THE MYTH OF THE UNIVERSAL ROOTSTOCK REVISITED: ASSESSMENT OF THE IMPORTANCE OF INTERACTIONS BETWEEN SCION AND ROOTSTOCK

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Abstract:

Aim- Rootstocks provide protection against soil borne pests and are a powerful tool to manipulate growth, fruit composition and wine quality attributes. The present study aimed to assess the consistency of rootstock effects on growth and fruit composition of scion varieties and identify scion x rootstock interactions.

Methods and Results- Vine performance and fruit composition of hot climate, drip irrigated, spur pruned Chardonnay, Cabernet Sauvignon and Shiraz grafted on 7 rootstocks was assessed over 5 seasons, 2013-2017. Rootstocks included Ramsey, 1103 Paulsen and 140 Ruggeri and 4 promising selections from the CSIRO rootstock development program. Vines were trained as quadrilateral cordons on a 1.8 m high 2-wire vertical trellis with a 3.0 m x 1.8 m, row x vine spacing and irrigated with 5.5 – 6.0 Ml/ha of water each season. The study was conducted with mature vines established in 2006, as a randomized block design with 5 replicates.

There were significant effects of both variety and rootstock on yield, bunch number, bunch weight, berry weight (scion only), berries per bunch, pruning weight and the Ravaz Index (yield/pruning weight). Despite identical management practices, there were large differences between scion varieties in key growth characteristics across rootstocks. Chardonnay produced a high yield (mean 25.2 kg/vine) with low pruning weight (2.3 kg/vine) and a high mean Ravaz Index value of 12.1. Shiraz had the highest yield (27.4 kg/vine) with high pruning weight (5.1 kg/vine) and a Ravaz index of 6.3. Cabernet Sauvignon had the lowest yield (15.9 kg/vine) and highest pruning weight (6.6 kg/vine) and a very low Ravaz Index value of 3.0. Effects of rootstock on growth characteristics were smaller than the effects of variety, with mean yields ranging from 19.5 to 25.9 kg/vine, pruning weights ranging from 3.24 to 6.13 kg/vine and mean Ravaz Index values ranging from 5.54 to 8.63. Each variety was harvested when mean total soluble solids reached 25.0 °Brix. There were significant effects of variety and rootstock on fruit composition including pH, titratable acidity (scion only), malate, tartrate (scion only), yeast assimilable nitrogen (YAN) and for the red varieties, total anthocyanins (scion only) and phenolic substances (scion only).

Significant interactions between scion variety and rootstocks were found for yield, bunch number, berry weight, pruning weight and Ravaz index. The effect of rootstock on bunch weight and berries per bunch was consistent across scions. Significant scion x rootstock interactions were also found for pH and YAN. For each variety, significant effects of rootstock on fruit composition were linked to growth characteristics. However, these relationships, based on correlation analyses, varied for each scion.

Conclusions- The study has shown that growth characteristics and fruit composition of the major varieties was not consistent across 7 rootstock genotypes, as significant scion x rootstock interactions were determined. Hence, different rootstocks may be required for each variety to optimise scion performance and fruit composition. The study has also shown that the new CSIRO rootstock selections, covering a range of vigour classifications, may be useful alternatives to those currently in use by industry.

Significance and impact of the study- The study has shown that the performance of scion varieties and to a lesser degree fruit composition, is dependent on rootstock choice. The inherent vigour of the scion variety must be considered in rootstock selection. Furthermore, individual scion/rootstock combinations may require specific irrigation, pruning or canopy management to achieve vine balance and optimise fruit and wine composition.

Keywords: Grapevine, Scion, Variety, Rootstock, Growth, Composition, Interactions

1.Introduction

Rootstocks were first widely used in viticulture in the 1800's to address the phylloxera outbreak occurring at that time in Europe and in California. Phylloxera resistant rootstocks, involving various combinations of *Vitis* species from northern America, the source of phylloxera, were developed to provide protection against the aggressive pest. In modern viticulture, rootstocks are now used to address a broad spectrum of production issues. For example, in Australia major drivers for rootstock adoption are tolerance of soil borne pests such as phylloxera and root-knot nematodes, appropriate vigour conferred to scions, enhanced fruit quality traits, in particular reduced potassium uptake to reduce grape juice pH and acid adjustment during winemaking, tolerance of abiotic stresses including drought and salinity, and sustainability involving improved productivity and enhanced water use efficiency (Walker and Clingeleffer 2009). It is unlikely that a single rootstock cultivar can be developed that is suited to all environments with the range of adaptive traits to address these issues. Indeed, Morton (1979) considered that the development of a 'universal rootstock' was a 'myth' because different rootstocks would be required to meet the challenges of different growing conditions and that varying combinations of different *Vitis* species would be required to breed rootstocks for varying soil characteristics, including resistance to lime induced chlorosis, suitability for wet or dry conditions, heavy clay and acid soils.

Morton (1979), citing the studies of Bioletti *et al.* (1921) and Husmann *et al.* (1939), suggested that different scion varieties may require different rootstocks to optimize performance. Rives (1971) analysed growth and yield data from a number of rootstock trials with different scions. In all cases Rives (1971) was able to demonstrate significant scion x rootstock interactions (i.e. non additive effects) and concluded rootstocks could be selected to modulate overall vine vigour and growth of different scions. In contrast, Ferree *et al.* (1996), did not find scion x rootstock interactions for cluster and fruit quality data in studies involving White Riesling and Cabernet Franc. Despite the issues raised above, the number of studies which adequately address issues involving rootstock x environment interactions or scion x rootstock interactions are very sparse or limited to a small number of rootstocks, for example (Habran *et al*. 2016; Ough *et al.* 1969; Wooldridge *et al*. 2010). Walker *et al*. (2010) showed that the performance of 8 common rootstocks grafted with either Chardonnay or Shiraz, across 4 Australian regions with varying climatic conditions, soil characteristics, irrigation practices and salinity of irrigation water was not consistent with respect to yield, pruning weight (conferred vigour) and chloride and sodium concentrations in leaves and grape juice, an indication of the importance of genotype (rootstock and scion) x environment interactions and scion x rootstock interactions. Such interactions are poorly understood, not only in regard to growth and productivity but also in respect to fruit composition and final wine quality. Gautier *et al.* (2018), propose various mechanisms by which the scion x rootstock interaction may influence phenotype, including capture and transport of soil resources (water and nutrients) and root to shoot or shoot to root signalling involving metabolites, hormones, peptides and micro RNA's.

The present study, undertaken in a hot irrigated vineyard, aimed to assess the consistency of rootstock effects on growth and fruit composition of major scion varieties grown in Australia (Chardonnay, Cabernet Sauvignon and Shiraz). It included the common use commercial rootstocks (Ramsey, 1103 Paulsen and 140 Ruggeri) and 4 promising rootstock selections from the CSIRO breeding program (Clingeleffer *et al.* 2011; Clingeleffer *et al.* 2017).

2.Materials and Methods

Rootstock evaluation was undertaken over 5 seasons (2012/13 to 2016/18) in a replant situation with well-established grafted vines in a hot irrigated vineyard located near Mildura, Victoria, Australia. The grafted vines, produced by chip budding of potted rootstock vines in a shade house, were planted in a sandy loam soil in spring 2005. The vines, trained on a 2-wire vertical trellis as a quadri-lateral cordon system with wires at 1.3 m and 1.7 m were hand spur-pruned, until conversion to simulate light mechanical hedging (Clingeleffer 2013), typical of that used in the region in winter 2015. A 3.0 m x 1.8

m, row x vine spacing was utilised. First crops were produced in 2009. The vines were drip irrigated with approximately 5.5-6.0 ML/ha of water each season.

When established, the trial included 3 commercial rootstocks (1103 Paulsen, 140 Ruggeri, and Ramsey), and 26 new rootstock genotypes from the CSIRO breeding program grafted with three scion varieties, Chardonnay (clone I10V5), Cabernet Sauvignon (clone 22-4) and Shiraz (clone PT23). The trial was a fully randomized replicated block design with single vine plots with 5 replicates. The new rootstock genotypes had been selected for low potassium uptake of ungrafted vines, high rate of root strike and grafting success, and moderate to high vigour of ungrafted vines. In this study, attention was focussed on 4 of the 26 rootstock genotypes, selected for their performance and resistance to root knot nematode (Smith *et al.* 2016) and phylloxera (Korosi *et al.* 2007) using rapid screening techniques. The new rootstock genotypes were C112 and C113 (*V. champinii* x *V. cinerea*), C114 (*V. champinii* x *V. berlandieri*) and C20 (*V. champinii* x (*V. rupestris* x *V. riparia*)).

Each season prior to harvest, a total of 100 berries were collected from each vine by sampling 5 berries from each of 5 bunches selected randomly from each of the cordons. Sampling dates ranged from 27th January to 10th February for Chardonnay; 15th February to 10th March for Cabernet Sauvignon and 4th February to 10th March for Shiraz. The berry samples were used to determine berry weight, fruit maturity and retained by freezing for fruit composition analyses. At harvest, yield and bunch number per vine were recorded for each vine. This allowed all yield components to be calculated including bunch weight and berries per bunch ignoring the rachis weight. Pruning weight was collected in winter and used to calculate the Ravaz Index (yield/ pruning weight, Ravaz 1903) as a measure of vine balance. Analysis of fruit composition included juice total soluble sugars (TSS) determined by refractometer, pH and titratable acidity by titration (Metrohm Auto-titrator) and organic acids (malate and tartrate) and yeast assimilable nitrogen (YAN) by FTIR (Oenphos) and total berry anthocyanin and phenolic substances using spectrophotometry (Thermo Scientific).

The data was subjected to analysis of variance using Systat statistical package v5, removing effects of Block and Season (data not shown). For each scion variety, correlation analyses were conducted using rootstock means generated across seasons to identify key factors contributing to rootstock effects on crop development and fruit composition.

3.Results

A. Yield and its components, pruning weight and Ravaz Index

There were highly significant effects of scion, rootstock and the scion x rootstock interaction on mean yield over the 5 seasons (Table 1). The yield results show that Chardonnay and Shiraz had similar yields whereas the yield of Cabernet Sauvignon was 40% lower, despite consistent management. Over all scions, there was a 25% difference in yield attributed to rootstock with Ramsey, C113 and C114 producing the highest yield and 140 Ruggeri, C112 and C20 the lowest yield. The main effects of the highly significant scion x rootstock interaction were associated with the low yield of Cabernet Sauvignon grafted on 1103 Paulsen, 140 Ruggeri and C112 compared to their performance when grafted with Chardonnay and the high yield of C114 when grafted with Cabernet Sauvignon and Shiraz, compared to Chardonnay.

Table 1. Mean yield per vine of 3 scion varieties (Chardonnay, Cabernet Sauvignon and Shiraz) grafted on 4 CSIRO rootstock selections and 3 standard rootstocks over 5 seasons (2013-17). Means followed by the same letter are not significantly different (p = 0.05). LSD values for the highly significant (p<0.001) scion, rootstock and the scion x rootstock interaction were 1.9, 3.1 and 5.4 respectively.

Rootstock	Chardonnay	Cabernet	Shiraz	mean
Ramsey	**29.3**	**18.0**	**29.9**	**25.8**a
1103 Paulsen	**29.5**	*12.9*	*22.4*	21.6b
140 Ruggeri	25.0	*11.8*	25.8	20.8b
C112	22.9	*10.3*	25.3	*19.5*b
C113	**28.4**	**18.7**	*23.4*	23.5ab
C114	25.7	**18.4**	**33.5**	**25.9**a
C20	*19.0*	**17.7**	24.2	20.3b
Mean	**25.2b**	**15.9c**	**27.4a**	

The **highest** and *lowest* mean values are shown in bold and italics respectively for each scion rootstock combination and overall rootstock response to facilitate interpretation of the scion x rootstock interactions.

There were highly significant effects of scion, rootstock and the scion x rootstock interaction on mean bunch number over the 5 seasons (Table 2). Chardonnay and Shiraz had similar bunch numbers whereas Cabernet Sauvignon had 20% fewer bunches. Over all scions there was a 26% difference in bunch number attributed to rootstock with Ramsey, C113 and C114 having the most bunches and 1103 Paulsen, 140 Ruggeri, C112 and C20 the lowest number of bunches. The main effects of the highly significant scion x rootstock interaction were associated with the low bunch number of Cabernet Sauvignon grafted on 1103 Paulsen, 140 Ruggeri and C112, particularly when compared to Chardonnay.

Table 2. Mean bunch number per vine of 3 scion varieties (Chardonnay, Cabernet Sauvignon and Shiraz) grafted on 4 CSIRO rootstock selections and 3 standard rootstocks over 5 seasons (2013-17). Means followed by the same letter are not significantly different (p = 0.05). LSD values for the highly significant scion, rootstock and the scion x rootstock interaction were 20, 32 and 55 respectively.

Rootstock	Chardonnay	Cabernet	Shiraz	mean
Ramsey	**309**	**235**	277	**273**a
1103 Paulsen	285	*175*	*208*	*222*bc
140 Ruggeri	254	*176*	264	*231*b
C112	245	*158*	242	*215*bc
C113	**302**	**246**	240	**263**ab
C114	251	231	**313**	**265**ab
C20	*179*	221	*207*	*202*c
Mean	**255a**	**209b**	**264a**	

The **highest** and *lowest* mean values are shown in bold and italics respectively for each scion rootstock combination and overall rootstock response to facilitate interpretation of the scion x rootstock interactions.

There was highly significant effects of scion and significant scion x rootstock interactions for bunch weight and berry weight, but the rootstock effects were not significant. Mean bunch weights of Chardonnay (103.5 g) and Shiraz (108.3 g) were similar and 20% larger than Cabernet Sauvignon (73.3 g). Shiraz had the largest berries (1.37 g), followed by Chardonnay (1.21 g) and Cabernet Sauvignon had the smallest berries (1.03 g). There was a highly significant effect of scion (p<0.001) and rootstock effect (p<0.05) on mean berries per bunch but the scion x rootstock effect was not significant. Chardonnay (86.6) and Shiraz (83.3) had a similar number of berries per bunch whereas Cabernet Sauvignon (71.3) had 20% fewer berries per bunch. Over all scions there was an 18% difference in berries per bunch attributed to rootstock with C20 (88.2) having the most berries, followed by 1103 Paulsen (81.3), C114 (81.0 g), Ramsey (79.5) and C113 (78.1), 140 Ruggeri (76.4) while C112 (73.0) had the fewest berries per bunch.

There were highly significant effects of scion and rootstock and a significant scion x rootstock interaction on mean pruning weight over the 5 seasons (Table 3). There was a 3-fold difference in inherent vigour between the scions, with Cabernet Sauvignon vines having highest pruning weight and Chardonnay lowest pruning weight. Over all scions there was a 2-fold difference in pruning weight attributed to rootstock with Ramsey, C112, C113 and C114 conferring the highest and 140 Ruggeri and C20 the lowest vigour respectively. The main effects of the highly significant scion x rootstock interaction were associated with the low pruning weight of Cabernet Sauvignon and Shiraz grafted on 140 Ruggeri and the high pruning weight of Shiraz grafted on C114.

Table 3. Mean pruning weight (kg/vine) of 3 scion varieties (Chardonnay, Cabernet Sauvignon and Shiraz) grafted on 4 CSIRO rootstock selections and 3 standard rootstocks over 5 seasons (2013-17). Means followed by the same letter are not significantly different (p = 0.05). LSD values for the highly significant (p<0.001) scion and rootstock effects and the significant (p<0.01) scion x rootstock interaction were 0.40, 0.64 and 1.12 respectively.

Rootstock	**Chardonnay**	**Cabernet**	**Shiraz**	**mean**
Ramsey	2.57	**8.42**	5.44	**5.49**ab
1103 Paulsen	2.53	7.08	4.58	4.73b
140 Ruggeri	2.21	*5.30*	*3.63*	*3.73*c
C112	2.32	**7.94**	**6.08**	**5.44**ab
C113	**2.88**	**7.63**	4.99	**5.17**ab
C114	2.77	7.12	**8.48**	**6.13**a
C20	*1.48*	*4.35*	*3.87*	*3.24*c
Mean	**2.27c**	**6.57a**	**5.12b**	

The **highest** and *lowest* mean values are shown in bold and italics respectively for each scion rootstock combination and overall rootstock response to facilitate interpretation of the scion x rootstock interactions.

There were highly significant effects of scion and rootstock and a significant scion x rootstock interaction on the Ravaz Index over the 5 seasons (Table 4). There was a 5-fold difference in Ravaz Index between the scions with Chardonnay having the highest and Cabernet Sauvignon the lowest value. Over all scions there was a 2-fold difference in Ravaz Index attributed to rootstock with C20 having the highest values and C112, C113, and C114 the lowest values. The main effects of the weak but significant scion x rootstock interaction were associated with the low value of Cabernet Sauvignon and to a lesser extent Shiraz, grafted on 1103 Paulsen and C112 compared to Chardonnay.

Table 4. Mean Ravaz index (yield/pruning weight) of 3 scion varieties (Chardonnay, Cabernet Sauvignon and Shiraz) grafted on 4 CSIRO rootstock selections and 3 standard rootstocks over 5 seasons (2013-17). Means followed by the same letter are not significantly different (p = 0.05). LSD values for the highly significant (p<0.001) scion and rootstock effects and the significant (p<0.05) scion x rootstock interaction were 0.70, 1.12 and 1.97 respectively.

Rootstock	**Chardonnay**	**Cabernet**	**Shiraz**	**mean**
Ramsey	11.81	2.44	5.69	6.65cd
1103 Paulsen	12.36	*1.95*	5.20	6.50cd
140 Ruggeri	12.16	3.22	**8.31**	7.89b
C112	11.15	*1.47*	*4.61*	*5.75d*
C113	*9.85*	2.51	*5.02*	*5.80d*
C114	*9.45*	2.95	*4.20*	*5.54d*
C20	**13.91**	**4.61**	**7.38**	**8.63**ab
Mean	**12.11a**	**3.03c**	**6.29b**	

The **highest** and *lowest* mean values are shown in bold and italics respectively for each scion rootstock combination and overall rootstock response to facilitate interpretation of the scion x rootstock interactions.

B. Fruit composition

All varieties were harvested at similar maturities with mean TSS values around 25 °Brix. The effect of rootstock on TSS was just significant ($p<0.05$) but the scion x rootstock interaction was not significant. Across the varieties 140 Ruggeri had the highest TSS (25.6 °Brix), followed by C113 (25.2 °Brix), Ramsey (25.1 °Brix), C20 (24.8 °Brix), C112 and C114 (24.7 °Brix) while 1103 Paulsen had the lowest TSS (24.2 °Brix).

There were significant effects of variety, rootstock and the rootstock x scion interaction on juice pH (Table 5). Despite there being no differences in maturity, Chardonnay juice had a lower pH, than Cabernet Sauvignon or Shiraz at harvest. The significant rootstock effect showed that 140 Ruggeri, C112, C113 had the highest pH followed by 1103 Paulsen, C20 and Ramsey with C114 having the lowest pH. The weak scion x rootstock interaction can be attributed to the high pH of C112 and C113 and low pH of C20 with Chardonnay; the high and low pH of C20 and Ramsey respectively with Cabernet Sauvignon and the low pH of Shiraz with C114.

Table 5. Mean pH of 3 scion varieties (Chardonnay, Cabernet Sauvignon and Shiraz) grafted on 4 CSIRO rootstock selections and 3 standard rootstocks over 5 seasons (2013-17). Means followed by the same letter are not significantly different ($p = 0.05$). LSD values for the highly significant ($p<0.001$) scion, significant ($p<0.01$) rootstock effects and the significant ($p<0.05$) scion x rootstock interaction were 0.04, 0.07 and 0.11 respectively.

Rootstock	Chardonnay	Cabernet	Shiraz	mean
Ramsey	4.04	*4.24*	4.34	4.21cd
1103 Paulsen	4.02	4.35	4.33	4.23bcd
140 Ruggeri	4.04	**4.42**	**4.48**	**4.31**a
C112	**4.13**	4.38	4.36	4.29abc
C113	**4.10**	4.33	4.33	4.25abcd
C114	3.99	4.33	*4.21*	*4.17*d
C20	*3.91*	**4.43**	4.43	4.22cd
Mean	**4.02**b	**4.34**a	**4.37**a	

The **highest** and *lowest* mean values are shown in bold and italics respectively for each scion rootstock combination and overall rootstock response to facilitate interpretation of the scion x rootstock interactions.

There was a significant effect of variety but not rootstock or the scion x rootstock interaction on the titratable acidity of juice. Chardonnay juice had highest titratable acidity (4.65 g/L), followed by Cabernet Sauvignon (3.69 g/L) and Shiraz (3.16 g/L). With respect to organic acids there were significant effects of both variety and rootstock on juice malate but the scion x rootstock interaction was not significant. Cabernet Sauvignon had the highest malate (4.64 g/L), followed by Chardonnay (4.40 g/L) and Shiraz (4.04 g/L). The significant rootstock effect on malate indicated that 140 Ruggeri (4.45 g/L), 1103 Paulsen (4.40 g/L) and C20 (4.38) had the highest malate concentrations; C113 (4.18 g/L) and C112 (4.01g/L) intermediate concentrations and C114 (3.89 g/L) and Ramsey (3.95 g/L) the lowest concentrations. There was a significant effect of variety on tartrate concentration but effects of rootstock or the scion x rootstock interaction were not significant. Cabernet Sauvignon (5.55 g/L) had higher tartrate concentration than Chardonnay (4.97 g/L) or Shiraz (4.95 g/L).

There were significant effects of scion, rootstock and the scion x rootstock interaction on juice YAN (Table 6). Chardonnay juice had highest and Cabernet Sauvignon the lowest levels of YAN. The significant rootstock effect shows that 1103 Paulsen had the highest levels of YAN, followed by 140 Ruggeri, C113, C20 and C112 while C114 had the lowest YAN level. The highly significant scion x rootstock interaction can be attributed to the high juice YAN of Ramsey and C113 grafted with Chardonnay, the low YAN of Cabernet Sauvignon on Ramsey and the high YAN of Shiraz grafted on C20.

Table 6. Mean YAN (mg/L) of 3 scion varieties (Chardonnay, Cabernet Sauvignon and Shiraz) grafted on 4 CSIRO rootstock selections and 3 standard rootstocks over 5 seasons (2013-17). Means followed by the same letter are not significantly different (p = 0.05). LSD values for the highly significant (p<0.001) scion, significant (p<0.01) rootstock effects and the highly significant (p<0.001) scion x rootstock interaction were 16, 25 and 44 respectively.

Rootstock	Chardonnay	Cabernet	Shiraz	mean
Ramsey	**279**	*156*	225	220b
1103 Paulsen	**280**	**233**	230	**247**a
140 Ruggeri	270	210	219	233ab
C112	247	199	235	227ab
C113	**295**	212	189	232ab
C114	233	187	*151*	*190*c
C20	221	213	**251**	228ab
Mean	**253a**	**198c**	**215b**	

The **highest** and *lowest* mean values are shown in bold and italics respectively for each scion rootstock combination and overall rootstock response to facilitate interpretation of the scion x rootstock interactions.

Cabernet Sauvignon had significantly higher levels of berry anthocyanin and phenolics than Shiraz (i.e. 1.0 compared to 0.81 mg/g and 1.48 and 1.21 a.u., respectively). However, the effects of rootstock and the scion x rootstock interaction on berry anthocyanin or phenolics were not significant (data not shown).

C. Relationships between growth characteristics and fruit composition

Correlation analyses were conducted for individual scions to identify differences in crop development contributing to the scion x rootstock interactions reported above. In the case of the low vigour Chardonnay scion, yield and bunch number were both highly correlated with pruning weight (r = 0.93, 0.90 respectively) across the rootstocks. The main determinant of yield across the rootstock genotypes was bunch number (r = 0.95). In contrast, with the high vigour scion, Cabernet Sauvignon, pruning weight was not correlated with yield or crop development variables. Both bunch number (r = 0.99) and bunch weight (r = 0.89), associated with berries per bunch (r = 0.92), were significant contributors to yield variability across the rootstock genotypes. Bunch weight was a function of both berry weight (r = 0.76) and berries per bunch (r = 0.99). With the moderately high vigour Shiraz scion, pruning weight was not correlated with yield or any crop development variable, except berry weight (r = 0.67). Bunch number (r = 0.95) and to lesser degree berry weight (r = 0.61) were significant contributors to yield variability across the rootstock genotypes. Bunch weight was positively correlated with berries per bunch (r = 0.95) and negatively correlated with berry weight (r = -0.62).

Correlation analyses were undertaken to explore the effect of rootstock genotype on relationships between vine growth characteristics and berry juice composition for the different scions. For the low vigour Chardonnay scion, rootstock pruning weight was positively associated with juice TA (r = 0.67), malate (r = 0.76) and YAN (r = 0.87). Both yield and bunch number were positively associated with malate (r = 0.63, 0.62, respectively) and YAN (r = 0.88, 0.91, respectively). Bunch weight was negatively correlated with TSS (r = -0.81) and pH (r = -0.65) but positively correlated with TA (r = 0.61). Berry weight was negatively associated with TSS (r = -0.60) and positively associated TA (r = 0.81) and malate (r = 0.62). Berries per bunch was negatively associated with pH (r = -0.70) and tartrate (r = -0.74). For the very high vigour scion, Cabernet Sauvignon pruning weight across rootstocks was positively correlated with TA (r = 0.60) and YAN (r = 0.70). There were no other significant correlations with crop development variables and fruit composition, an indication that the high inherent vigour of Cabernet Sauvignon across all rootstocks may be masking effects of individual rootstocks on fruit composition, including anthocyanins and phenolics. With Shiraz, there were significant impacts of pruning weight on juice composition as shown by the negative correlations with TSS (r= -0.72), pH (r = -0.90), malate (r = -

0.76), tartrate (r = -0.79) and YAN (r = -0.74). Across the rootstock genotypes, yield and bunch number were negatively correlated with TA (r = -0.84 and -0.86, respectively) and malate (r = -0.69 and 0.63, respectively). Berry weight correlated negatively with pH (r = -0.61) and malate (r = -0.87).

3.Discussion

The study was conducted over 5 seasons with mature grafted vines of Chardonnay, Cabernet Sauvignon and Shiraz grown in a hot irrigated vineyard. It has shown that scion performance and fruit composition of the major varieties was not consistent across 7 rootstock genotypes, as significant scion x rootstock interactions were determined. These findings indicate that specific rootstocks will be required to optimise scion variety performance. The underpinning cause for the interactions were associated with the large, 3-fold difference in the inherent vigour of the scion varieties (Table 3). Rives (1971) found that that both the inherent vigour of the scion (own- vigour) and that conferred by the rootstock were contributing factors' to yield performance. This study has extended the approach to include not only yield but also yield components and fruit composition. It has demonstrated significant scion x rootstock interactions not only for yield, but for bunch number, bunch weight, berry weight, berries per bunch, pruning weight, Ravaz index, pH and YAN.

Currently, the Australian industry is reliant on rootstocks bred and selected overseas for conditions that may not be the same as those in Australia (Walker and Clingeleffer 2009). Breeding and selecting new locally adapted rootstocks offers the potential to have a positive impact on vine performance and wine quality while addressing the issues of sustainability and risk management. This study has shown that the phylloxera and nematode resistant CSIRO selections offer alternatives to existing commercial rootstock varieties. In the context of this study, the 7 rootstocks could be classified into 3 conferred vigour categories based on mean pruning weight, with C114, Ramsey and C112 having high vigour; C113 and 1103 Paulsen, moderate vigour; and 140 Ruggeri and C20, low vigour. However, the significant scion by rootstock interaction shows that care must be taken in using general vigour classifications, a view supported by Lefort and Legisle (1977), based on their studies with young grafted vines. For example, highest vigour was recorded by C113 with Chardonnay; by Ramsey and C112 with Cabernet Sauvignon and by C112 and C114 with Shiraz. C20 rootstock consistently produced low vigour. The vigour of 140 Ruggeri was also low with both Cabernet Sauvignon and Shiraz. Santarosa *et al.* (2016) found that the scion x rootstock interaction for vegetative growth of Cabernet Sauvignon and Merlot was associated with differences in the vascular systems, specifically xylem vessel size. The results of this study are consistent with the results of Tandonnet *et al*. (2010), who demonstrated in pot studies that the scion had a significant effect on root growth and biomass allocation. It is possible that the relative low vigour of 140 Ruggeri, and to a lesser degree 1103 Paulsen, may be due to breakdown in resistance to root knot nematodes in the replant situation (Smith *et al.* 2017).

The significant, scion x rootstock interaction for yield, provides evidence that different rootstocks may be required for each scion to maximize productivity. For example with the low vigour Chardonnay, Ramsey, 1103 Paulsen and C113 were most productive whereas C20 was least productive. In contrast, with the very high vigour Cabernet Sauvignon, Ramsey, C113, C114 and C20 produced the highest yield while 1103 Paulsen, 140 Ruggeri and C112 were the least productive. The most productive rootstocks with Shiraz were Ramsey and C114 while 1103 Paulsen and C113 were least productive. These responses can be attributed to differences in crop development across the rootstocks for the different scions. In the case of the low vigour Chardonnay, bunch number, which was strongly linked with conferred vigour, was the main driver of yield. In contrast, with the higher vigour scion varieties Cabernet Sauvignon and Shiraz, conferred vigour was not correlated with yield. With Cabernet Sauvignon, bunch number and bunch weight both contributed to yield variability across the rootstocks. With Shiraz, bunch number and to lesser degree berry weight (r = 0.61) were significant contributors to yield variability across the rootstock genotypes. Further detailed studies of crop development including assessment of retained nodes, budburst, shoot fruitfulness, inflorescence flower number and % fruit set are required to further elucidate the different varietal responses. It is likely shading, associated with the high vigour of Cabernet Sauvignon and Shiraz may have contributed to reduced shoot fruitfulness as shown for Sultana (May 1965; May and Antcliff 1963) and that the use of larger, more open trellis may have produced higher bunch numbers and potentially yield for these varieties (Clingeleffer 2009; Kliewer and Dookoozlian 2005; May *et al.* 1976).

The Ravaz Index (yield/pruning weight), often referred to as vine balance, provides surrogate estimates for carbon assimilation efficiency and water use efficiency based on total assimilation and transpiration by the canopy with pruning weight used as an indicator of canopy size (Clingeleffer *et al.* 2011). Kliewer and Dookloozian (2005) found that the Ravaz Index generally ranged from 5-10 across varieties. Wooldridge et al. 2010 showed that wine quality of Chardonnay and Pinot Noir was inversely proportional to pruning weight but positively correlated with the Ravaz Index. In this study, vigour of the scion variety had a stronger impact than rootstock on the Ravaz Index. The very low values (mean 3.3) for Cabernet Sauvignon were well below the desirable values between 8 and 10 determined by Dookloozlian *et al.* (2011) to optimise wine quality attributes for that variety. In this study, the low yield and high vigour of Cabernet Sauvignon contributed to the very low Ravaz Index, indicative of reduced carbon assimilation efficiency and low water use efficiency. In contrast, Chardonnay with a high Ravaz Index (mean 12.1) associated with its high yield and low inherent vigour, had increased carbon assimilation and water use efficiency and was capable of easily maturing the large crop. The Ravaz Index value of Shiraz (6.3) which fell between that of Cabernet Sauvignon and Chardonnay was close to the optimum described by Dookloozlian *et al.* (2011). While the results for Ravaz Index were dominated by the inherent scion vigour, the results also provide evidence of potential to select rootstocks with enhanced carbon assimilation and water use efficiency. In this study C20 rootstock consistently had a high Ravaz Index with all scions. The weak scion x rootstock interaction for the Ravaz Index indicates inconsistencies in the combined yield and vigour responses for the different scions. For example, Ravaz Index values were lowest for Chardonnay with C113 and C114, for Cabernet Sauvignon with 1103 Paulsen and C112 and for Shiraz, with 140 Ruggeri and C20. These results suggest that individual scion/rootstock combinations may require specific irrigation, pruning or canopy management to optimise the relationship between yield and pruning weight. In this study, mechanical hedging was imposed in the last 2 seasons. Comparing the results from different seasons, the preliminary results indicate that the lighter pruning treatment has enhanced vine balance with shifts in the Ravaz Index for Cabernet Sauvignon from 2.81 to 4.21 and for Shiraz from 4.87 to 8.21.

Over the 5 seasons, the individual scion varieties were harvested with similar levels of maturity (i.e. 25 ^{o}Brix) across the rootstocks, indicating that maturity can be eliminated as a source of variability in assessing the effects of scion x rootstock interactions on fruit composition. The significant effect of rootstock on TSS (24.2 - 25.2 ^{o}Brix) indicates some potential to select rootstocks for early maturity (140 Ruggeri and C113) or to delay ripening (1103 Paulsen), although the difference of 1.0 ^{o}Brix is unlikely to be of practical significance to industry (i.e. less than one week).

Commercial experiences and research results have shown that the widely adopted high vigour, nematode tolerant rootstock varieties contribute to negative impacts on wine quality associated with high potassium uptake, high pH and malate levels, which require tartaric acid supplements in winemaking for pH adjustment, and reduced colour in berries and poor spectral properties in red wine (Walker and Clingeleffer, 2009, 2016). Rootstocks with low potassium uptake offer a solution to problems of high juice and wine pH and associated negative impacts on wine quality (Clingeleffer 1996; Walker and Clingeleffer 2009, 2016). While juice potassium was not measured in this study, the results indicate potentials to manipulate fruit composition using rootstocks with significant effects on pH (4.17-4.31), malate (4.45 - 3.95 g/L) and YAN (189-251 mg/L). However effects of rootstock were not significant for titratable acidity, tartrate and for the red varieties, berry anthocyanin or phenolic substances. This result was unexpected as other studies in the same region have reported rootstock effects on these parameters (Clingeleffer 1996; Ruhl *et al*. 1988; Walker and Clingeleffer 2009; Walker *et al*. 1998).

Effects of rootstock on pH have been reported in similar environments previously with high pH linked to high vigour and high potassium uptake (Clingeleffer 1996; Hale and Brien 1978; Ruhl *et al.* 1988; Walker and Clingeleffer 2009; Walker *et al*. 1998). The overall low juice pH of low the vigour C20 rootstock is consistent with such results. However, the low pH of the high vigour rootstock C114 was unexpected suggesting it could be a useful high vigour rootstock to enhance fruit composition compared to high vigour rootstocks such as Ramsey. However, other factors such as the weak, but significant scion x rootstock interaction; the confounding effects of the significant effect of rootstock on TSS and vine conferred vigour and growth characteristics must also be considered in assessing the rootstock effects on pH. In particular, it should be noted that C20 and Ramsey had the highest and lowest pH respectively with the high vigour Cabernet Sauvignon. The effects of growth characteristics on pH varied with the scion variety. With the low vigour Chardonnay, pH was positively linked to bunch weight and berries per bunch. With the very high vigour Cabernet Sauvignon growth characteristics were not associated with pH suggesting that expected rootstock effects were masked by the effect of excessive shade (Hale and Brien 1978; Smart *et al.* 1985). In contrast, with the moderately high vigour Shiraz, pH was negatively linked to pruning weight and berry weight. This unexpected result can be explained at least in part by the confounding effect of rootstock on maturity as there was a high highly significant correlation between TSS and pH (p=0.82), a relationship not found with the other scion varieties. The confounding effect of TSS, although significant only with Shiraz indicates that detailed studies of changes in fruit composition during ripening, as undertaken by Walker and Read (2000) are required to fully understand rootstock effects on composition.

The effects of rootstock on malate were consistent across scions despite large differences in inherent vigour with 140 Ruggeri, 1103 Paulsen and C20 having the highest malate concentrations and C114 and Ramsey the lowest concentrations. This result was unexpected, based on previous studies linking high vigour and excessive shade with high malate concentrations (Hale and Brien 1978; Walker and Clingeleffer 2009). Unlike pH, the effects of rootstock on malate concentration were not linked to fruit maturity for any variety. While the effects of rootstock on malate concentration were consistent across rootstocks, the relationship between pH and malate appeared to be dependent on inherent scion vigour. With Chardonnay there was no relationship between pH and malate whereas with Cabernet Sauvignon (r = 0.93) and Shiraz (r = 0.74) the relationships were strong. Measurement of juice potassium and its links to pH and malate concentrations (Clingeleffer, 1996; Walker and Clingeleffer 2016; Ruhl 1989) would provide further insights into these responses.

All rootstocks produced acceptable concentrations of YAN required for successful fermentation (i.e. > 150 mg/L). However, the significant scion x rootstock interaction indicates that YAN juice concentrations of C114 may be an issue with Shiraz, and to a lesser degree with Cabernet Sauvignon. For all varieties YAN was strongly linked to rootstock conferred vigour and for Chardonnay, with yield and bunch number, again highlighting the importance of scion variety in assessment of rootstock effects on fruit composition. In this case, Chardonnay and Cabernet Sauvignon had the highest and lowest YAN, respectively. For all varieties YAN was strongly correlated with juice malate concentration and for both red varieties, with pH. Further study of the impacts of both scion and rootstocks on plant nitrogen status and linkages with fruit composition is required. For example, with Shiraz grafted on 60 different rootstocks Clingeleffer (2000) demonstrated strong correlations between juice N and pH (r=0.78), TA (0.80) and K (0.82). Ough *et al.* 1968 showed that nitrogen and free amino content of wines could be influenced by rootstock. Habran *et al*. (2016) in studies with grafted Cabernet Sauvignon and Pinot Noir found that YAN, primary metabolites, particularly malate and amino acid content, and secondary metabolites were impacted by scion, rootstock and nitrogen supply.

In conclusion this study has shown that scion performance and fruit composition of the major varieties was not consistent across 7 rootstock genotypes, as significant scion x rootstock interactions were determined. These findings indicate that specific rootstocks will be required to optimise scion variety performance and fruit composition. The study has also shown that the new CSIRO rootstock selections, covering a range of conferred vigour classifications, may be useful alternatives to those currently grown. These results suggest that individual scion/rootstock combinations may require specific irrigation, pruning or canopy management to optimise the relationship between yield and pruning weight and optimise fruit and potentially wine composition.

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