grapes with natural acidity, as opposed to wine that has had tartaric acid additions. Between 45 and 70% of growers have used vineyard methods to manipulate berry pH and titratable acidity directly, but there was interest in finding more economical and time efficient ways to do this. Lack of solid research evidence for region-specific solutions was cited as significant barrier to improving grape acid levels in warm climates.

Introduction

How warmer climates change berry acidity

Grape acidity is important to wine quality. Acidity imparts a fresh attribute to the wine. Acidity is also important to the microbiological and chemical stability of the wine (Ribéreau-Gayon et al. 2006). Some varieties such as Montepulciano are naturally good at maintaining acidity under warm conditions, while other varieties such as Pinot Noir, Shiraz and Malbec tend to undergo a rapid decline in acid (Howard, 2015). Malic and tartaric acid are the most dominant organic acids in the grape and have a significant influence on acidity and pH (Morris et al. 1983). Tartaric acid accumulates prior to veraison but declines during ripening through dilution as it is insensitive to light and temperature (Cholet et al. 2016; Duchêne et al. 2020). In contrast, malic acid is degraded through respiration or diverted to gluconeogenesis and other pathways (Ruffner, 1982; Sweetman et al. 2014). This loss in malate decreases titratable acidity (TA) (Kliewer, 1965) and alters the sugar-acid balance. While harvesting decisions are often based on flavour, wines that are too low in titratable acidity or too high in pH are less desirable.

Warming in NSW vineyards

A number of wine regions across Australia are vulnerable to climate change as a result of the narrow climate window for the production of premium wine grapes (Jones 2005; Hall and Jones 2009; Hannah et al. 2013). Using empirical models of future scenarios for warming as a result of climate change, Barnuud et al. (2014) have projected TA of Chardonnay to decline by 40% by 2070 in the warmer wine regions. Other varieties such as Shiraz and Cabernet Sauvignon were expected to follow similar trends.

TA has decreased over the past decades in the Loire Valley and this has been attributed to warmer temperatures as the region shifted from a cool to a temperate climate between 1960 to 2010 (Neethling et al. 2012). The higher temperatures are compounded by the observation that advancements in the timing of key phenological stages are shifting the ripening period into the warmer period of the growing season (Fraga et al. 2016; Sadras and Moran, 2012; Sadras and Petrie, 2011; Webb et al. 2011,). The loss of acid appears to be more likely in cool rather than warm- adapted cultivars (Barnuud et al. 2014).

Minimalist intervention

Acidity of the must or the wine post-malolactic fermentation can be improved with the addition of supplementary acids. However, this is not always desirable, especially if the winemaker prefers a minimalist intervention approach (Howard, 2015). Wines with supplementary acid additions may also be considered inferior to wines with natural acid (Gladstones, 1992). Moreover, acid addition imparts an extra cost to wineries. The acid additions may not always be effective because the high K^+ concentrations in grape berries that are associated with high sugar accumulation (Coetzee et al. 2017) can further exacerbate loss of acidity since K^+ binds to acids to form salts (Rogiers et al. 2017, Duchêne et al. 2020). K^+ can be removed from musts and wines but requires specialised equipment (Ojeda et al. 2011).

Adoption barriers

While environmental conditions have a dominating effect on a particular cultivar's berry composition, viticultural practices can also have an influence. The integration of new vineyard methods to improve berry quality is not new to the wine industry. More specially, those manipulations that decrease berry exposure, decrease berry temperature, manipulate the phenology of the vine and the ripening patterns of the berry are known to alter compositional characteristics at harvest. The Australian wine industry has a competitive advantage because of its leading viticulture and winemaking practices (Aylward, 2005). Through good collaboration across a number of industry sectors, and effective transmission of knowledge from research organisations, the development and adoption of new practices and innovations has been exemplary. However, those innovations that do not necessarily have an immediate economic advantage may be rejected. Similarly, those practices that have intensive labour inputs or long-term management costs are less likely to be adopted.

Given the projected unfavourable losses in grape acidity, the objective here is to determine the likelihood for the adoption of methods that will improve wine acidity in an environmentally suitable manner. The aim, specifically, is to **determine whether natural wine acidity is important to the NSW wine industry and to determine the likelihood for the adoption of new soil management, canopy or crop load interventions, or alternative rootstocks to address this issue.**

Materials and Methods

A mixed method approach for data collection was used involving an on-line cross-sectional survey across several segments of the wine industry and a follow-up qualitative study using semi-structured interview questions to gather more in-depth information.

The target population for the questionnaire and interviews included grapegrowers, technical specialists in the vineyard and winery, vineyard managers and winemakers.

Participation recruitment

Information detailing the purpose of the survey and a call for participation was placed on various sites that reach a broad section of the wine industry (Wine Australia, Vinewatch (NSW DPI monthly Newsletter) and National Wine and Grape Industry Centre. Two media releases calling for participation were also released (The Land Australia and Get Farming Australia).

The questionnaire was delivered online using Survey Monkey between October 2021 to April 2022. It consisted of 48 questions.

In the second phase, 45-60 min semi-structured interviews were conducted in May 2022 using participants from different sized operations. At the end of the questionnaire, participants had the opportunity to nominate their interest in taking part in an interview. They were directed to a new page to provide contact details and answer a few short demographic questions. Participants (10) were chosen from a range of regions and operations.

All research activities were approved by the Human Ethics Committee at Charles Sturt University.

Questionnaire and interview topics

The questionnaire and interview addressed

1. Profile and current role in operation (age, education, experience, day-to-day operations)

2. Goals and motivations (region, yield vs quality, market, obstacles, size, environmental sustainability)

4. Current method for managing vine nutrition (tissue analysis, nutrient sources, method of application, costs involved, skills/consultants, soil health)

5. Factors that currently drive decisions in vine nutrition/soil and undervine management/rootstock selection.

6. Sustainable growing practices (current practice, drivers) (Results described elsewhere)

7. Barriers that exist to adopting a new practice (Results described elsewhere)

8. Enablers (benefits) that would support adoption of new practices (Results described elsewhere)

Results:

Demographics

See previous chapter on demographics information.

Is berry composition a priority?

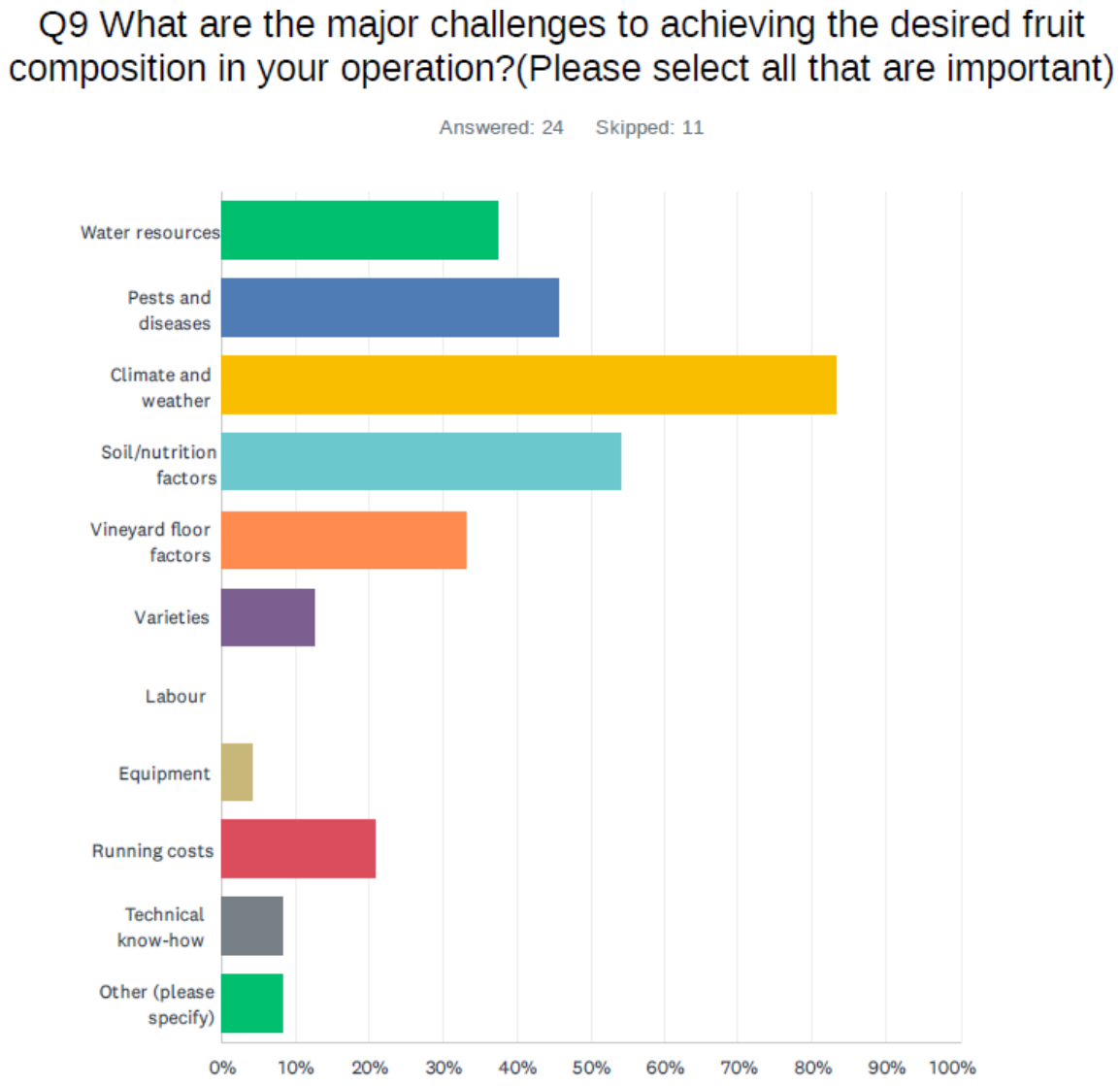
The relative importance of yield versus berry composition was assessed. 17% of the participants rated yield as more important while 25% rated berry composition more important. However, 58% of the participants ranked both yield and berry composition as equally important.

The importance of both yield and berry composition was also evident in the interview response. For large operations in the Riverina, a warm growing region, the major driver is yield, however depending on the targeted product, quality was also considered. “Yield is king, but we want to maintain colour”.

For small and intermediate operations in the majority of NSW the major driver is grape quality (Orange, Canberra, Hunter Valley) or a combination of yield and quality (Hilltops): “Quality, but the yields need to be viable”.

What are the challenges to achieving yield and the desired berry composition?

Climate/weather (67%), pests/diseases (63%) and water resources (54%) were considered to be the most important factors limiting yield, with soil/nutrition (46%) and vineyard floor (42%) factors also rating highly. Variety, labour, running costs, equipment, technical know-how and weed control were also mentioned. With regard to fruit composition, climate/weather was rated highest at 83%, soil/nutrition ranked second at 54% and pests/diseases ranked third at 46%. Water resources, vineyard floor factors and running costs were also ranked highly.



Is wine acidity a priority?

When asked if the target range for berry total soluble solids was important in achieving goals, 65% of growers and 76% of wine makers agreed.

When asked if a target pH was important, 83% of the growers and 100% of the wine makers agreed, thus ranking it even more important than TSS.

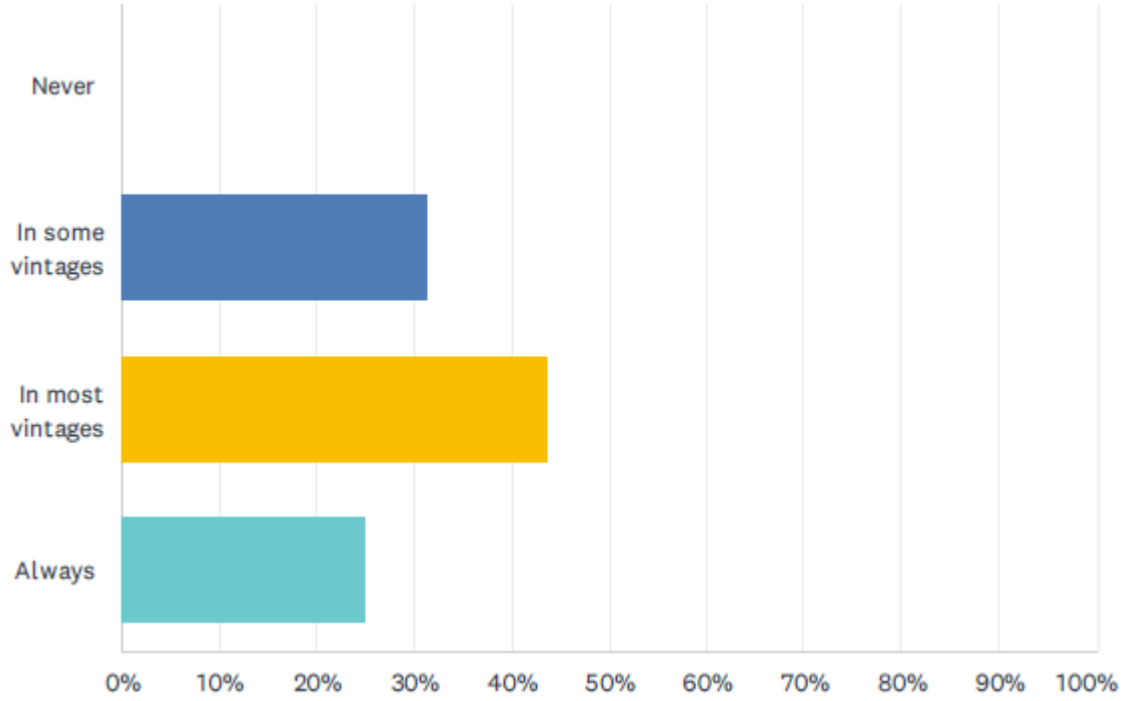
Similarly, 71% of the growers and 83% of the winemakers considered that TA was important.

Interviews confirmed that all three quality parameters were important.

> In Griffith: Quality assessments were carried out in the field by eye and taste. This was followed up by rigorous lab testing. Since taste includes aromas, sugar-acid balance then pH and TA are part of this equation.
> In Orange: Baume is dominant, but pH and TA are important
> In Hilltops: as above but also 'vibrancy' was important
> In Canberra: Primarily it is about flavours, but pH and TA are part of it.
> In Hunter: Flavour is the main driver, followed by colour in the red cultivars, then sugar, and finally pH
>
> "It's important to pick it over a week to see the flavour developing. That way you can earmark the fruit for the premium grade (for their palate). There is always pH and TA, and if TA is dropping away quickly then you need to make a decision. Other winemakers will wait till June before they assess the quality of the fruit! This develops a lack of confidence." (Grower, Hunter Valley).
>
> "There should be a formula where the retail price of the wine should relate to the cost of the purchase of the fruit." (Grower, Hunter Valley).
>
> "I think they are critical. Tempranillo - Spanish red - it drops pH rapidly as it gets riper. So, we add Semillon to add acid and other flavours. We have done this so that we need to add less tartaric." (Grower and winemaker, Mudgee)
>
> "For larger operations Baume is the major driver and for reds colour is also considered. For smaller operations the sugar-acid balance is important." (Grower and winemaker, Griffith).

Status quo of tartaric acid additions

The respondents stated that tartaric acid was added in some vintages (31%), in most vintages (44%), or always (25%). None of the respondents stated that tartaric acid was never applied.



The frequency of tartaric acid addition was dependent on region, with some regions adding it every season. In contrast, a winemaker in Canberra found that low TA was rarely a problem. Acid additions were not often required.

Interviews also revealed that variety differences were important (Grower and winemaker, Canberra). "Tempranillo needs the colour and tannin that is present at high Baume (13.5) - but that comes at the expense of pH and TA. It does drop quite a bit of acid and so we must adjust a lot."

Acid addition to Tempranillo was also mentioned by a grower from Mudgee.

It was noted that the cost of tartaric acid additions has been increasing in recent years and was considered significant for a large operator in the Riverina.

A smaller operator also found it significant, "Availability and cost (of tartaric acid) is an issue. Other means of addressing the problem is important. We all have the problem. Australia really has a problem with pH".

Similar sentiments were expressed by a Mudgee grower: "It is a significant cost - but we add it because have to. We do analysis prior to adding. I'm sure in large commercial vineyards they add it for risk minimisation."

The questionnaire revealed that sample analysis occurred prior to the addition of tartaric acid 100% of the time. 56% stated that the samples were taken from each individual delivery, while 44% stated the samples were assessed at the crusher using a combined sample from several sources. These results suggest that tartaric acid is not added indiscriminately.

Value of wines with natural acidity

When asked if tartaric acid addition is a good-value option to manage pH, 69% of questionnaire respondents agreed, 25% were neutral and 6% disagreed. When asked if wines made from fruit with natural acidity are of higher quality than wines made through adjustments with tartaric acid, 44% agreed, 31% were neutral and 25% disagreed.

Most interviewees considered wines made with natural acidity to be of superior quality. They suggested that the more adjustments that were required, the more problematic the grapes were originally.

However, these sentiments were not universal. A grower from Canberra said, "The wine industry is full of people making statements like that. They say it based on gut feeling and on what they like to believe rather than doing a careful trial of that. It is much better to adjust than not adjust if you need to."

"The addition of too much acid is not natural. However, the yeasts have evolved in complexity to handle that part of it. It has become a real science. If it is a minor adjustment, it isn't an issue- and it is a better financial result."

A grower from Hilltops said that tartaric acid is a natural acid and should not decrease wine quality. However, "Intense flavours are associated with the high acid levels which are related to the low temperatures."

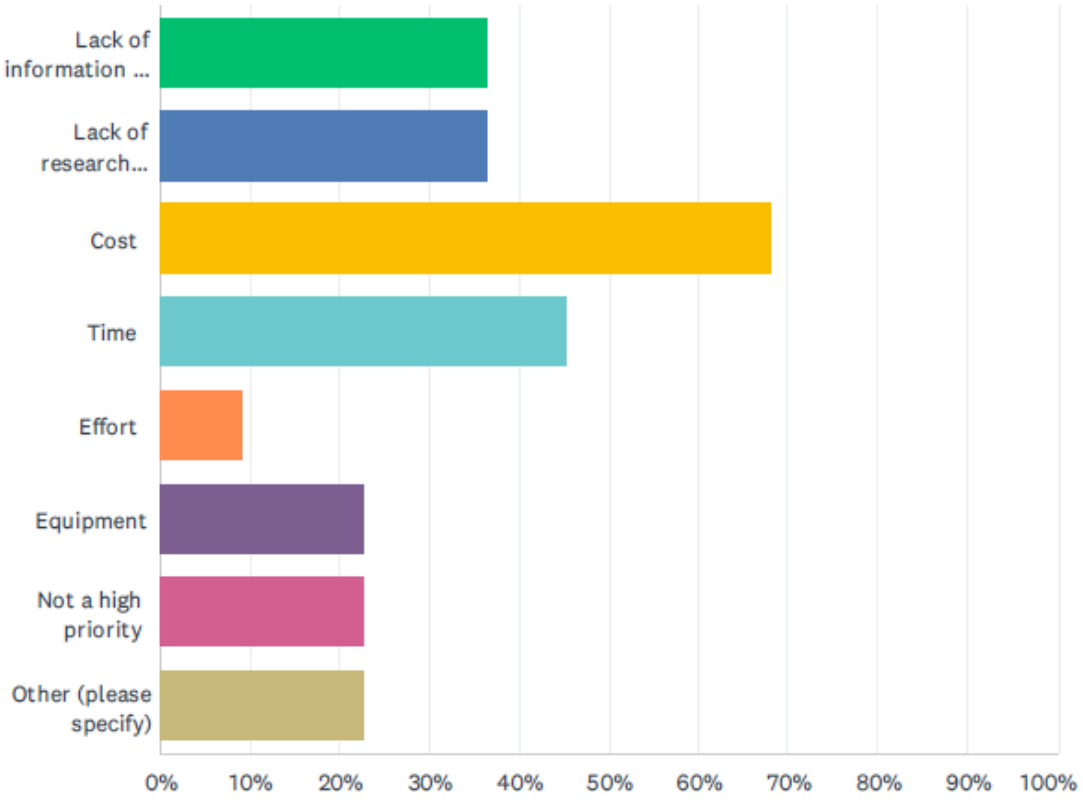
Current management practices used to manipulate berry composition

	TOTAL SOLUBLE SOLIDS (TSS - SUGAR)	PH	TA	COLOUR	FLAVOUR / AROMA	TOTAL RESPONDENTS
Pruning and canopy management	75.00% 15	45.00% 9	45.00% 9	80.00% 16	80.00% 16	20
Row orientation/vine spacing	100.00% 8	50.00% 4	50.00% 4	87.50% 7	87.50% 7	8
Soil/nutrition/vineyard floor management	76.47% 13	70.59% 12	64.71% 11	58.82% 10	76.47% 13	17
Rootstocks	66.67% 2	66.67% 2	66.67% 2	33.33% 1	0.00% 0	3
Water management	84.21% 16	63.16% 12	57.89% 11	57.89% 11	78.95% 15	19

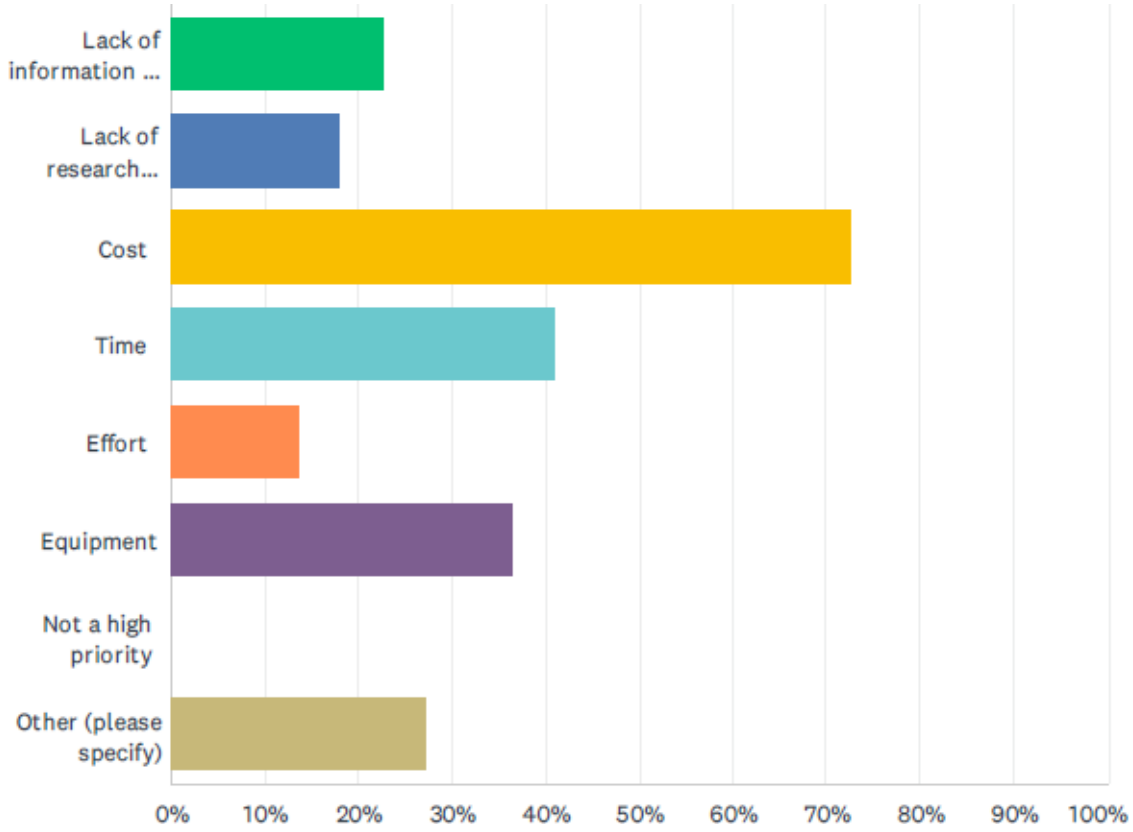
TSS was manipulated most often with row orientation/vine spacing but water management, pruning/canopy management, soil/nutrition/vineyard floor management and rootstocks were also common. pH and TA were most often addressed with soil/nutrition/vineyard floor management but rootstocks, water management also rated highly. Colour was mostly managed by row orientation/vine spacing and pruning/canopy management. Flavour/aroma were also manipulated by these factors as well as water management.

Barriers to adoption of new **canopy management protocols** for optimal berry quality.

Cost was considered a major barrier to the adoption of new canopy management protocols. Time, inadequate information, and lack of research evidence were also considered important. The availability of labour was also noted.


Lack of information ...
Lack of research...
Cost
Time
Effort
Equipment
Not a high priority
Other (please specify)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

Barriers to adoption of new **soil management protocols** for optimal berry quality.



The questionnaire also revealed similar barriers to the implementation of soil management protocols. Cost and time were cited as the major barriers, along with information overload. The information that was available was deemed unclear, impractical or too costly to implement.

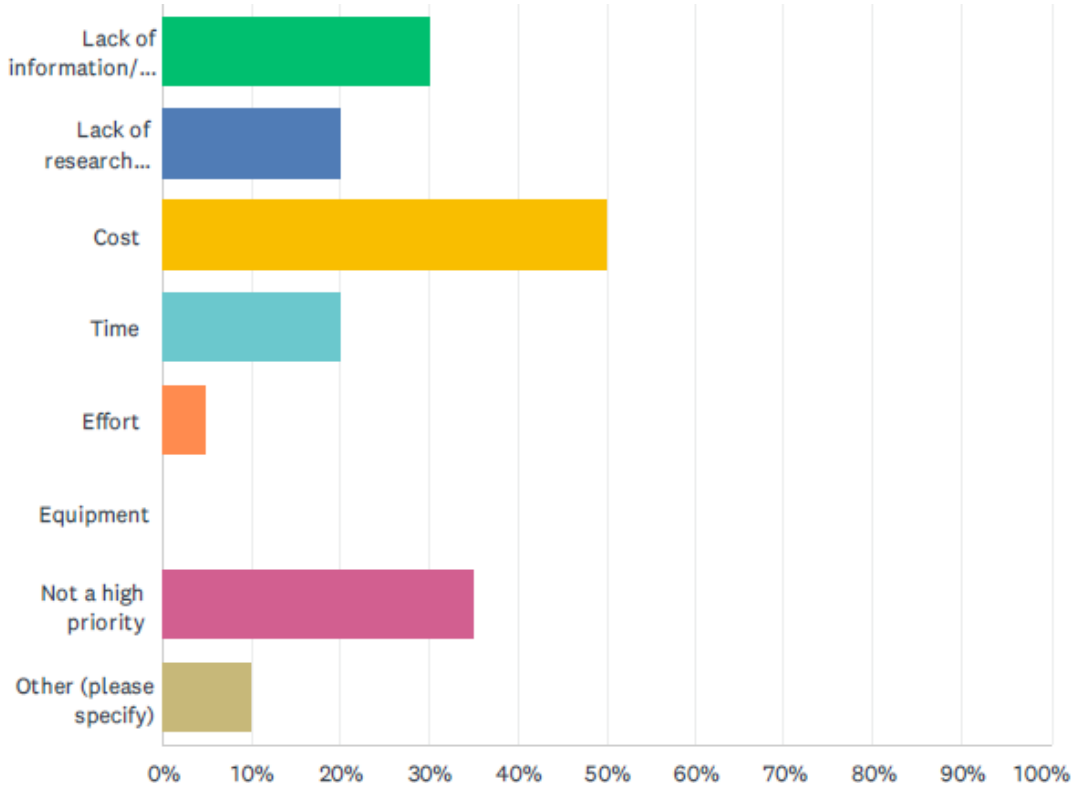
A. Fertiliser practices. 85% of the respondents used soil tests and tissue tests, while 90% used visual observations to guide fertiliser practices. Feedback from grape buyers and winemakers was also mentioned. 85% of the respondents have interpreted some of the soil and or plant/tissue diagnostic lab reports themselves, but many of these simultaneously rely on professionals (65%) or on peers (20%). 62% of the respondents used synthetic fertilisers and 95% used organic fertilisers.

	BROADCAST	BANDING	FERTIGATION	FOLIAR SPRAYS	NOT APPLIED	TOTAL RESPONDENTS
Nitrogen	15.79% 3	21.05% 4	68.42% 13	68.42% 13	5.26% 1	19
Phosphorus	38.89% 7	22.22% 4	38.89% 7	38.89% 7	11.11% 2	18
Potassium	10.53% 2	21.05% 4	47.37% 9	57.89% 11	21.05% 4	19
Sulphur	5.26% 1	10.53% 2	21.05% 4	89.47% 17	5.26% 1	19
Calcium	27.78% 5	11.11% 2	44.44% 8	55.56% 10	11.11% 2	18
Magnesium	27.78% 5	11.11% 2	22.22% 4	61.11% 11	11.11% 2	18
Micronutrients	5.26% 1	10.53% 2	31.58% 6	78.95% 15	15.79% 3	19

Foliar application was common for most nutrients, followed by fertigation, broadcasting and banding. A small proportion did not apply some of the macro or micronutrients.

B. Likelihood of mulches/composts
65% of the respondents applied mulches under-vine or in the mid-row, while 40% applied composts.

Barriers to adoption of **new rootstocks**.



Again, cost was rated as the highest barrier for the adoption of new rootstocks, but it was also not deemed a high priority. One participant commented that once a vineyard is established it is not likely to be changed for 20 years.

"It's hard to change the rootstocks. But where we are planting new blocks - they are on rootstocks and if there was information on better, for example, excluding potassium in Tempranillo, I would consider it. But it has to be weighed up against the other reasons for picking particular rootstocks."

Another grower stated he would not consider rootstocks for berry quality: "I think we can manipulate it just as well via management techniques".

Overall likelihood for the adoption of new management practices to manipulate berry pH and TA:

Approximately half of the questionnaire respondents (52%) knew other producers who are using practices to optimise berry quality.

Interviews revealed that new methods would be considered to improve vine health and optimise ripening and quality. "We haven't done anything for acid levels, but it makes good sense".

Discussion

Wine acidity and the sugar-acid balance are a priority for winemakers.

Wine quality is directly linked to the sugar-acid balance and therefore, alongside 'flavour-ripe' characters, acidity was regarded to be of primary sensory importance by both growers and winemakers. Wines that are too high in acid are regarded as too sharp while low acidity results in a flat, more monotonous flavour profile (Mato et al. 2005). Sweeter wines require more acid for a positive organoleptic experience. Tartaric acid and malic acid contribute the most to acidity but their concentrations are dependent on cultivar and maturity, with cooler regions generally having more acidity. Acetic, citric, lactic and succinic acids are also present at low concentrations (Mato et al. 2005). Each of the acids has its own flavour attribute, with malic acid imparting harsh sour notes and tartaric acid resulting in a perception of 'tartness' and 'freshness' (Chidi et al. 2018).

Wines made with grapes with natural acidity are preferred but tartaric acid additions are regarded as a good option to deal with low acidity.

Acidity adjustments are frequently carried out in Australian wineries. This is practiced not only to improve the sensorial properties of the wine, but also for managing wine stability and contamination risks (Waterhouse et al. 2016). Tartaric acid is the acid most employed during adjustments because it is not metabolised by the yeast and other wine microorganisms (Volschenk et al. 2006). Tartaric acid is chemically unstable and will bind with K^+ in the must to form tartrate crystals and so additions may not be wholly effective (Vicente et al. 2022). Other methods are available, but cost and flavour distortion are a concern (Nagle et al.,1975). Most winemakers considered fruit with natural acidity to be superior to fruit requiring acid adjustment because low acid fruit is often associated with overripe characters (De Orduna, 2010). Blending with acidic musts from low maturity grapes is another feasible option (Comuzzo and Battistutta, 2019).

Growers are interested in finding practical means to manipulate berry pH and titratable acidity. The current solutions available were however deemed insufficient, too labour intensive and costly. There is a desire for not only high natural acidity, but there must also be tolerance to heat and drought. The planting of alternative varieties that are better able to hold acid under these conditions, including late ripening varieties is already being practiced, but variety and clonal selection needs to meet the conditions of the region, site characteristics and available resources such as water. Similarly, rootstock selection targeted at increased vigour or directly at berry composition, for instance to limit K^+ uptake, needs to be considered along with several other factors such as Phylloxera and drought resistance. Row orientation can also be important, with an east-west orientation limiting exposure to the hot late afternoon sun. The implementation of these solutions is costly and are usually only considered during new vineyard establishment. Other management options may include vine architecture and canopy management techniques. These have long been used to manipulate berry quality through light exposure for increased anthocyanins, open canopies for better aeration for disease management. Late winter pruning, severe shoot trimming and apical leaf removal may also delay grape ripening (Gutiérrez-Gamboa et al. 2021). Again, these may be labour intensive and costly to implement. Alternatively, sprawling canopies can reduce sunburn and slow ripening rates through increased vegetative competition with reproductive development. Finally, cooling of grapes through efficient misting and spraying may slow the degradation of malic acid, but this may have implications for water conservation and freshwater ecosystems.

The K^+ ion that is accumulated by the berry has a significant role in acidity as it can bind with organic acids (Boulton 1980; Walker and Blackmore, 2012). The potential of using cation antagonists to reduce the uptake of K^+ by the berry has been proposed as a method to maintain berry acidity (Moss 2016). Cations such as Ca^{2+} and Mg^{2+} may compete with K^+ (Hannan 2011) and may improve berry and must acidity through the inhibition of K salt formation (Philip and Kuykendall 1973). Soil Ca^{2+} and Mg^{2+} availability can be improved through liming, or these cations may be added to the soil through composts or mulches, or synthetic fertilisers. Questionnaire respondents and interviewees expressed a strong consciousness of land protection, and as custodians of the land there was interest in using sustainable practices including fewer synthetic fertilisers. Thus, natural sources of these cations would be preferred, along with rootstocks that discriminate against K^+. Reducing unnecessary K fertiliser applications would be another cost-saving solution that would agree with these responsible sentiments. Similarly, under adequate moisture, unnecessary irrigation can be restricted as this may lead to the dissolution of K^+ into the soil and increased K^+ availability to the roots (Freeman and Kliewer 1983; Moss 2016). Preliminary investigations, however, indicate that it may take several years to manipulate berry composition because vine nutrient reserve stores will influence what nutrients are transported to the berry. There is also the risk of inducing a K deficiency in the vine.

Careful matching of the variety with the site will reduce vineyard and winemaking costs, so that the varietal characteristics are expressed along with the retention of natural acidity.

Region-specific solutions are required for the manipulation of berry composition, including pH and TA.

The interviewees stated that evidence for solid returns for new strategies were required prior to implementation. The extensive variation in climate and soil across Australia's 65 viticulture regions dictates region specific assessment of new practices. Properly replicated on-farm trials allow researchers to test new techniques that would improve the production system specific to that region and context, along with the application of appropriate statistical methods to allow the isolation of natural variation from true treatment effects. Participatory on-farm trials have been ongoing for more

than a decade in Australia and allows growers to develop new skills and gain confidence in the applicability of the new practice. It also encourages acceptance and adoption by the neighbouring growers (Hood and Shearer, 2001). While larger operations can support this type of research in-house, smaller operations with a limited workforce benefit from these types of participatory trials. Adequate technical support is required to ensure that the labour and time commitments by the grower do not become arduous. Involving both new and well-established growers will encourage the formation of networks and information sharing across the region. Moreover, encouraging participation by the end-user from the initial stages of project design will encourage implementation.

Summary

Along with flavour, berry acidity is important to winemakers and those growers who are rewarded for quality, but applied knowledge is required to maintain optimal composition in the vineyard. Practical solutions need to be cost-effective and relevant to a particular climate and soil. The development of a clear adoption pathway should thus be based on region specific trials using methods that are cost-effective and easy to implement. Clearly defining the needs of the end-users in a co-design framework (Coutts 2021) will encourage better adoption.

Adoption Strategy

Roger's Diffusion of Innovation Model outlines five steps to adoption: knowledge generation, curiosity, knowledge transfer, perception change and finally, experimentation. An adoption strategy defines the behaviour change that is required, develops a road map that facilitates adoption, and finally measures if and how well adoption has occurred. Adoption is achieved when practice or behaviour change occurs. It is complex and repeated efforts are required through communication and education.

Reduced grape quality resulting from climate pressures demands new and flexible vineyard management strategies. The Australian wine industry is diverse with 65 growing regions spread across several climate zones. The likelihood of adoption of new cultivars, rootstocks, soil management, canopy or crop load interventions will depend on the balance between a number of drivers and stressors.

A cross-sectional on-line questionnaire (40 questions) was administered to the wine industry and follow-up in-depth interviews were conducted to better understand these drivers and stressors. The questionnaire and interview provided baseline information on the characteristics of the population, their behaviours, values and aspirations.

The questionnaire and interview gathered information on:

1. Profile and current role in operation (age, education, experience, day-to-day operations).
2. Goals and motivations (region, yield vs quality, market, obstacles, size, environmental sustainability).
3. Current method for managing vine nutrition (tissue analysis, nutrient sources, method of application, costs involved, skills/consultants, soil health).
4. Factors that currently drive decisions in vine nutrition/soil and undervine management/rootstock selection.
5. Sustainable growing practices (current practice, drivers).
6. Barriers that exist to adopting a new practice.
7. Enablers (benefits) that would support adoption of new practices.

The outcomes can be summarised as follows:

- The most important drivers of profitability were yield (17% of responses), berry composition (25%), or equally yield and composition (58%).
- Wine acidity and the sugar-acid balance are a priority for winemakers.
- Wines made with grapes with natural acidity are preferred but tartaric acid additions are regarded as a good option to deal with low acidity.
- Growers are interested in finding practical means to manipulate berry pH and titratable acidity. The current solutions available were however deemed insufficient, too labour intensive and costly.
- Region-specific solutions are required for the manipulation of berry composition, including pH and TA.
- Growers had strong personal values that encourage the adoption of sustainable solutions. These changes must agree with the economics of the vineyard and the grower's time commitment.
- Long-term viability was highlighted as a major driver for implementing sustainable practices.

- Practices that improved soil health, increased species diversity and beneficial insects were considered to lead to long-term profitability.
- Notably, 83% of respondents would consider changing their production practices if there was no immediate economic incentive to do so. 8% were unsure and 8% said they wouldn't.

  "There is an understanding that it is not profitable right now but it will be over a ten year period. Rather than getting the most profit in the current year but have a reasonable profit over many years. Younger people working in a business are pushing for change so that the farm is future-proofed." (Orange grower/ winemaker)

- However financial hardship experienced by many growers is a significant barrier to the adoption of new skills, machinery, and tools.

- Most respondents used a combination of visual observations, soil tests and tissue tests to guide fertiliser practices. Soil and or plant/tissue diagnostic lab reports were assessed independently but professional advice was also frequently sought. A combination of synthetic and organic fertilisers was used. Foliar application was common for most nutrients, followed by fertigation, broadcasting and banding. A small proportion did not apply some of the macro or micronutrients.

	BROADCAST	BANDING	FERTIGATION	FOLIAR SPRAYS	NOT APPLIED	TOTAL RESPONDENTS
Nitrogen	15.79% 3	21.05% 4	68.42% 13	68.42% 13	5.26% 1	19
Phosphorus	38.89% 7	22.22% 4	38.89% 7	38.89% 7	11.11% 2	18
Potassium	10.53% 2	21.05% 4	47.37% 9	57.89% 11	21.05% 4	19
Sulphur	5.26% 1	10.53% 2	21.05% 4	89.47% 17	5.26% 1	19
Calcium	27.78% 5	11.11% 2	44.44% 8	55.56% 10	11.11% 2	18
Magnesium	27.78% 5	11.11% 2	22.22% 4	61.11% 11	11.11% 2	18
Micronutrients	5.26% 1	10.53% 2	31.58% 6	78.95% 15	15.79% 3	19

One of the aims of this study was to address the decline in berry acidity through cation antagonism. The regional soil survey results suggested improved berry acidity and pH under a soil with high Mg/K but the field and pot fertiliser treatments were inconclusive and therefore it is too early to develop an adoption plan for this specific strategy.

Vine nutrition is a component of long-term sustainability and there are numerous studies that have shown the strong role that vine nutrition can have on berry composition. Therefore, the adoption plan we have formulated is focused on vine nutrition management not only for productivity but also for optimal berry composition.

Adoption Plan for implementation of sustainable growing practices that focus on optimal vine nutrition

The CSIRO ADOPT TOOL (https://adopt.csiro.au/home.aspx) was applied to assess the proportion of the population that is likely to adopt 'optimal vine nutrition for improved berry composition' (Peak Adoption Level) and also the time required to achieve adoption (Time to Near Peak Adoption).

The ADOPT tool is structured around the characteristics of the innovation, the characteristics of the population, actual advantage of using the innovation, and the learning of the actual advantage of the innovation. The information gathered from the questionnaire and interviews was used to populate the model

The problem: Declines in long-term productivity and grape quality as a result of extreme weather events, global warming and soil degradation

The Innovation: We have found that a high Mg/K ratio improves grape pH and TA in warm regions.

Short term goal: Maintain financial viability.

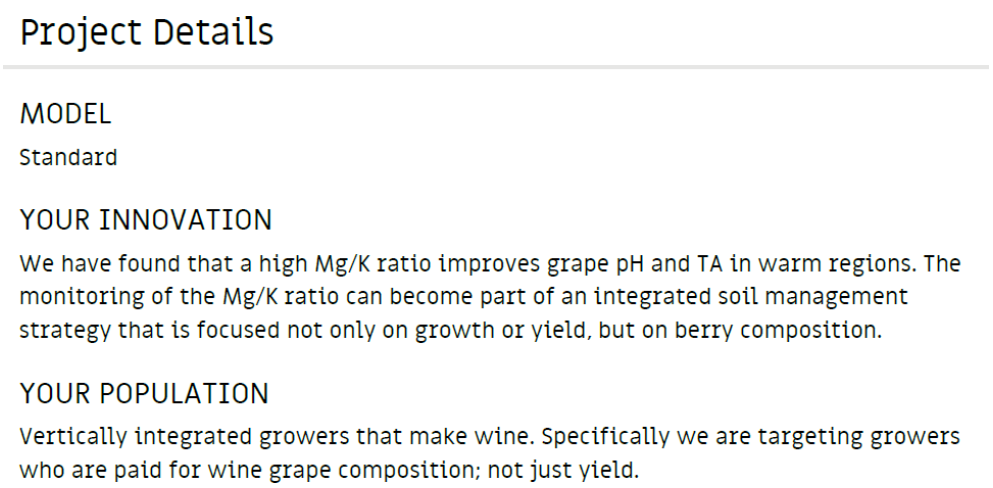
Long term goal: Economic, environmental and social sustainability.

Missing knowledge and resources: Region specific trials demonstrating the benefits of optimal vine nutrition on berry composition.

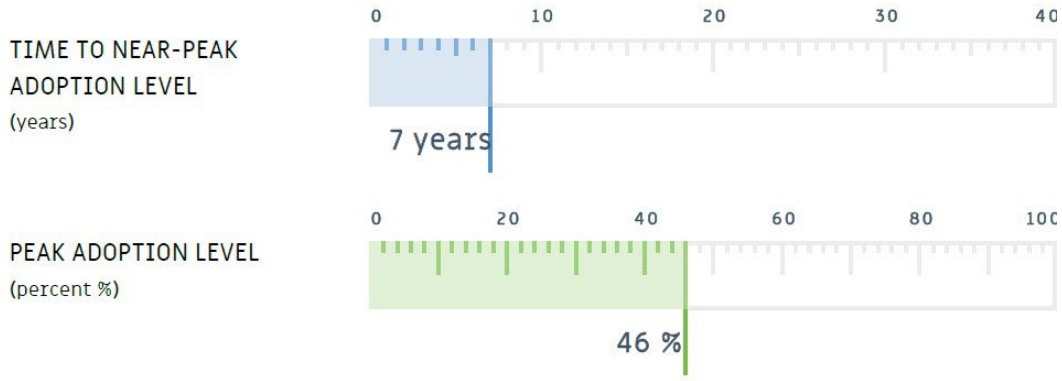
Target audience: Growers that are rewarded for berry quality, not just yield. Vertically integrated operations that produce wine from their own grapes.

Communication channels available: Vinewatch, Wine Australia website, AWRI website, Grapegrower and Winemaker, Wine and Viticulture, workshops/field days (demonstration site), webinars, instructional videos, ABC rural.

Key Message: Targeted vine nutrition for productivity and desired berry composition.



Adoption Level

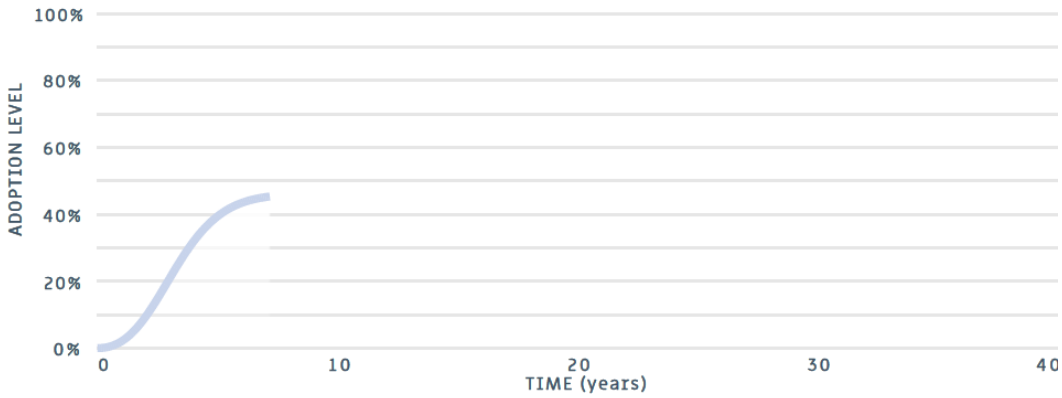


Predicted adoption levels



Adoption level S-Curve

The following chart shows how the level of adoption in the relevant population of farmers changes over time.



Yearly Adoption Levels

Year	Adoption %
1	2
2	9
3	21
4	32
5	39
6	43
7 (Peak Adoption)	45

Conclusions/Outcomes

A survey of the Riverina and Orange growing regions has demonstrated that a low [Mg]/[K] ratio in the soil and in the vine is associated with high berry pH and low TA.

Summary of 2018-19 growing season survey:

- Juice pH was positively correlated with juice [K] in Chardonnay, Semillon, Pinot Gris, Shiraz, Cabernet Sauvignon (five out of the six cultivars tested)
- Juice TA was negatively correlated with juice [K] in most cultivars
- Juice [Mg]/[K] and [Ca]/[K] have an influence on juice pH and TA in most cultivars
- Juice [K] was correlated with berry [K] in only some cultivars
- Berry [K] was correlated with petiole [K] (close to harvest) in some cultivars
- Petiole [K] was inversely correlated with petiole [Mg] in most cultivars
- Berry [K] was inversely correlated with petiole [Mg]/[K] in some cultivars

Summary of 2019-20 growing season survey:

- Juice pH was inversely correlated with soil exchangeable Mg % and soil [Mg]/[Ca] ratio in Riverina Shiraz but not for Orange Shiraz. Juice TA was positively correlated with these two parameters. Riverina Chardonnay juice pH was inversely correlated with soil Mg %, Mg/K ratio as well as soil Ca/K ratio. These parameters did not have an influence on TA, however, for this cultivar.

- Riverina Shiraz juice pH was inversely correlated with petiole [Mg]/[K] and [Ca]/[K] ratios. TA was positively correlated with petiole [Mg]/[K] ratio. Riverina Chardonnay juice pH was similarly negatively correlated with lamina [Mg]/[K] ratio, while TA was positively correlated with this parameter.

Summary of Nutrition Trials:

- In the potted-vine and field-vine trials the application of Mg did not affect berry pH, TA or TSS.
- However, a further in-depth analysis of the potted-vine study revealed inverse correlations between mid-ripening juice pH and the mid-ripening petiole and blade [Mg]/[K] ratios.

What could this mean for the industry?

Impact on the consumer - Wines produced from grapes with natural acidity are considered to be superior in quality than acid adjusted wines (Howard 2015). Wines with low acidity are more susceptible to microbial spoilage.

Impact on the winemaker - Acidity is one of the most important considerations for wine quality. Grapes with higher natural acidity require less manipulation during winemaking (AWRI 2018). Acid adjustment by quality L(+) tartaric acid is costly, therefore wine companies will reward a grower for higher quality grapes.

Impact on the grower - The results we have obtained so far hint that appropriate regulation of vine nutrition may offer a practical means for obtaining grapes with high natural acidity. This can potentially be achieved through managing the vineyard floor, carefully regulating soil inputs to optimise the vine Mg/K ratio, vine balance, reducing bunch overexposure, irrigation strategies or rootstocks. The grower has always needed to maintain soil and vine health and to use rootstocks for the wider benefits provided, such as tolerance to Phylloxera and nematodes, so that productivity is maintained - the challenge is to ensure that those running costs do not increase but that vineyard processes are made more efficient.

Impact on the environment - Soil management is a complex process that needs to address overall soil health and long-term sustainability for long-lasting productive vines. The prevention of nutrient leaching and an assessment of other environmental impacts are required prior to the implementation of any adoption strategy.

Recommendations

Optimising the vine Mg/K ratio

Undertake plant tissue analysis to ensure the vine nutrients are in the adequate range. Additionally assess soil nutrient levels, particularly CEC, K, Mg, Ca and Na. If the cations are in the deficient or excessive range, they should be corrected through appropriate interventions. Reduce K fertilisation if not required and apply Mg fertiliser if needed using the following guidelines:

Reduce K if in oversupply

1. Reducing the over-application of blended products (such as NPK products, MKP etc) can reduce soil K.
2. Careful analysis of organic matter (such as grape marc, straw mulch etc) for K content prior to addition (Chan and Fahey 2011) may also improve the soil Mg/K ratio.
3. The reduction of potassium metabisulfite usage as a source of sulfur dioxide to control diseases and microbial infection should be considered.
4. The planting of inter-row species such as kale that can draw out soil K may offer an additional sustainable avenue to remove excess K (Thompson et al. 2010).
5. K-excluding rootstocks have been/are being trialled (Walker and Blackmore 2012, Walker et al. 2019, Xiao et al. 2020). Experiments conducted at Padthaway with Shiraz and in the Coonawarra with Cabernet Sauvignon have confirmed the effectiveness of lowering K concentration in the vegetative tissue using Merbein 5512 and Merbein 5489. The potential for Merbein 5512 and Merbein 5489 in lowering juice K^+ and pH of Shiraz has been demonstrated in Sunraysia (Walker and Clingeleffer 2009).
6. K accumulates through the transpiration stream. Careful soil and plant water status monitoring may help to curtail excessive K uptake. However, there may be limits to the

potential benefits, since irrigation is critical for withstanding heatwaves. Water stress can hamper berry development, reduce yields and increase canopy and berry temperature, increasing the respiratory loss of malate and decreasing TA (Edwards and Clingeleffer 2014). Additionally, low soil moisture levels will limit uptake of many other essential nutrients, aside from K^+.

7. Opening the canopy (by shoot thinning, basal leaf removal, hedging, shoot positioning, etc) can reduce K accumulation by the fruit (Smart et al. 1985), but in warm climates, the negative impact of over-exposure makes this impractical.

Increase Mg if deficient:

1. The addition of synthetic Mg through the sulfate form ($MgSO_4$) is one of the cheapest options for applying Mg (other options include magnesium oxide, magnesium carbonate and dolomite). More than one application may be necessary depending on the soil characteristics. However, because the addition of sulfate fertilisers may acidify the soil, Richard Merry has developed a simple method/calculator for monitoring and correcting soil acidity (Merry et al. 2004, Thomas 2007).

PRODUCT / ELEMENT	Element	%	Max kg/ha
Dolomite	***Mg***	10	1500
Magnesium oxide	***Mg***	53	250
Magnesium sulfate	***Mg***	9.9	250
Magnesite carbonate	***Mg***	27	1500

2. Mg becomes available in soils that have a pH above 6.0 (and K at less than 5.5). Therefore, adjustments in the pH of acidic soils may also increase the availability of Mg. Since each block has its own suite of soil characteristics and nutrient history it will be critical that each block undergoes a thorough soil assessment prior to devising a nutrition and soil amendment plan.

Sustainable practice:

The overall aim of any vineyard manager is to increase productivity and fruit quality with better managed inputs. We do not recommend the indiscriminate application of synthetic Mg, but rather a holistic approach. The addition of dolomite or other organic sources of Mg may be advantageous. Biostimulants such as fulvic acid, for instance, may improve Mg uptake and reduce overall requirements for fertilisers (Xu et al. 2019), however further research is required. The composition of the rhizospheric biomes may also influence nutrient uptake (D'Amico et al. 2018). Complementing the rootstock microbiome through the supplementation of probiotic microbes to the soil is an emerging field of research worthy of exploration.

Each vineyard is unique in its soil-cultivar-climate-history and the desired final wine style may change from one growing season to the next. The monitoring of the soil [Mg]/[K] ratio can become part of an integrated soil management strategy that is focused not only on growth or yield, but on berry and must composition. With further research, the current reference standards can be updated for berry composition. The results of this study will undoubtedly contribute to the revision of these standards.

Appendix 1: Communication

Refereed Publications:

Rogiers SY, Greer DH, Liu Y, Baby T, Xiao Z. 2022. Impact of climate change on grape berry ripening: an assessment of adaptation strategies for the Australian vineyard. Frontiers in Plant Science 13:1094633. doi: 10.3389/fpls.2022.1094633

Rogiers SY, Greer DH, FJ Moroni, Baby T. 2020. Potassium and magnesium mediate the light and CO_2 photosynthetic responses of grapevines. Biology 9, 144; doi:10.3390/biology9070144

Refereed Conference Proceeding:

Baby T, Holzapfel BP, Schmidtke LM, Walker RR, Rogiers SY. 2022. Differential accumulation of potassium in leaf tissues and bunch stems of three grapevine cultivars. Acta Horticulturae 1333, 115-124. doi: 10.17660/ActaHortic.2022.1333.16.

Industry publications:

Rogiers SY and Walker RR. 2018. Implications of potassium nutrition for grapes and wine. Grapevine Management Guide 2018-2019, p.63

Rogiers SY, Baby T, Xiao Z, Holzapfel B, Schmidtke L, Walker R. 2023. Grape potassium, acidity and pH in a changing climate. Grapegrower and Winemaker, February 2023 issue.

Rogiers SY, Adkins M, Fahey D, Jarrett M, Baby T. 2023. Stressors and facilitators to adoption of sustainable viticulture- a focus on soil health. Grapegrower and Winemaker, March 2023 issue.

Oral Presentations:

Spring Vine Health Field Days August-September 2021: Griffith, Tumbarumba, Murrumbateman, Orange

Spring Vine Health Field Days August-September 2022: Griffith, Mudgee, Hunter Valley, Tumbarumba, Murrumbateman, Orange

Granite Belt Field Walk - Glen Aplin, 7 December 2022

Media:

Managing wine pH in a changing climate https://www.csu.edu.au/nwgic/about-us/news/newsletters/2019/ decanted-issue-1/managing-wine-ph-in-a-changing-climate	February 2019	Decanted, the NWGIC newsletter

Less K = less acid = less money https://www.wineaustralia.com/news/articles/less-k-less-acid-less-money	January 2020	Wine Australia news
Wagga's climate warms by two degrees, data shows	December 10, 2020	Daily Advertiser

Appendix 2: Intellectual Property

No new IP was created by the project

Appendix 3: References

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Appendix 4: Staff

Name	Organisation	Role
Suzy Rogiers	NSW Department of Primary Industries	Project Lead
Bruno Holzapfel	NSW Department of Primary Industries	Principal Investigator
Leigh Schmidtke	Charles Sturt University	Principal Investigator
Rob Walker	CSIRO	Principal Investigator
Tintu Baby	Charles Sturt University	Postdoctoral Fellow
Francesca Moroni	Charles Sturt University	Technical Assistant
Nicholas Moroni	Charles Sturt University	Technical Assistant
Pedro Gascon-Aldana	Charles Sturt University	Technical Assistant
Dewatage Perera	Charles Sturt University	Technical Officer
Di Hubbard	Charles Sturt University	Technical Officer
Helen Pan	Charles Sturt University	Technical Officer
Jennifer Manyweathers	Charles Sturt University	Principal Investigator
Lynne Hayes	Charles Sturt University	Principal Investigator

Marta Hernandez-Jover	Charles Sturt University	Principal Investigator
Gail Fuller	Charles Sturt University	Principal Investigator

Appendix 5: On-line Questionnaire

Managing wine pH- Survey Questions

What is your age?

- 18-34
- 35-50
- 51-65
- 66-80
- older than 80

Your Role and context (for growers and winemakers)

- **What is your role in your organisation?**
  - Growing grapes
  - Making wine
  - Both growing grapes and making wine
  - Other (specify)
  - **How long have you been working in the grape and wine industry?**
  - Less than 12 months
  - 1-5 years
  - More than 5 years
- **Which Geographic Indication (GI) region(s) do you operate in?**

Goals and Motivations (for growers)

- **Which is the more important driver of profitability for your operation- yield or berry composition?**
  - Yield
  - berry composition
- **What is the area yield (t/ha) for your operation?**
  a. <5
  b. 5-10
  c. 10-15
  d. 15-20

e. 20-25

f. 25-30

g. >30

- **What are the major challenges in your operation to achieving high yield?**
- **What are the major challenges in your operation to achieving the desired fruit composition?**
- **Do you consider that berry pH and titratable acidity are important to achieving your goals? Y/N COMMENT**

Goals and Motivations (for winemakers)

- **What is the size of your winery (t)?**

  - <50
  - 50-1,000
  - 1,000-10,000
  - >10,000

- **What is the major driver of profitability for your operation?**
- **What are the major challenges in your operation to achieving this?**
- **Do you consider that berry/must pH and titratable acidity are important to achieving your goals? Y/N COMMENT**

Barriers and Enablers of Adoption (for growers)

- **Are you currently employing any vineyard methods to manipulate berry pH? Y/N skip logic**
  Which ones

- **Have you implemented any trials within your vineyard to test new practices, materials or interventions to manipulate berry composition? Y/N skip logic**
  What was the outcome

- **What would you consider to be barriers to adoption of implementing new rootstocks for maintaining berry pH?**
- **What would you consider to be barriers to adoption of new nutrition or soil/vineyard floor management protocols for maintaining berry pH?**
- **What would you consider to be barriers to adoption of new canopy management protocols for maintaining berry pH?**
- **What opportunities do you have to adopt new practices related to optimal pH? For example, do you know other producers who are using these practices? Do you have the facilities to adopt new practices?**
- **Do you agree or disagree that 'resistance to change' is a significant barrier to adoption in your region?**
- **Do you agree or disagree that 'social and peer acceptance' is an important driver for adoption in your region?**

Payment Structure (for growers and winemakers)

- **How is price determined on the fruit you sell/buy?**
- **Please indicate your level of agreement with the following statement. (Likert Scale: 1 = disagree, 2 = neutral, 3 = agree)**

Grape quality (in terms of composition) should be considered in the pricing scheme

- **Do you think this pricing system could be improved? Y/N COMMENT**

Vine Nutrition (for growers)

- **Please indicate your level of agreement with the following statements: (Likert Scale: 1 = disagree, 2 = neutral, 3 = agree) Please indicate how much the following ideas contribute to your decision making (1 = not at all, 2 = somewhat, 3 = very important)**

  Long-term soil health is considered in your vineyard management protocols

  Long term soil health when thinking about your vineyard management protocols

  Vine nutrition is important to berry flavour and composition

  Vine nutrient when thinking about berry flavour and composition

  Greenhouse gas emissions contribute to your decisions on your fertiliser management protocol

  Greenhouse gas emissions when thinking about your fertilizer management protocols

- **Please select the types of analysis used to guide fertiliser practices**
  - Soil
  - Tissue
  - Both soil and tissue
  - Visual observations
  - Other
- **When you interpret the soil/plant tissue diagnostic lab report do you -**
  - Do it yourself
  - Seek professional/peer help to do so
- **If fertilisers are applied do you use -**
  - Only synthetic (inorganic) fertilisers
  - Only use organic fertilisers
  - Use a combination

- **If fertilisers are applied, which ones do you commonly apply**

	Currently apply (Y/N)
Nitrogen	
Phosphorus	
Potassium	
Sulfur	
Calcium	
Magnesium	

Micronutrients	

- **When applying nutrients, this is done by (select all those that apply)-**
  - Broadcast
  - Banding
  - Fertigation
  - Foliar sprays

- **Do you apply mulches under-vine? Is so, which ones? Y/N details**

Winemaking (for winemakers)

- **How often is tartaric acid used in your operation to manage acidity during winemaking**
  - Never
  - Some vintages
  - Most vintages
- **Are there any sample analyses (of the fruit) completed prior to tartaric acid addition? Y/N COMMENT**
- **How is this analysis carried out**
  - On each individual delivery
  - At the crusher using a combined sample from several sources
- **Please indicate your level of agreement with the following statements : Likert Scale: 1 = disagree, 2 = neutral, 3 = agree)**

  Tartaric acid additions are a good-value option to manage pH

  Wines made from fruit with natural acidity are of higher quality than wines made through adjustments with tartaric acid

- **Can you provide an estimate of how much tartaric acid costs your business per litre of wine made?**

Sustainable Growing/Winemaking Practices (for growers and winemakers)

- **Please indicate your level of agreement with the following statements : Likert Scale: 1 = disagree, 2 = neutral, 3 = agree)**

  Climate change is impacting on grape production in Australia

  Climate change is impacting on grape production in your region

  Climate change is impacting on fruit quality in Australia. Which quality parameters?

  Climate change is impacting on fruit quality in your region. Which quality parameters

  Consumers are willing to pay higher prices for products that are produced in a sustainable manner

- **Compared to conventional farming, do you consider sustainable farming to be –**

- More profitable
- Less profitable

- **Are long-term sustainable growing practices important to you? Y/N**
  Which ones do you implement? (select all)
  - no-till
  - cover cropping
  - compositing
  - biodiversity
  - water efficiencies
  - integrated pest management (IPM)
  - non-synthetic fertilisers
  - waste management
- **Is your environmental footprint important to your decision-making process? Y/N**
- **How important is the sustainable use of natural resources to your operation? Likert scale; 1 = Not at all, 2 = a little, 3 = moderately, 4 = very , 5 = extremely)**
- **Please indicate your level of agreement with the following statements : Likert Scale: 1 = disagree, 2 = neutral, 3 = agree)**
  Greenhouse gas emissions as a result of your operation's activities are a concern to you
  Changes in biodiversity as a result of your operation's activities are a concern to you
- **What do you consider to be the greatest knowledge gap in mitigating or adapting to climate change in the wine industry?**
- **Would you consider changing your production practices if there was no immediate economic incentive to do so? Y/N skip logic**
  What would be the driving factors?

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