Australian Government

Wine Australia

CSIRO

Field trials - new scion-rootstock combinations and evaluation of new technology for improved water use efficiency and reduced costs



FINAL REPORT TO WINE AUSTRALIA

Project Number: **CSA1701-1.5**

Principal Investigator: **Everard J Edwards**

Research Organisation: **CSIRO Agriculture & Food**

Date: **12th January 2022**

Field trials - new scion-rootstock combinations and evaluation of new technology for improved water use efficiency and reduced costs

CSA1701-1.5

July 2017 to December 2020

Everard J Edwards, Mahmood Hassan, Mark Thomas

CSIRO
Locked Bag 2
Glen Osmond
SA 5064

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Abstract

Four novel ‘no-spray’ scion varieties with complete mildew resistance, produced through the CSIRO breeding program, were utilised in a multi-factorial vineyard trial with different planting density and irrigation management strategies. Two of the scion varieties combined ‘no-spray’ with a ‘no-prune’ trait, meaning that both spray and pruning costs were avoided. All of the varieties produced commercially viable yields and commercially acceptable table wine. Combining high-density planting with reduced water inputs and the cost saving from not requiring fungicide sprays and/or pruning maintained commercially viable production levels, but with higher profitability indicated.

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Executive summary

The wine industry is under increasing pressure to demonstrate its environmental credentials to consumers, who are more likely to make purchasing decisions based on those credentials. A significant driver of this is the public awareness of the here-and-now impact of climate change. Those impacts will require the industry to reduce inputs in the future as well as use growing systems and cultivars/clones able to cope with a hotter, drier climate.

CSIRO has produced grape varieties that are 'no spray' with multi-genic resistance to both powdery and downy mildew. This trait has also been combined with a 'no-prune' growth habit to produce varieties that don't require annual pruning in order to limit growth and stimulate fruit production. Both red and white fruited varieties have been produced from the 'no-spray' and combined 'no-spray' 'no-prune' traits.

A previous project, also co-funded by Wine Australia (CSA1305), established a trial planting using this new varieties at the SARDI Nuriootpa Research Station. This trial not only incorporates a red and white varieties of these new scions (four in total), but has them grafted to three rootstocks as well as being own-rooted. The scion: rootstock genotype combinations are grown at two planting densities (1,572 and 5,249 vines per hectare) and under two irrigation regimes.

This project has monitored the trial for three seasons (2017/18 to 2019/20), with harvest data being collected for a fourth vintage (2021), assessing growth, production, fruit composition and winemaking suitability of the scion:roostock/management treatment combinations. The impacts of the 'no-spray' and 'no-prune' traits on fruit production costs were then determined, together with the impact of management strategies employed. Finally, the project also used the trial to examine the potential of canopy temperature to be used in irrigation management decisions as a measure of vine water status. Most the work on this latter subject was moved to another Wine Australia co-funded project (CSA1701-3.1), but results from initial testing with the 'ArduCrop' sensor are provided here and support the viability of using canopy temperature to estimate vine water status.

Crucially, the project results demonstrated that all four new varieties ('no-spray' red, 'no-spray' white, 'no-spray'+'no-prune' red and 'no-spray'+'no-prune' white) were suitable for table wine production under the various management treatments and irrespective of rootstock, with both micro-ferments and small-lot winemaking producing wines with acceptable ethanol, pH, acid, colour and phenolics. The 'no-prune' red had a longer fruit maturation requirement at the natural crop load to reach a total soluble solid concentration of 22°Brix, but was typically able to achieve this where there were no other problems (extreme weather, COVID-19 restrictions on vineyard access). No mildew infection was observed on any of the vines during the three seasons of work, despite no fungicide sprays at any time.

Harvest yield was also commercially acceptable, with the two 'no-spray' only scions averaging 12.3 and 11.1 t ha^{-1} under standard management conditions for the red and white varieties

respectively. Production with reduced irrigation was reduced by approximately 20% in both, but slightly more than doubled by high-density planting. The two 'no-spray'+'no-prune' scions produced 13.6 and 17.7 t ha^{-1}, despite not having filled the cordon wire by the end of the project. This was with high-density planting, but was still close to the regional production levels, even taking that into account.

Vine vigour varied between genotypes, with the red varieties having lower vigour than the white varieties and the two 'no-prune' genotypes, not surprisingly, having lower vigour than the 'no-spray' only genotypes, which had a typical 'wild-type' (WT) *vinifera* growth habit. In fact, by the end of the project (six years after planting) the 'no-prune' genotypes' had yet to completely fill the cordon wire. For the WT vines vigour was greater at high-density planting than at standard-density and, surprisingly, was not only unaffected by reduced irrigation in the standard-density treatment, but actually higher with reduced-irrigation than standard-irrigation at high-density. It is possible that this was due to carry-over from higher irrigation rates in the high-density plot during vineyard establishment. Soil moisture and canopy temperature data both indicated that the reduced-irrigation treatments did indeed have less water available to the vines during the course of this project.

The 'no-prune' varieties suffered significant damage from climate extremes early in the project and were protected with shade netting. However, by the end of the project this was not required.

Rootstock genotype affected both vigour and yield to some extent, with known low and high conferred vigour rootstocks having the expected influence on the 'no-spray' WT scion genotypes. For the 'no-prune' varieties, grafting somewhat reduced production with own-rooted vines performing better.

The cost of production analysis was limited in detail and had to make assumptions about potential fruit value as the varieties are unreleased, but indicated that all the varieties should be able to be grown profitably and that the red 'no-spray' WT variety in particular would likely be more profitable grown at high-density, than at standard-density planting.

In summary, the results of the project indicate that all the scion varieties could produce commercially viable quantities of fruit and make acceptable table wines. Further, that combining high-density planting and reduced irrigation (per unit length row) has the potential to improve vineyard profitability.

Chapter 1

1.1 Project Background

This project incorporated Wine Australia project CSP1504, which commenced on 1/7/2016 but was subsequently incorporated into the Wine Australia-CSIRO bilateral agreement that began on 1/7/2017.

Wine Australia project CSP1305 "Climate change ready varieties and management technologies that reduce GHGs in the vineyard" completed in June 2016 and established a trial site to assess the cost savings that could be achieved by industry through the use of new varieties (no spray and no prune) and different vineyard layouts and management approaches. The current project has utilised the trial to determine the cost savings and benefits as the vines reached maturity and optimum yield production. Evaluation of the mature vines also allowed assessment of the impact of the different treatments on fruit and wine quality.

The new varieties and rootstocks in the trial were chosen based on their potential to perform under a warming climate. The trial directly targeted reducing major costs to industry: spraying for mildews and pruning. The Wine Australia document "*Opportunities for investment in the priority area of climate adaptation*" listed "additional advances in water use efficiency and irrigation management" as a research area of interest and this project has also targeted this major cost to industry (water), through the evaluation of different irrigation treatments applied to the trial and the use of new digital technologies to measure the canopy temperature of vines to determine when the vines require water. These technologies do not require labour (people to take measurements in the field) and may be more accurate than soil water measurements as they are a direct measure from the plant.

World agriculture will be forced to undergo dramatic rapid changes to address the challenges of climate change, limited resources (water, land, energy) and population growth well before the projected population peak in 2050 (The Royal Society 2009). This can only be achieved by sustainable intensification of agriculture using less inputs and higher outputs per unit land.

For addressing the challenge of higher outputs per unit land for the Australian wine industry, it has been previously demonstrated that vines grown as high-density plantings in Australia yield more per hectare and are more water use efficient (McCarthy 1992). The main issue with the study at that time was controlling vine vigour. This project will evaluate solutions to the vine vigour problem through investigating new scions that do not require pruning, rootstocks that reduce scion vigour and irrigation treatments.

The challenge of using less inputs is addressed in this project by evaluating the performance of new varieties that are mildew resistant and don't require sprays and new varieties that also do not require pruning. One of the largest known contributors to greenhouse gases in the vineyard is fuel usage (Carlisle et al. 2010) to manage plant growth and control diseases such

as mildews. Reduced water usage and evaluation of improved methods, such as canopy temperature, to monitor plant water requirements will also be beneficial. One such system, ArduCrop, is a CSIRO invention, takes measurements 24/7 and has been successfully trialled in research trials of field crops (Jones et al. 2018).

Maintaining a competitive wine industry into the future will depend in part on successfully adapting to climate change, reducing costs and producing a desirable product. This project will utilize a unique trial site to evaluate new scion and rootstock material and new management methods and tools for investigating reductions in costs resulting from reductions in inputs (sprays, labour, water and pruning). Measurements of plant performance (yield/ha), water use efficiency, and fruit and wine quality will provide important information on whether such reductions can be achieved without affecting yield and wine quality and the potential gains from sustainable intensification of Australian viticulture.

1.2 Project Aims and Performance targets

This project aimed to:

- Collect data on management costs of the different treatments in a “no-spray” vineyard to calculate cost savings and benefits.
- Evaluate new sensor technology that measures the canopy temperature of vines in real-time (24/7) to identify differences between treatments.
- Investigate the potential of canopy temperature sensors as a decision making tool to determine when vines require irrigation and if they can improve irrigation management and water use efficiency.
- Measure differences in vine performance and compare grape and wine quality differences between the treatments.

The project also attempted to provide answers to the following research questions:

- What is the best scion-rootstock combination and irrigation treatment that produces the best vine performance (yield/ha), crop water use index (kg/water used) and grape and wine quality?
- Do ‘no-prune’ vines produce similar yield and grape & wine quality as standard vines?
- Is the canopy temperature sensor a more accurate measure of vine water requirements than soil moisture sensors for research and is there potential application in industry?
- What are the management benefits and total cost savings per ha for the different treatments compared to a standard Australian vineyard?

Management costs were recorded during the term of the project to calculate financial benefits of the different treatments.

Chapter 2: Site design, history & experimental detail

The work utilised a vineyard block specifically established for this work through Wine Australia project CSP1305, which incorporated different planting densities, new scion genotypes resistant that are to mildews, dwarf scion genotypes that do not require pruning, rootstocks genotypes with high or low-moderate conferred vigour, and the ability to impose different irrigation regimes across planting densities and various genotype combinations.

2.1 Vineyard establishment and layout

2.1.1 Trial site

The trial site establishment is fully described in the final report for CSA1305 (Thomas & Hassan 2017). In brief, the site consisted of a 0.4 ha vineyard with 13 rows, each 140 m long, at the SARDI Nuriootpa Research Centre (NRC: 34°28'36.52"S, 139° 0'32.15"E). The row direction was approximately NW-SE (70°) and the ground was close to flat. The block was split into two densities, with rows 1-6 being spaced 3 m apart, whereas the row spacing between rows 6 and 13 was 1.5 m (Figure 1 top). Vines were planted at 2.12 m spacing in rows 1-5 (standard density) and 1.27 m spacing in rows 6-13 (high density), providing 1570 and 5250 vines per ha respectively.

All rows had a single permanent cordon wire 1 m above the ground and a single foliage wire on each side of the row. For the wild-type vines, the foliage wires were lifted to 0.25 m above the cordon in mid-November each season. For the no-prune micro-vines the foliage wires were permanently installed 0.1 m above the cordon to support the shoots. Irrigation was supplied using a single 4 L/h Toro 'Turbo-Key' emitters per vine throughout the trial, except for the microvines that used 2 L/h emitters until 2018/19, when they were replaced with 4 L/h emitters. Two lines per row and six controller stations were used in order to be able to apply standard and reduced irrigation treatments by varying the irrigation timings. Each row was split into four irrigation zones, two standard and two reduced (Figure 1 middle).

2.1.2 Plant material

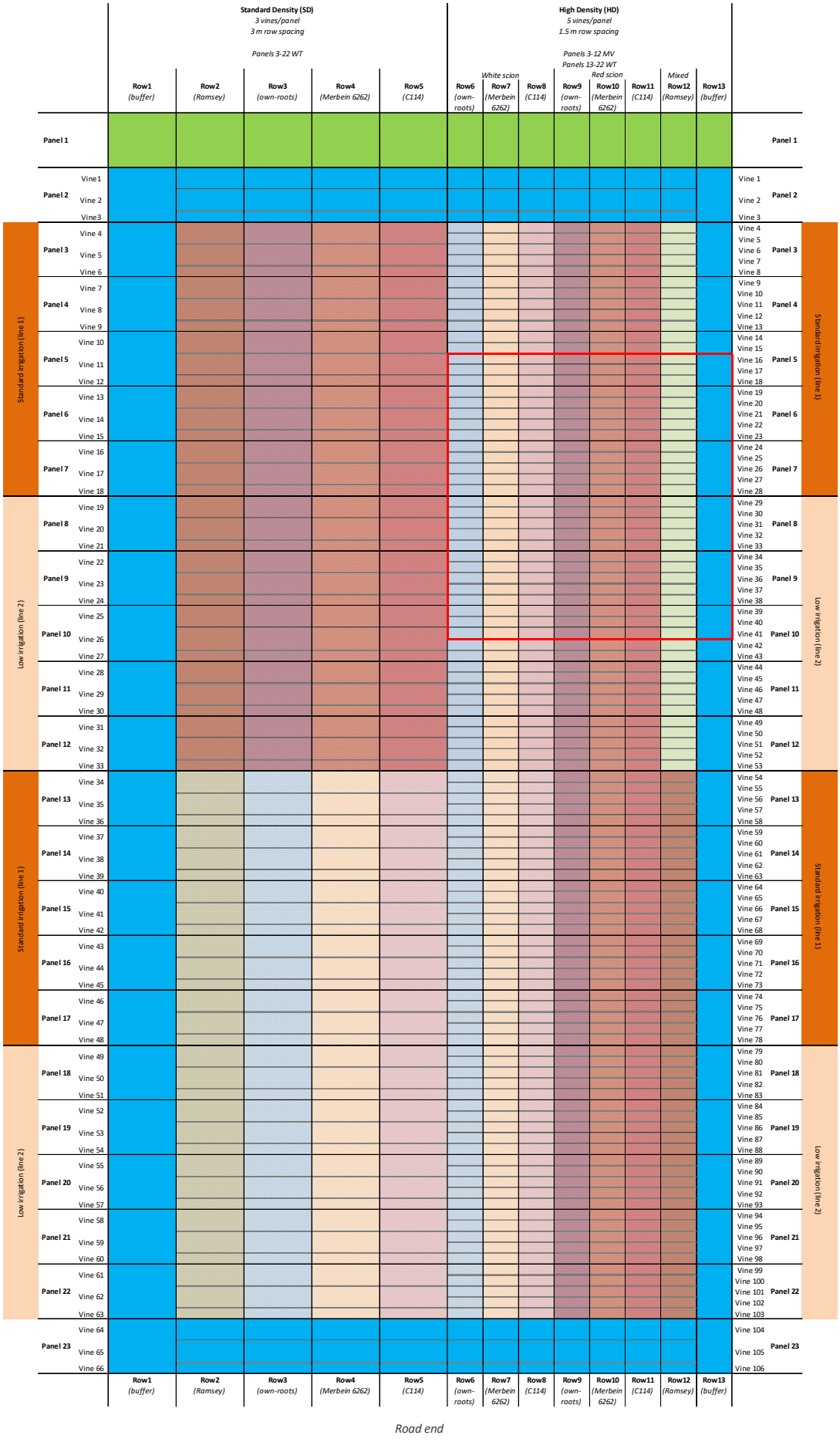
Four scion genotypes were used, two 'wild-type' (WT: standard growth habit and pruning requirements) and two 'no-prune' micro-vine (MV: dwarf growth habit) with one red and one white variety in each case. All four were CSIRO bred lines and 'no-spray'; resistant to powdery and downy mildews. The MV vines were only planted in the high-density section of the vineyard, whereas the WT vines were planted in both the standard and high-density sections, with each area sub-divided into red and white varieties (Figure 1 bottom).

The scion varieties were grafted to one of three rootstocks, Ramsey, Merbein 6262, C114 (a CSIRO bred line) or on own-roots. Limitations to the block size resulted in only one section of Ramsey rootstock for the high-density treatment, meaning that the Red MV:Ramsey and White WT:Ramsey combinations were unable to be included. Rootstocks were arranged by row, with each row containing a single rootstock genotype, irrespective of scion or other

treatment. The full site layout and list of treatments/genotype combinations is given in Figure 2.



Figure 1: block treatment layout for density (top), irrigation (middle) and scion genotype (bottom). Note aerial image was taken whilst shading was in place over the MV vines.


Standard Density (SD)
3 vines/panel
3 m row spacing
Panels 3-22 WT
High Density (HD)
5 vines/panel
1.5 m row spacing
Panels 3-12 MV
Panels 13-22 WT
White scion
Red scion
Mixed
Row1 (buffer)
Row2 (Ramsey)
Row3 (own-roots)
Row4 (Merbein 6262)
Row5 (C114)
Row6 (own-roots)
Row7 (Merbein 6262)
Row8 (C114)
Row9 (own-roots)
Row10 (Merbein 6262)
Row11 (C114)
Row12 (Ramsey)
Row13 (buffer)
Standard irrigation (line 1)
Low irrigation (line 2)
Road end

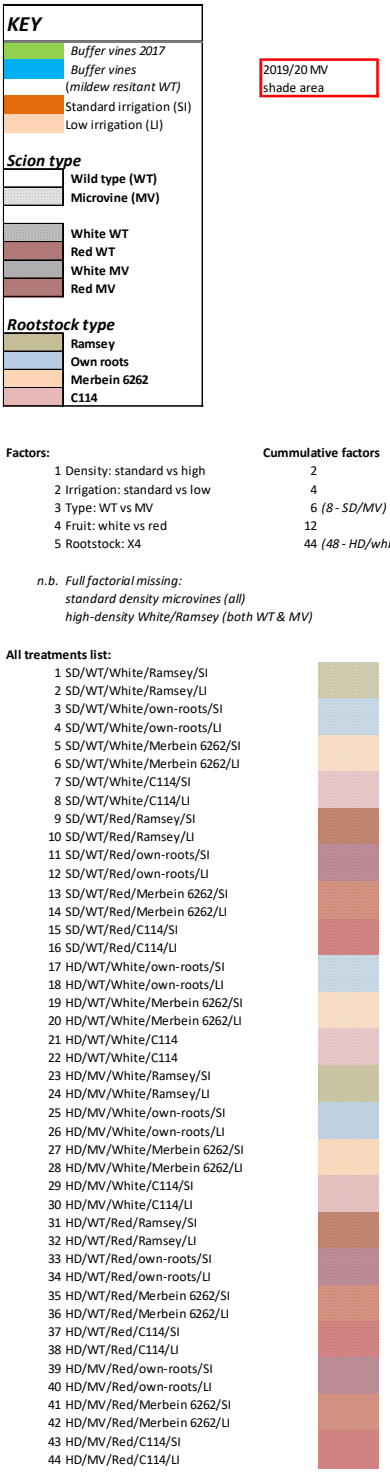


Figure 2: detailed diagram of block layout with all genotype combinations and treatments indicated, including the microvine shade trial in 2019/20 season.

2.2 Vine management

As all the vines were 'no-spray' genotypes with multi-gene mildew resistance, so no fungicide sprays were applied during the trial and the cost-savings involved in this are examined in Chapter 5.

2.2.1 Fertiliser

Fertiliser inputs were applied using fertigation. During the block establishment nitrogen fertilizer was applied monthly to aid establishment. Post-establishment, but prior to the work reported here, mono-ammonium phosphate (MAP39, supplied by SARDI) was applied four times during the season, but from the 2017/18 season onwards 54 kg of MAP39 was applied as a single dose, equating to 44 g per vine, irrespective of density.

2.2.2 Irrigation

From the start of planting in October 2014 until the end of the 2016/17 season a single irrigation regime was used across the whole block, with each vine receiving the same volume of water, irrespective of density. Timing of irrigation was based on that used by the farm manager over the rest of the SARDI NRC, approximately weekly from mid-December until harvest. From the 2017/18 season onwards the reduced irrigation treatment was applied to the designated areas (Figure 1 middle). All irrigation used town water, with four zones prior to 2018/19 (as noted in Table 1) and six from 2018/19 onwards (MV standard irrigation and MV reduced irrigation were separated from the WT high-density zones, Figure 3). Zones could not be irrigated simultaneously.



Figure 3: irrigation controller, valves and flow meters for the six irrigation zones.

For the 2017/18 and 2018/19 seasons irrigation was calculated per vine, which resulted in much more irrigation being applied to the high-density section than the standard-density section on a row length or ground area basis (Table 1).

In addition, the microvines had drippers with half the output of the rest of the trial until the 2018/19 season, when they were replaced to match the other sections. The intention was to ensure the MV vines did not become waterlogged as a result of their much smaller canopies (see Chapter 3).

For the 2019/20 season, irrigation times were calculated on a row length basis under the assumption that canopy size, and therefore water demand, was similar per m of row, irrespective of vine density or row spacing (Table 2). Note that when calculated on an area basis the high-density section still received more water than the standard density section.

Table 1: Nominal irrigation applied for the 2017/18 season, based on 4 L/h dripper output and 265 or 165 hrs irrigation per season for standard (std) or reduced (low) irrigation regimes respectively. The MV vines received half the indicated volume in 2017/18 (2 L/h drippers).

Treatment	Vine no. (per panel)	Vine no. (per ha)	Irrigation (per m row)	Irrigation (per ha)
Std density, std irrigation	3	1570	0.50 kL	1.67 ML
Std density, low irrigation	3	1570	0.31 kL	1.04 ML
High density, std irrigation	5	5250	0.83 kL	5.56 ML
High density, low irrigation	5	5250	0.52 kL	3.46 ML

Table 2: Nominal irrigation applied for 2019/20 season, based on 4 L/h dripper output.

Treatment	Irrigation hours	Vine no. (per panel)	Vine no. (per ha)	Irrigation (per m row)	Irrigation (per ha)
Std density, std irrigation	230	3	1570	0.43 kL	1.43 ML
Std density, low irrigation	115	3	1570	0.22 kL	0.73 ML
High density, std irrigation	135	5	5250	0.43 kL	2.87 ML
High density, low irrigation	73	5	5250	0.23 kL	1.53 ML

*Table 3: Measured volume of irrigation per trial block section per season and estimated volume per vine. WT = Wildtype, MV = microvine, SD = standard density, HD = high-density, SI = standard irrigation, RI = reduced irrigation. *estimated from total for HD SI/RI using dripper number.*

Section	Dripper no.	2017/18 Total volume (kL)	2017/18 Volume per vine (kL)	2018/19 Total volume (kL)	2018/19 Volume per vine (kL)	2019/20 Total volume (kL)	2019/20 Volume per vine (kL)
WT SD SI	150	217	1.45	271	1.81	216	1.44
WT SD RI	195	222	1.14	189	0.97	144	0.74
MV HD SI	200	181*	0.91*	348	1.74	165	0.82
MV HD RI	248	124*	0.50*	259	1.04	109	0.44
WT HD SI	200	342*	1.71*	317	1.59	186	0.93
WT HD RI	224	206*	0.91*	190	0.85	103	0.46

Irrigation was controlled using a Galcon GSI web-based irrigation controller, which recorded water flow through each zone using an inline flow meter, in addition to the duration of each irrigation event. Irrigation volume per season, and estimated volume per vine are given in Table 3.

2.2.3 Microvine protection

Significant damage to the 'no-prune' MV vines was observed during the 2017/18 season. This was thought to be due to a combination of high air temperatures, sun exposure and lower irrigation due to the use of 2 L/h drippers. To prevent this reoccurring, drippers were changed to match those for the WT vines and the MV section was covered with an improvised shade system, using 70% shade cloth. There was no obvious damage in the subsequent season, but it was unclear whether this was due to the shade system, dripper changes, differences in weather between the seasons or vine development. Consequently, in 2019/20 a decision was made to shade half of the two MV sections (standard and reduced irrigation) and assess any differences in vine damage (Figure 2, Figure 4).

2.2.4 Environmental measurements

Weather data was taken from the onsite automated weather station. In addition, in canopy air temperature and relative humidity were recorded using HOBO MX2301A data loggers (One Temp, Adelaide, SA).

Continuous measurement of soil moisture in all of the treatment combinations was impractical, but irrigation efficacy was monitored using two EnviroPro sensors connected to a GreenBrain cellular logger (MEA, Magill, SA). The sensors were installed in the 'no-prune' MV vines, one in each of the two irrigation treatments. Figure 5 provides a trace of the



Figure 4: view of the 2019/20 partial shade setup in the 'no-prune' MV section of the trial.

2018/19 season, where the difference in soil moisture with irrigation treatment is clear, as is the irrigation frequency and recovery of the reduced irrigation treatment after leaf-fall with autumn rain. During the growing season the average difference between the treatments was 78 mm, approximately 20% of transpirable water.

For the 2019/20 season access tubes for a Diviner 2000 sensor (Sentek, Adelaide, SA) were installed in 24 of the treatment combinations to give four replicates each of the irrigation treatments in the standard-density WT, the high-density WT and the 'no-prune' MV vines, which equated to two replicates for each scion*irrigation*density combination.

Measurements were taken after budburst, before the irrigation season, and during the peak irrigation season (January to March). The measurements were timed to provide alternate pre- and post-irrigation values (Figure 6). The highest soil moisture during the season was in the 'no-prune' MV plots, followed by the WT standard-density plot and the WT high-density plot had the lowest soil water content over the irrigation season. However, for the 2019/20 season the irrigation of the high-density plots had been reduced by around 40%, so it is possible that prior to this season, the WT high-density plot had a higher water content than the WT standard-density plot. Indeed, the data in Figure 5 suggest a much higher water content in

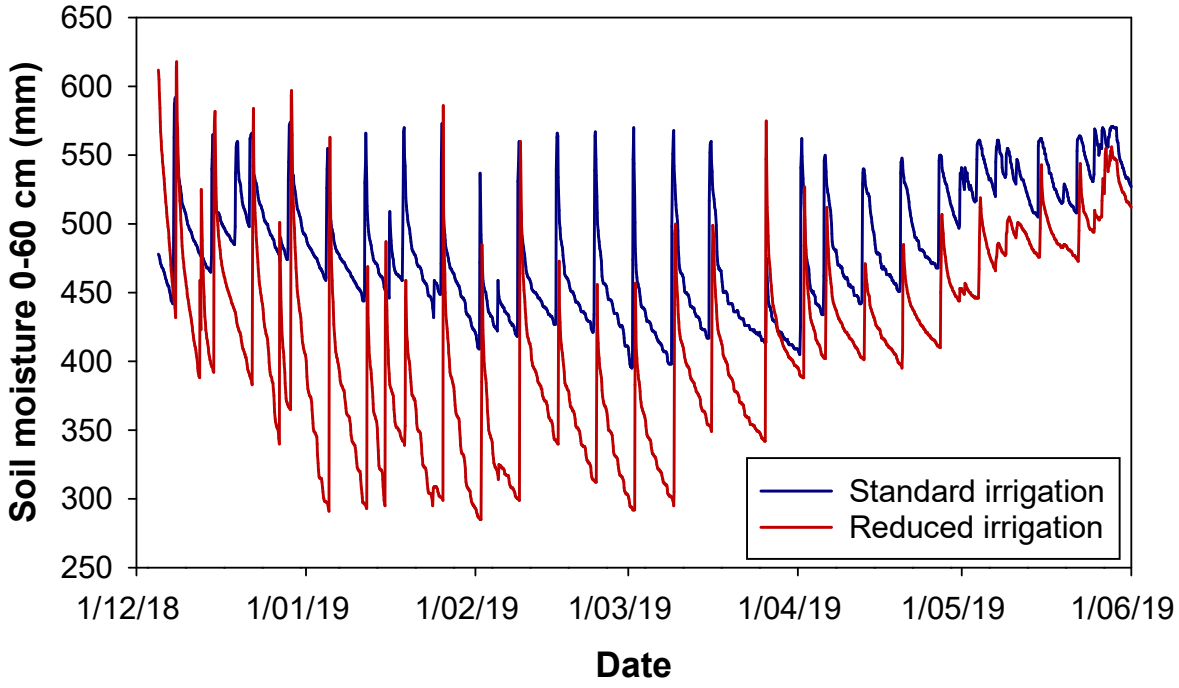


Figure 5: soil moisture content in the top 0.6 m during the 2018/19 season. Recorded under two irrigation regimes in the high-density section of the trial using a logging capacitance sensor.

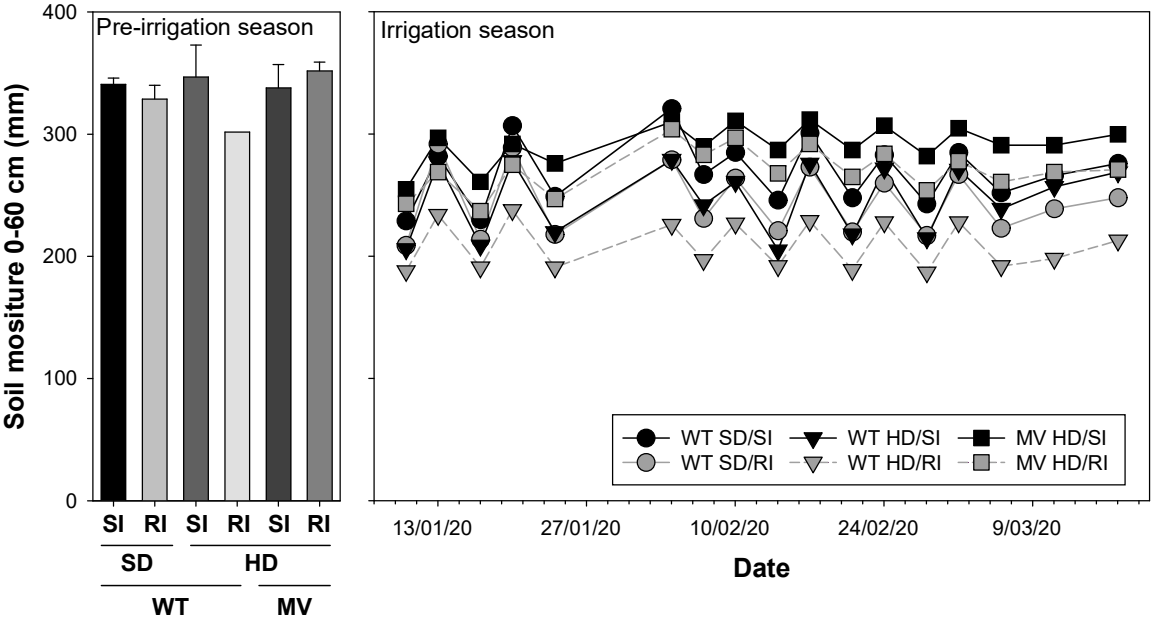


Figure 6: soil moisture content in the top 0.6 m during the 2019/20 season. Recorded pre- and post-irrigation under all irrigation/planting density regimes using removable capacitance sensor

the high-density plot in 2018/19, although this was recorded using different sensors and there are no comparable readings in other plots or replication.

The average within season difference in soil water content due to the reduced irrigation in 2019/20 was 20 to 50 mm depending on treatment, with the biggest difference between standard and reduced irrigation being in the WT high-density plot.

2.3 Vine and fruit assessment?

2.3.1 vine growth

The primary measure of vine growth used was fresh pruning mass (PM), which was assessed after leaf fall in all of the WT treatment combinations for each growing season. Growth in the 2016/17 season was measured on 11/7/2017, in the 2017/18 season on 14-16/8/2018, in the 2018/19 season on 28-29/8/2019, in the 2019/20 season on 24-25/8/2020 and in the 2020/21 season on 19/8/2021. A panel was considered as a replicate, and PM was measured for the total panel, irrespective of the number of vines. For the 2016/17 season, where the reduced irrigation treatment was not yet applied, three panels per treatment combination were measured and for the four subsequent seasons all five panels were measured.

For the 'no-prune' MV vines, PM could not be used as a measure of growth. To allow differences in 'no-prune' vines to be determined and a comparison be made to the WT vines, leaf area index (LAI) was measured on all panels at peak canopy size in the 2020/21 season using a LiCOR Li2200c Plant Canopy Analyzer (LiCOR Inc. Nebraska, USA). As winegrapes are a row crop with a non-continuous canopy, for a true LAI, a transect of measurements across multiple rows is required. This wasn't possible due to the trial layout, so LAI was estimated using a view restricted to a single panel in a single row for each measurement, this measurement is referred to as 'apparent' LAI (LAIapp) hereafter.

LAIapp was also measured at peak canopy size in the 2018/19 season, but only as a single measurement per treatment combination and only on the WT vines.

Finally, trunk diameter was measured on all vines, at the end of the project (May 2021), except the grafted MV vines due to the trunks being roostock, not scion. Diameters were measured approximately equidistant between the cordon and the ground using digital calipers. Diameter was taken as the mean of two measurements taken perpendicular to each other.

2.3.2 Fruit production

Fruit yield was measured by hand harvesting all bunches for each panel and then weighing the total. This was carried out when the fruit total soluble solids (TSS) was at 22°Brix for the 2018 and 2019 harvests, then at 24°Brix for the 2020 and 2021 harvests. The 'no-prune' MV Red vines didn't always reach the target TSS and were harvested as late as possible before leaf senescence if so.

In 2018 and 2019 all bunches were counted during harvest to provide bunch number and an average bunch fresh mass was calculated by dividing the yield per panel by the bunch number per panel. In 2019 and 2020 bunch number was estimated from the mean bunch fresh mass of the bunches taken for chemical analysis (see below) and the bunch number calculated by dividing the yield per panel by the mean bunch mass per panel.

Mean berry fresh mass was measured using a 100 berry sample taken from the bunches used for chemical analysis (see below). This was done per panel for the 2018, 2020 and 2021 harvests, but the fruit for chemical analysis were combined for the 2019 harvest, so only one estimate of berry fresh mass per treatment was made.

2.3.3 Fruit composition

Grape bunches were selected at random from the harvested fruit for each panel for chemical analysis. For the WT vines, five bunches were typically used and for the MV vines, ten. These numbers were adjusted according to bunch size and micro-vinification requirements in any particular season (see below). Two 100 berry samples were taken from these bunches for red varieties and one for white varieties, frozen and kept at -40°C until use.

For the laboratory analysis the frozen samples were defrosted at room temperature and then crushed by hand in a plastic ziplock bag. Two methods were used to assess fruit composition. Firstly, juice was analysed using an ATR-FTIR instrument with commercial calibrations (Oenofoss, Fossanalytics, Mulgrave, VIC), which provided data on pH, total organic acids, malic acid, tartaric acid, total soluble solids (TSS), sample density, volatile acidity (VA), yeast assimilable nitrogen (YAN), free amino acids (alpha-amino), gluconic acid and ammonia. For the red varieties, a second juice sample was prepared in the same way and used to estimate berry anthocyanin and phenolic content using a spectrophotometric assay (Iland et a. 2000), adapted for use in UVB transparent micro-titre plates.

2.3.4 Fruit maturity assessment

Maturity was assessed as TSS and was undertaken weekly in each genotype/management treatment. A small number of individual berries were taken from multiple bunches in a single panel, with the five panels being alternated by week. The berries were crushed in a plastic ziplock bag and measured with an Atago digital refractometer (Test Equip, Dandenong South, VIC). Assessment began at the start of maturation in 2017/18, approximately 11°Brix (mid-January 2018), but mid-maturation in subsequent seasons (approximately 16°Brix, early February).

2.4 Wine production and assessment

2.4.1 Micro-ferments

The berries were removed from the rachis by hand and 1.3 kg were collected for the ferments. These were crushed in a plastic ziplock bag and the total contents of the bag emptied into a fermentation vessels (modified 1.5 L coffee press). Must parameters of the juice were

measured using an OenoFoss and the pH adjusted to 3.5. The juice was allowed to temperature adjust to 22°C, then diamonium phosphate was added at 200 ppm, followed by 17 mL of an overnight yeast culture.

The must was plunged on a daily basis and the plunger sealed with parafilm. When sugars reached 2.5 g L^{-1} the wine was racked by pushing down on the plunger to separate the solids before being poured into a clear wine bottle. Finished wine analysis was done for each wine using an OenoFoss. Red wines were analysed for total phenolics and tannins using the method of Harbertson et al. (2003) modified for use in micro-titre plates.

In 2017/18, 26 wines (13 red and 13 white) were made from standard irrigation treatments only. In 2018/19, 45 wines (22 red and 23 White) were made using fruit both from standard and reduced irrigation treatments.

2.4.2 Small-lot winemaking

For the 2019/20 season small lot winemaking was undertaken by the AWRI. Fruit were taken from all rootstocks for a given scion/management treatment combination and combined. Approximately 100 kg of fruit for each wine was taken to the AWRI winemaking facility, cooled overnight and split into two 30 kg lots, which were crushed and fermented separately as winemaking replicates. The standard AWRI red and white winemaking protocols were used, including acid adjustment, if required, and malolactic fermentation.

A total of 24 wines were made, two per scion/management combination. For the 'no-prune' MV vines, rather than two winemaking reps, shade and non-shade wines were made, with one wine using fruit from the shade treatment and one from the non-shaded vines.

Wine anthocyanin and phenolic content was measured using the methods of Iland et al (2000) and tannins using a modified epicatechin precipitation method. The wines also underwent a preliminary tasting session with the AWRI for sensory assessment, with the WT red wines then being formally assessed through triangle difference testing.

2.5 Statistical analyses

The trial layout was a nested design, with the main plot split into standard and high-density, the standard density plot split into red and white WT scions and then split again into standard and reduced irrigation, and the high-density plot split into MV and WT vines, and then split again into red and white scions then standard and reduced irrigation. All plots were further subdivided by rootstock. Replication only occurred within the final subdivided plots as five individual panels. As it was impractical for the trial to be laid out as a complete randomized block due to the density and irrigation treatments any attempts to examine treatment interactions are confounded with physical position in the site. Further, the lack of MV Red or WT White scions on Ramsey rootstock make a strict nested ANOVA design impossible to complete.

Consequently, a pragmatic approach to the statistical analysis was taken. In general a multi-way ANOVA, fitted using a GLM, was generated for the multi-season average-per-panel of the parameter in question, with the data split into subsets:

i. WT vines, excluding Ramsey – tests for planting density, irrigation, scion and rootstock effects+interactions (limited to WT scions and three rootstocks).
ii. Standard-density vines – tests for irrigation scion and roostock effects+interactions (limited to WT scions).
iii. High-density vines, excluding Ramsey – tests for irrigation, scion and rootstock effects+interactions (limited to three rootstocks).
iv. where significant rootstock effects or interactions were indicated in the high-density data these were tested using individual factorial models for each of the four scions due to the two missing rootstock:scion combinations in the high-density plot.
v. where other complex interactions were indicated in any of the results, ANOVA models were fitted to data subsets as required to investigate these.

The effect of season and interactions between season and main effects were examined via a similar approach, but using a repeated-measures ANOVA, rather than the multi-season average.

Chapter 3: The effect of low input strategies on vine growth and production

The trial site was designed to allow a number of vine management factors to be manipulated, with a focus on reduced inputs, namely spraying, irrigation, and pruning. Further, the site utilised novel scion genotypes and allowed for the production of these to be compared across a range of rootstocks. Assessing the impact of the management strategies and genotype combinations on vine production was a major aim of the project.

3.1 Vine growth

3.1.1 pruning mass

PM taken following the 2016/17 season, one-two seasons after planting, was lower than in subsequent years (Figure 7) likely due to the later planted vines not being at full canopy growth potential yet. There was no evidence of year-on-year increases in within-season growth following 2017. Further, the irrigation treatments were only imposed from the 2017/18 season. Consequently, the analysis of PM data focused on the 2017/18 season onwards. Although the irrigation application for the high-density plots was altered for 2019/20 and 2020/21 seasons (to provide the same irrigation per unit row length, irrespective of vine spacing), three-way interactions between season, irrigation and other factors appeared to be driven by primarily by magnitude (data not shown). Due to this, together with the limitations as a result of the nested design of the trial site and high degree of correlation between seasons for individual panels (Table 4), most of the following results are based on all four seasons being analysed together.

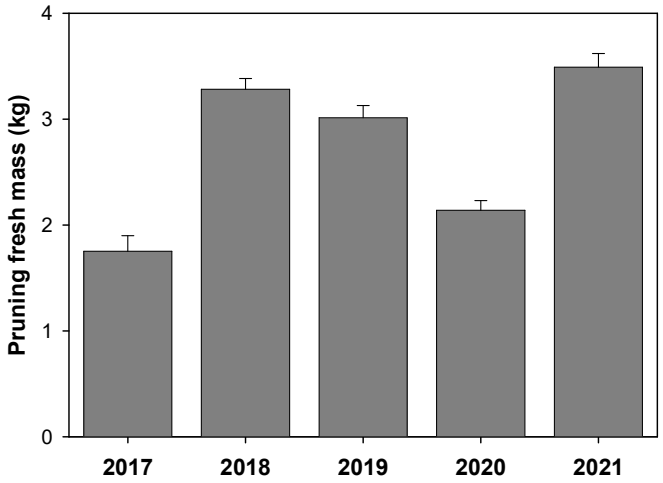


Figure 7: PM of all WT vines across the trial site by season. Data are means + SE.

Table 4: correlation matrix for trial site PM. Values are Pearson Correlation, n=150.

	2017/18	2018/19	2019/20	2020/21
2017/18	1			
2018/19	0.796	1		
2019/20	0.747	0.767	1	
2020/21	0.824	0.796	0.813	1

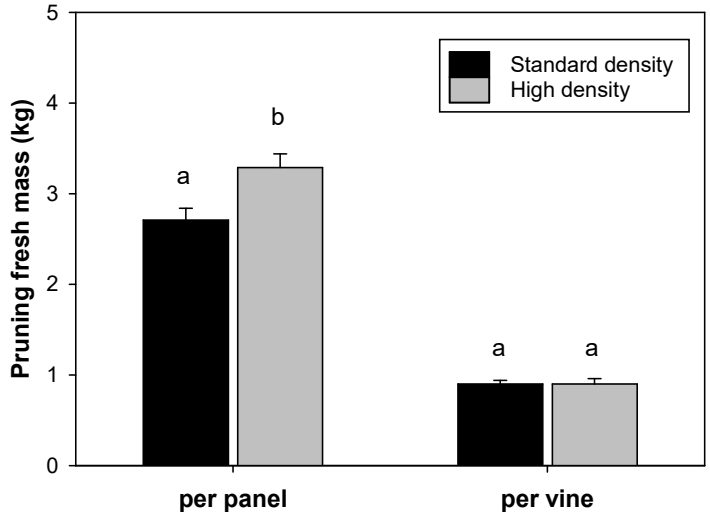


Figure 8: Effect of planting density on WT vine PM, expressed per panel (left) or per vine (right). Data are means + SE, letters denote significant differences (p<0.05).

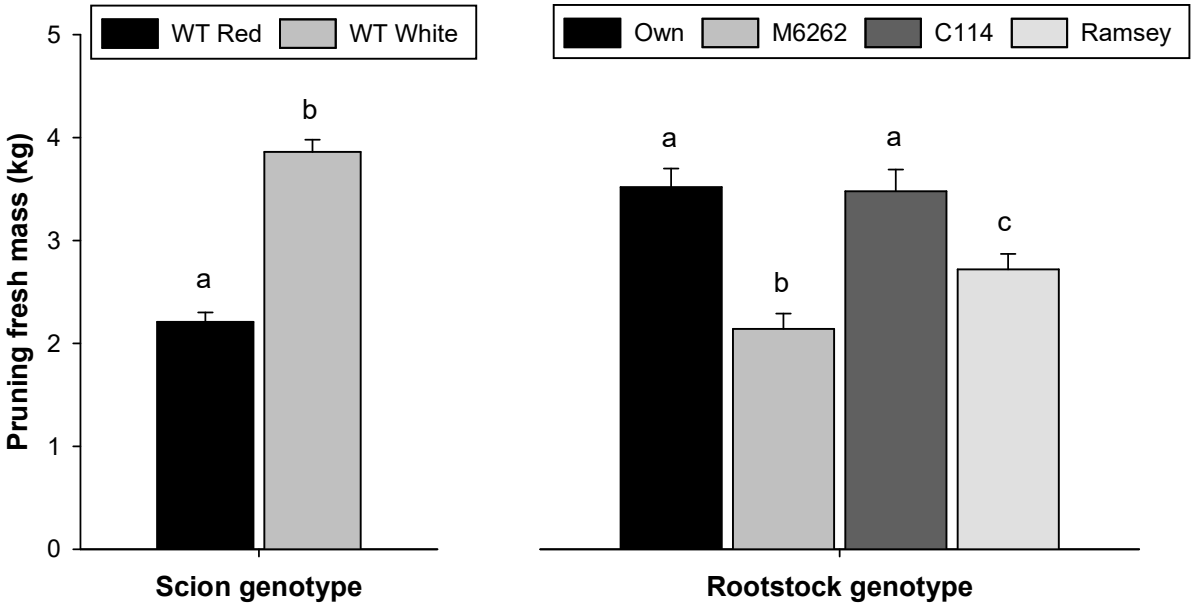


Figure 9: Effect of scion or rootstock genotype on WT vine PM. Data are means + SE, letters denote significant differences (p<0.05).

Across the entire four season dataset, density, scion and rootstock all affected PM ($p<0.001$ in each case), but the irrigation treatment was not significant (Figures 8-9). PM per panel (or per m of row) in the high-density plot was greater than the standard density plot, but if expressed on a per vine basis there was no difference (Figure 8). Data, such as shoot number, that might aid establishing the cause of this were not available. It is possible that the higher rates of irrigation per unit ground area on the high-density plot throughout the trial led to higher vigour, as higher-density planting has been traditionally viewed as devigorating, rather than envirgorating (Dry & Loveys 1998).

As PM was not available for the 'no-prune' MV vines, only the two WT scions were assessed using this method. The WT White scion had almost double the PM of the WT Red scion and this was true, irrespective of rootstock, planting density or irrigation applied. Similarly, the effect of rootstock on scion PM was consistent, irrespective of other factors, with own roots and C114 conferring the highest vigour with M6262 the lowest. Given the common reports of high vigour in Ramsey (e.g. May 1994) it is perhaps surprising that Ramsey produced vigour closer to M6262 than own roots, however, there are reports of Ramsey vigour increasing with vineyard age (Edwards et al. under review).

Other than seasonal variation, there were only two statistically significant interactions on PM between the treatments applied to the WT vines. The first was between density and rootstock, with no difference in PM conferred by Ramsey between high and low density, where the other three rootstocks all increased PM at high density, but the order of rootstock conferred vigour was unaffected (data not shown). The second was an interaction between density and irrigation, with the increase in PM under high density being greater with reduced irrigation (Figure 10). Again, the reason for this not clear, but as the reduced irrigation did not have a significant effect on PM under standard density and the irrigation applied per unit ground area was much higher in the high-density area of the trial it may be that soil water was high enough to negatively affect growth (Stevens et al. 1999).

3.1.2 'Apparent' leaf area index

Due to the limited LAI_{app} data collected in 2018/19 (only WT vines, one measurement per treatment combination) a full factorial statistical analysis would only have a single measurement for the highest level of treatment interaction and n=2 for three-way interactions. Consequently, the statistical analysis was restricted to main effects and the two-way interactions of the main effects. This indicated a significant higher LAI_{app} under high-density ($p<0.001$), a significant effect of rootstock ($p=0.018$; using Tukey's HSD test, own-roots were significantly higher than M6262, with no significant difference between any other rootstocks) and a significant interaction between density and irrigation treatments, with reduced irrigation increasing LAI_{app} under high density, but reducing it under low density ($p=0.011$). A regression between the individual panels measured in 2018/19 and the same panels measured in 2020/21 produced a significant correlation with adjusted $R^2 = 0.372$. Overall, the LAI_{app} data from 2018/19 supported the data from 2020/21 and the density*irrigation interaction observed in the PM data.

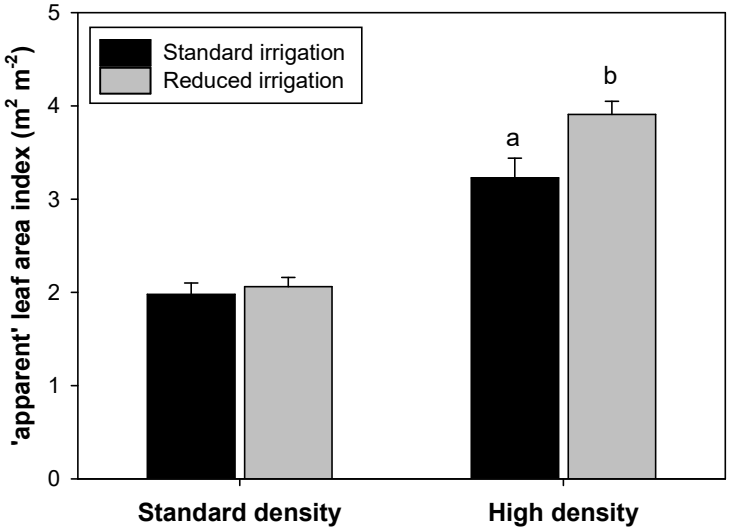


Figure 11: The interaction between density and irrigation effects on WT vine LAI_{app}. Data are means + SE, letters denote significant differences (p<0.05).

The LAI_{app} data collected in the 2020/21 season covered all of the treatments, including the MV vines, and all of the panels (replicates) for each treatment combination. As was observed with the WT PM data across four growing seasons, LAI_{app} was significantly higher in the high-density area than the standard density area, despite being measured on a single row (p<0.001). Due to the 'no-prune' MV vines not being part of the standard-density section and the two missing scion:Ramsey combinations from the high-density a statistical analysis across the full data set was too unbalanced to examine further, so the data was split into WT or MV and high/standard-density subsets for examination of the other factors.

Analysing the WT vines only was equivalent to the PM analysis above. As with the PM data there was a significant density by irrigation interaction, with reduced irrigation leading to higher LAI_{app} under high-density planting (Figure 11). Also similar to the PM data, WT White scions were significantly more vigorous than WT Red (LAI_{app} of 3.05±0.14 vs 2.48±0.13; p<0.001) and there was a significant effect of rootstock genotype on LAI_{app}. However, the ranking of rootstock conferred vigour varied with density (p=0.041; Figure 12), although in both cases C114 had the highest LAI_{app}. Furthermore, the relative differences between rootstocks were smaller than for PM, suggesting that the LAI_{app}:PM relationship varied between rootstocks.

When only the 'no-prune' MV vines were analysed, the only significant main effect was scion, with the MV White scion having a greater LAI_{app} than the MV Red scion (2.27 vs 1.51 respectively, p=0.004). There was no effect of irrigation or rootstock (Figure 13); the missing MV Red on Ramsey combination may have affected the rootstock result, but even excluding Ramsey from the analysis there was only a marginal effect (p=0.09).

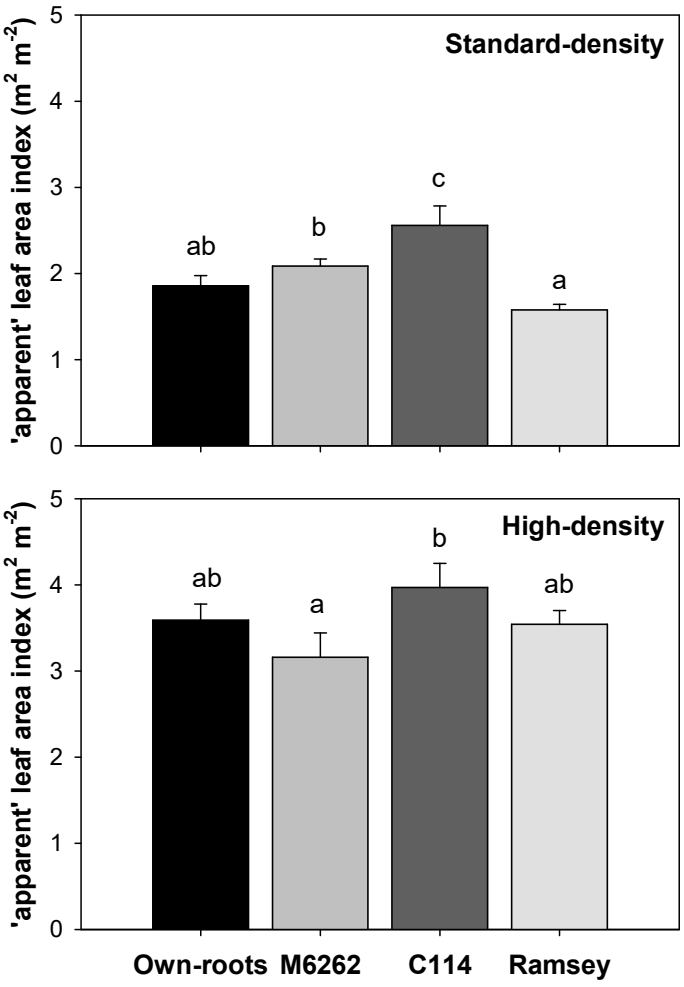


Figure 12: The effect of rootstock choice on WT vine LAI_{app} in the standard-density planting (top) and high-density planting (bottom). Data are means + SE, letters denote significant differences (p<0.05).

Using the high-density plot only, differences in LAI_{app} due to scion genotype were able to be assessed across all four scions. Whilst the was a strong effect of scion (p<0.001, Figure 14-15) there was also a significant interaction with irrigation (p=0.008). Irrespective of irrigation the White varieties were more vigorous than the red varieties and the WT vines more vigorous than the 'no-prune' MV vines, but the 'no-prune' MV vines were not affected by the irrigation treatment, whereas the WT vines had higher LAI_{app} under reduced irrigation (Figure 14). Again, this result supported the PM data, were WT vines had higher PM under reduced irrigation in the high-density plot.

3.1.3 Trunk diameter

Although trunk diameter could be measured on all vines, the 'no-prune' MV vines were grafted to their rootstock at the cordon, meaning that the trunk was rootstock not scion. Rootstock diameters are often different to the scion, so only the own-rooted microvines

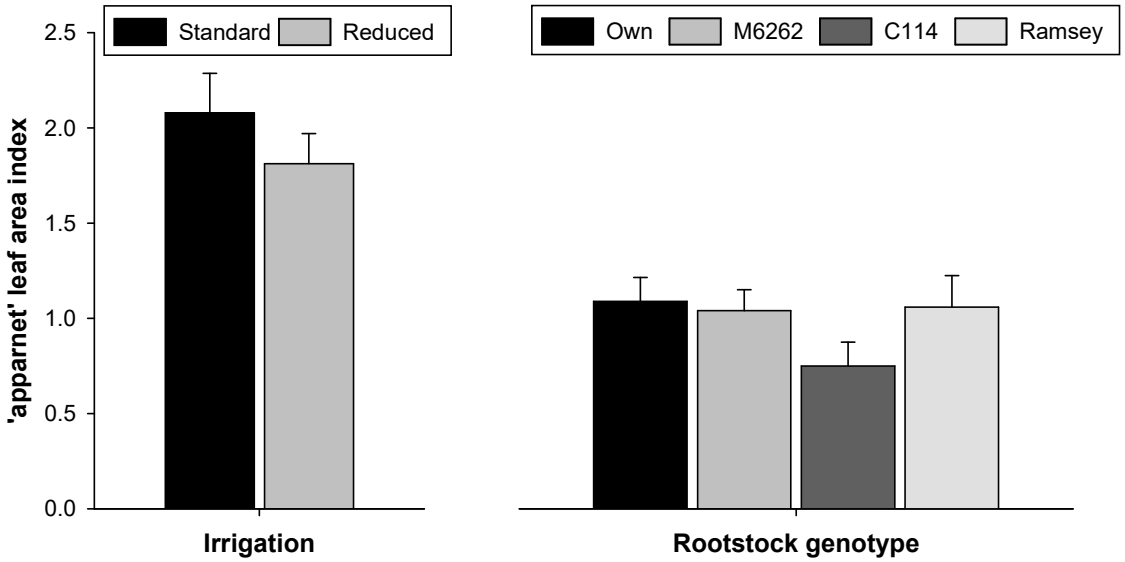


Figure 13: Effect of scion or rootstock genotype on MV vine LAI_{app}. Data are means + SE, there were no significant differences.

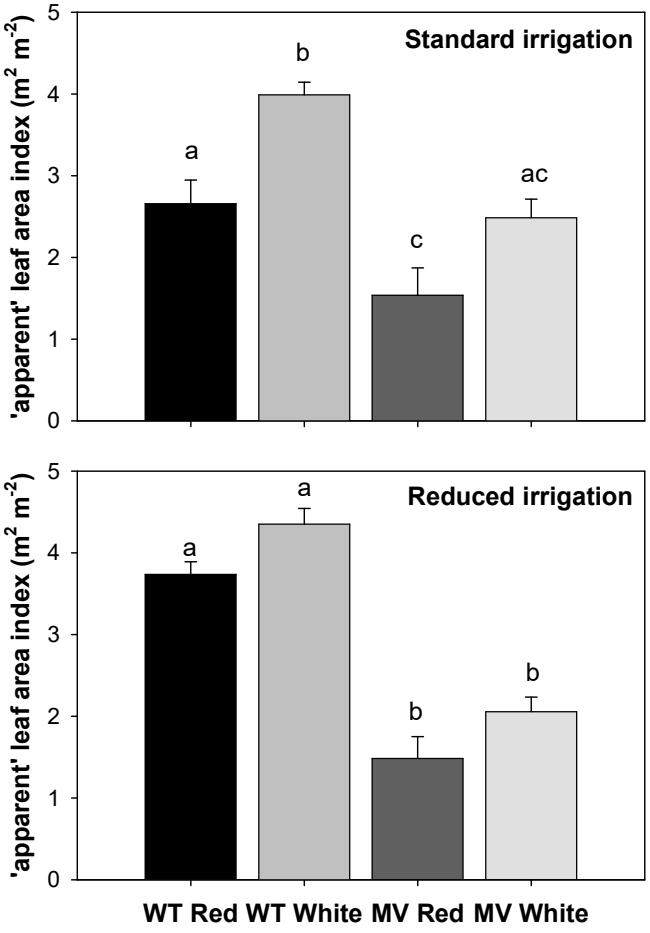


Figure 14: The effect of scion genotype on vine LAI_{app} under standard irrigation (top) and reduced irrigation (bottom) in the high-density plot. Data are means + SE, letters denote significant differences ($p<0.05$).



Figure 15: Example of the canopy size and structure differences between a WT vine and an adjacent 'no-prune' MV vine.

could be compared with the WT vines. There was a large difference between the 'no-prune' MV vines and the WT vines ($p<0.001$; Figure 16), with WT vines having trunk diameters almost double those of MV vines. This was similar to the difference observed in LAI_{app}. Again, there was a significant interaction between irrigation and scion ($p=0.031$), but the effect was smaller than for LAI_{app} (data not shown). Although the trunk diameter data was for own-roots only, the LAI_{app} results were across all rootstocks, so it is likely that the pattern seen here for own-roots would be broadly true of scion wood in the other scion:rootstock combinations.

This is further supported by the rest of the WT trunk diameter data, as the WT White vines had larger trunk diameters than the WT Red vines across all rootstocks and also in both the high- and standard-density plots. However, there was a significant interaction between WT scion and planting density, with a greater reduction in trunk diameter of WT White vines, than WT Red vines under high-density planting ($p<0.001$; Figure 17).

Rootstock also had some effect, with WT vines grafted to Ramsey rootstock having significantly smaller diameters than the other rootstocks (Figure 18). This was again broadly in line with the other vine growth data where Ramsey vines generally had lower results than the other rootstocks.

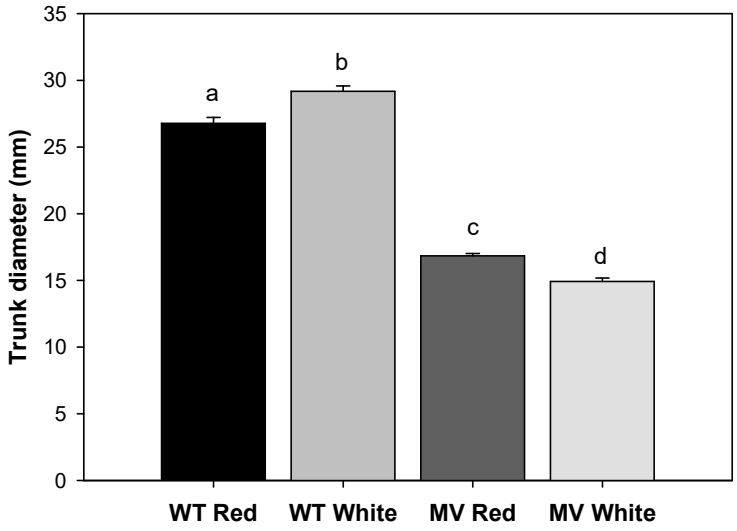


Figure 16: The effect of scion choice on trunk diameter in the high-density planting for own-rooted vines. Data are means + SE, letters denote significant differences (p<0.05).

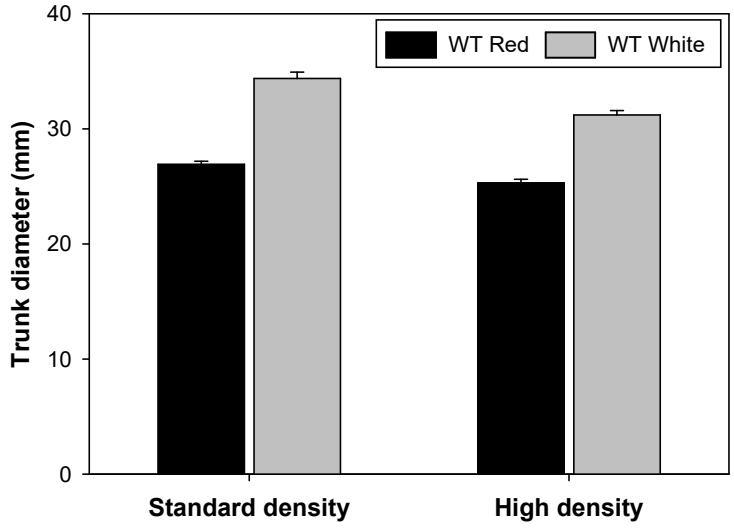


Figure 17: The interaction between density and scion choice on the trunk diameter of WT vines. Data are means + SE, letters denote significant differences (p<0.05).

3.1.4 Vine water use estimate

During maturation in the 2019/20 season soil water content was measured before and after each irrigation (Figure 6). By comparing the two values for each irrigation an estimate of the system water use could be calculated using the change in volumetric water content. This was done using the data to 1.0 m depth. Whilst there was no means to separate the components

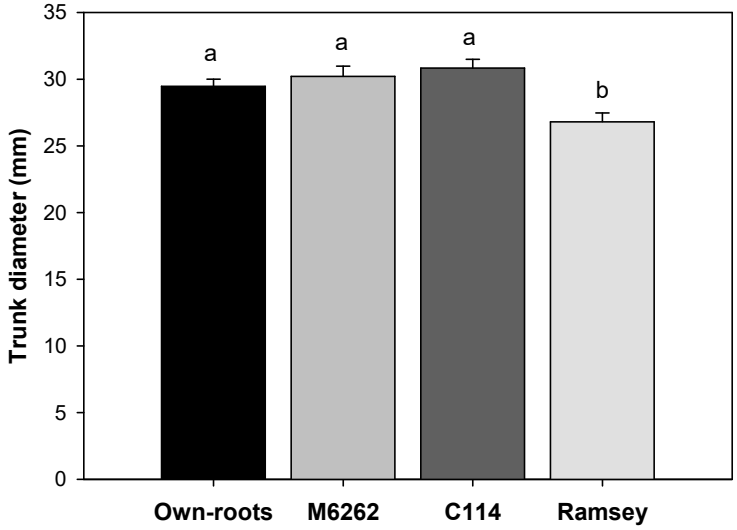


Figure 18: The effect of rootstock choice on trunk diameter of WT vines. Data are means + SE, letters denote significant differences (p<0.05).

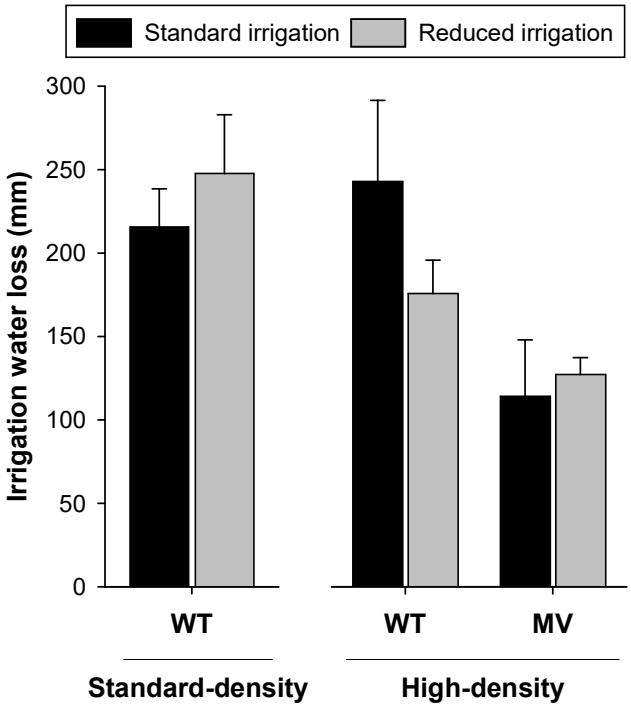


Figure 19: Estimate of whole system water loss during maturation calculated using changes in soil water content.

- soil evaporation, plant transpiration and deep drainage – it was of interest to examine the results. There was 31.2 mm of rainfall during this period, but only one fall was likely to have provided any effective rainfall, estimated at 15 mm and this was added to the irrigation water loss. For the standard-density plot the calculated estimates were higher than the applied

irrigation (Tables 2-3), suggesting stored water was being accessed. Indeed, the soil water content measured in November was 70-80 mm higher than the soil water content at harvest. Further, the largest decreases in soil water content were in the earlier part of the maturation period and were smaller pre-harvest. Perhaps most useful, was the evidence that the 'no-prune' MV vines used much less irrigation that the equivalent WT vines, despite having the most exposed soil surface, suggesting that significant improvement in irrigation efficiency could be made (see also 3.2.4).

3.2 Fruit production

3.2.1 Vine yield

Vine yield is the major component of vineyard income and the project aims included assessing the relative performance of the CSIRO lines under the various vineyard management strategies included in the Nuriootpa field trial. Fruit was harvested from entire panels, rather than individual vines, to ensure a reasonable sample, and all five panels for each genotype/treatment combination were harvested.

As is usually observed during field trials, vine yield varied significantly from season to season (e.g. Figure 20). In general, this was a difference in magnitude and the ranking of various treatments was similar. However, overlaid over this, there were specific effects due to certain treatments and changes in irrigation. During the 2017/18 season the microvines suffered significant damage to the canopy and fruit from heat and sun exposure, leading to an attempt to physically protect these vines in 208/19 and 2019/20. Yield in 2018 wasn't affected to a great extent as fruit fresh mass was largely in place prior to the damage occurring and a partial early harvest was undertaken to ensure some fruit ripened despite the canopy damage, but there was a carry-over effect in the following season, particularly in the MV White variety. This also led to the irrigation of the MV vines to be reverted to the strategy previously in place (i.e. for the 2016/17 season and earlier), which was to match the WT vines in the high-density plot, doubling irrigation applied. However, the major change in irrigation was to alter the irrigation strategy in the entire high-density treatment from a per vine calculation to a per unit length of row calculation for the 2019/20 and 2020/21 seasons.

Across the four-season dataset, planting density, irrigation, scion genotype and rootstock genotype all had a significant effect on vine yield and these were largely additive, although some significant interactions with density were observed. Yield per panel of the WT vines under standard irrigation was unaffected by planting density (24.6±0.7 kg vs 25.9±1.1 kg and 20.4±0.8 kg vs 19.7±0.9 kg for WT Red and WT White respectively), but the irrigation response was changed, with no effect of reduced irrigation in the high-density plot in contrast to a significant reduction in the standard-density plot (Figure 21). Despite the larger canopy size in the high-density plot it is likely that this was due to the higher rate of irrigation per panel for much of the trial lifetime, meaning that even the reduced irrigation was adequate for

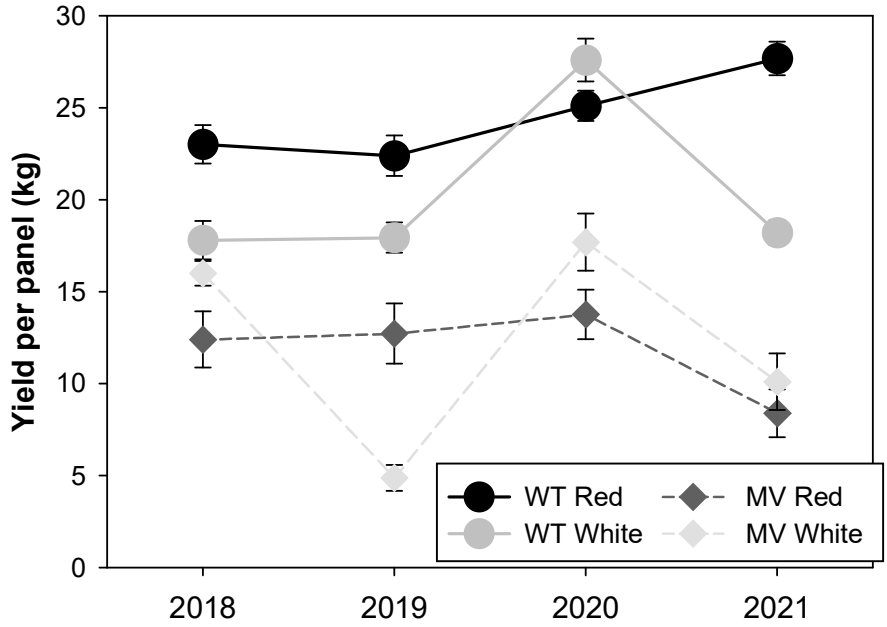


Figure 20: vine yield between 2018 and 2021 of the standard-density, standard irrigation WT vines and the standard irrigation MV vines. Data are means ±SE.

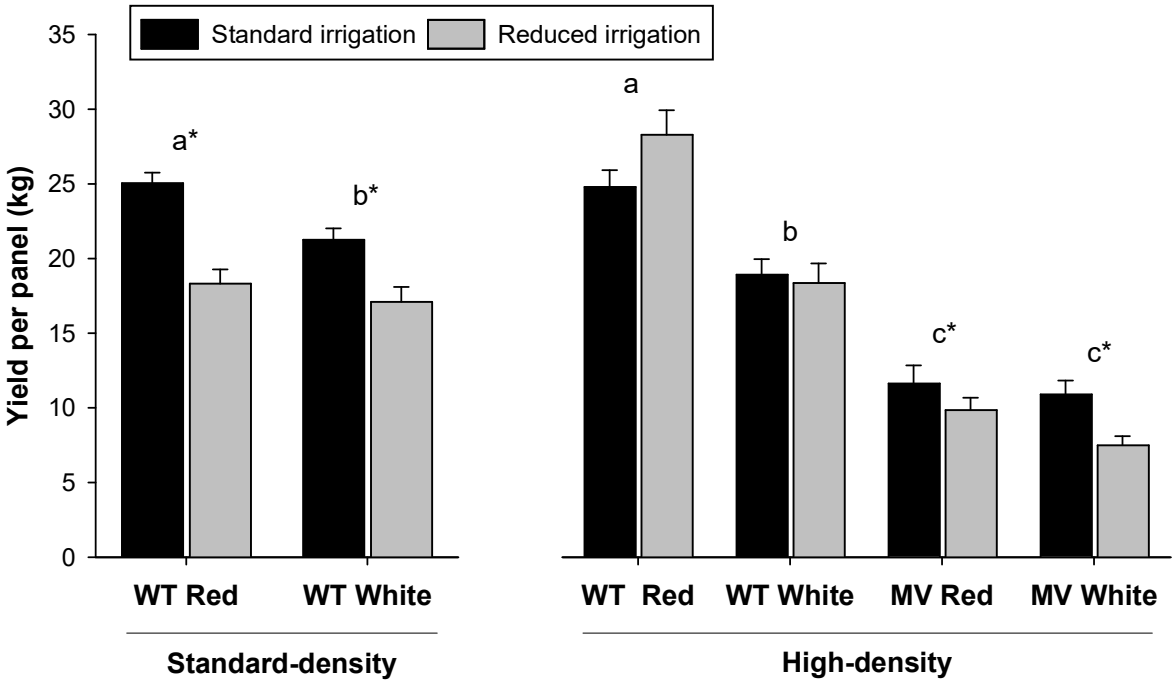


*Figure 21: the effects of density, irrigation and scion choice on four year mean fruit yield per panel. Data are means + SE, letters denote significant scion differences ($p<0.05$) and an * denotes a significant effect of irrigation ($p<0.05$).*

production and the standard-irrigation treatment was receiving excess water. However, there was a significant effect of the reduced irrigation treatment in the 'no-prune' MV vines, which appeared to have the highest soil water content (Fig 6). Other factors, such as root system size, or positioning of the root system, which may have been quite different in the MV vines than the WT vines due to the much smaller canopies and likely lower total carbon gain by the vines, may have been involved in this response. Unfortunately, it was not possible to investigate these within the scope of the project.

Rootstock also had a significant effect on yield, but this varied with planting density and scion (Figure 22). For the WT vines, the low-vigour M6262 rootstock had the lowest yield and this was exacerbated under high-density planting. For the 'no-prune' MV vines, the highest yield was achieved when the vines weren't grafted and the high-vigour CSIRO line, C114, generated the lowest yield.

3.2.2 Yield components

Given the number of factors in this trial and the complex interactions between them yield components were examined to attempt to elucidate the underlying treatment effects on the total fruit yield. These were determined as:

```
yield = bunch number*mean bunch weight
bunch weight = berry number*mean berry weight
```

Bunch number and weight were determined in all four seasons, except for the 'no-prune' MV vines, where COVID-19 restrictions meant that it wasn't possible to collect the data in 2020. Also, in 2019, bunch weight for the same vines was only collected on a per treatment combination basis, not per panel.

The largest impact on bunch number was scion genotype, with WT White vines having significantly fewer bunches than WT Red across the four seasons of data (153±3 vs 210±4 per panel) and the high-density planting resulting in slightly higher bunch number in the WT Red genotype (Figure 23 top). The 'no-prune' MV Red variety had the highest bunch number, although the MV White variety was higher than WT White. The only effect of irrigation on any of the bunch number results was a small decrease in WT Red as a result of reduced irrigation in the standard density plot (from 218 to 189 bunches per panel), but this did not occur in the high-density plot.

In contrast, the reduced irrigation treatment resulted in a decrease in bunch weight across all scion genotypes in both planting-densities (Figure 23 bottom). Bunch weight in the 'no-prune' MV varieties was only around a third of the WT varieties, explaining the reduced yield, despite those varieties having a much higher bunch number.

The small but significant effect of irrigation on bunch weight in the WT high-density vines, despite no effect on yield suggests that bunch number in these vines must have been affected, even though no statistically significant result was observed. In fact, the numerical result did

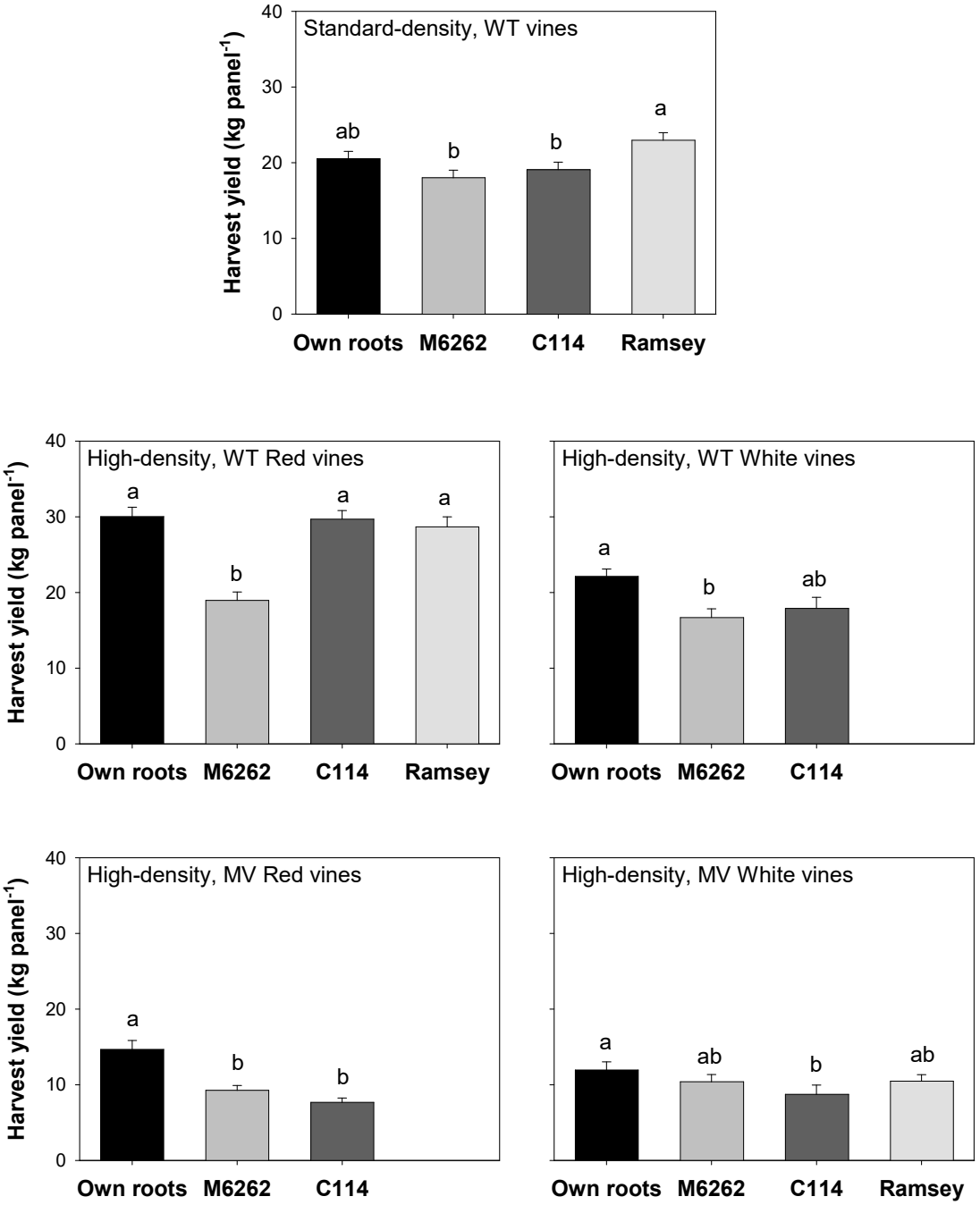


Figure 22: the interaction between rootstock choice, planting density and scion choice on four year mean fruit yield per panel. Data are means + SE, letters denote significant scion differences ($p<0.05$).

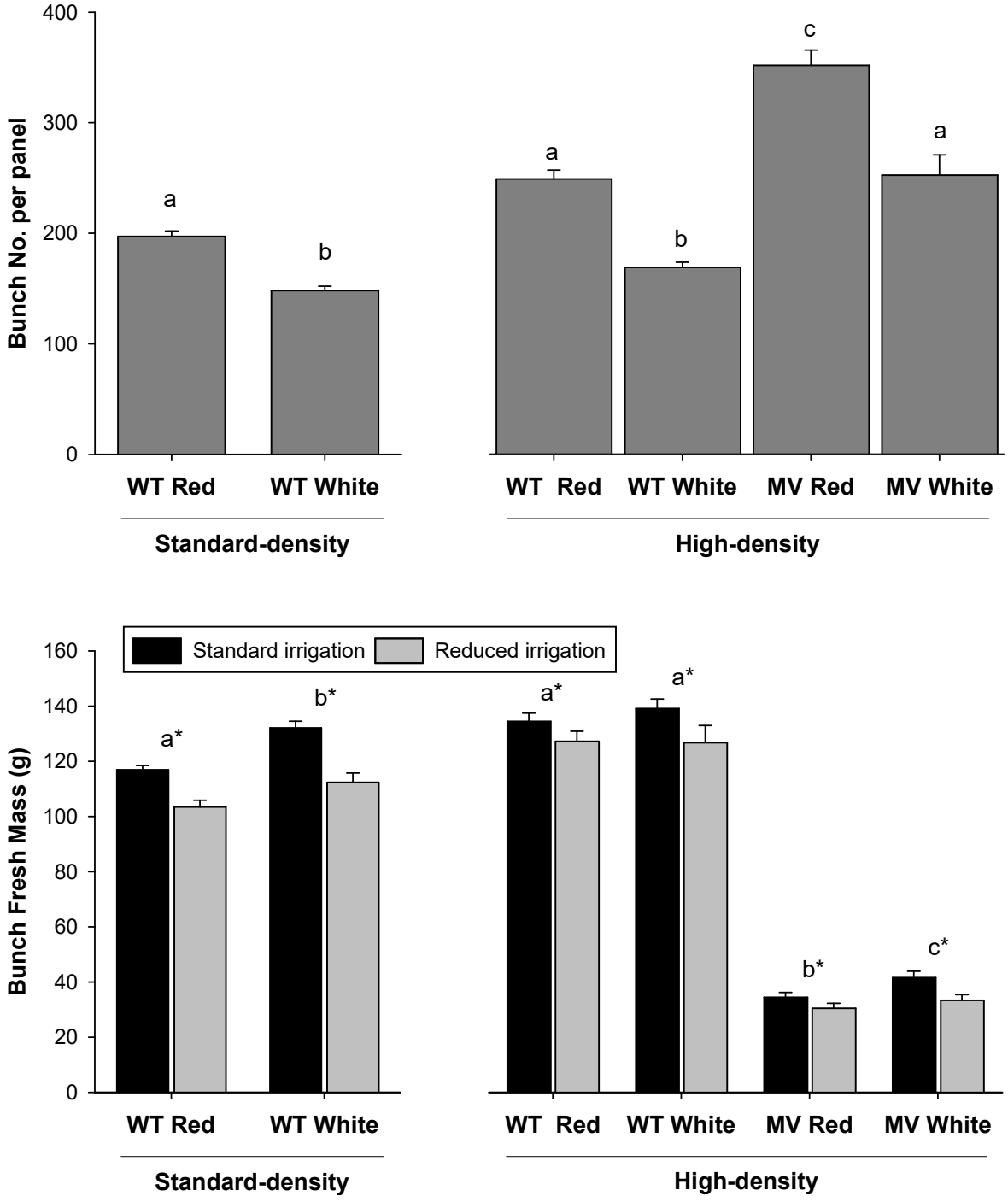


*Figure 23: the effects of density, irrigation and scion choice on yield components: bunch no per panel (top) and bunch fresh mass (bottom). Data exclude the Ramsey rootstock results and are means + SE, letters denote significant scion differences ($p<0.05$) and an * denotes a significant effect of irrigation ($p<0.05$).*

show a change in bunch number for WT Red (229±9 bunches per panel in the high-density reduced irrigation treatment vs 204±7 in the standard irrigation), but not the WT White (148 vs 146). There was a significant season*density*irrigation interaction, so it may also be that taking a long-term average is masking more complex season by season effects.

Rootstock affected both bunch number and bunch weight, with both parameters lower in WT vines grafted to M6262, irrespective of planting density (data not shown). In the 'no-prune' MV vines, both parameters were lower when grafted to C114. These results were consistent with the observed rootstock effects on yield.

The changes in bunch mass were further examined by assessing changes in berry number and weight. As with bunch number, there was no effect of irrigation on berry number in any of the statistical analyses. On the other hand, high-density planting reduced berry number per bunch, the WT White vines had fewer berries per bunch than the WT Red, irrespective of density, and the 'no-prune' MV vines had half the berry number of the WT vines (Figure 24 top). Effects on berry mass, were mostly the opposite of those on berry number, with the WT White vines having higher berry mass than WT Red, WT vines in the high-density planting having higher berry mass than the standard-density planting and MV White vines having higher berry mass than MV Red vines (Figure 24 bottom). Reducing irrigation always had a negative effect on berry mass, explaining the smaller bunch mass under reduced irrigation.

In summary:

- irrigation effects on yield were primarily due to changes in berry fresh mass;
- although planting density did not affect yield in WT vines, the bunches consisted of fewer, heavier berries and this effect was greater under reduced irrigation, partially explaining the lack of irrigation effect on WT vines at high-density,
- the lower yield in the WT White variety, relative to WT Red, was due to decreased bunch number and occurred despite an increase in mean berry mass;
- rootstock effects on yield were via changes in both bunch number and bunch mass.

3.2.3 Yield:vigour relationships

Efficient production of wine grapes requires maximizing the crop value versus the input costs. The role of the genotypes and management strategies examined in this project in minimizing input costs will be examined later (Chapter 5), but a critical component of this is matching fruit production and vine vigour, as vine vigour can affect water use, nutrient use and fruit quality. Differences in both vigour and fruit yield between genotypes and management strategies have been described above (sections 3.1 and 3.2 respectively), but they don't necessarily correlate. For example, the WT White variety exhibited higher vigour than WT Red, but lower yield.

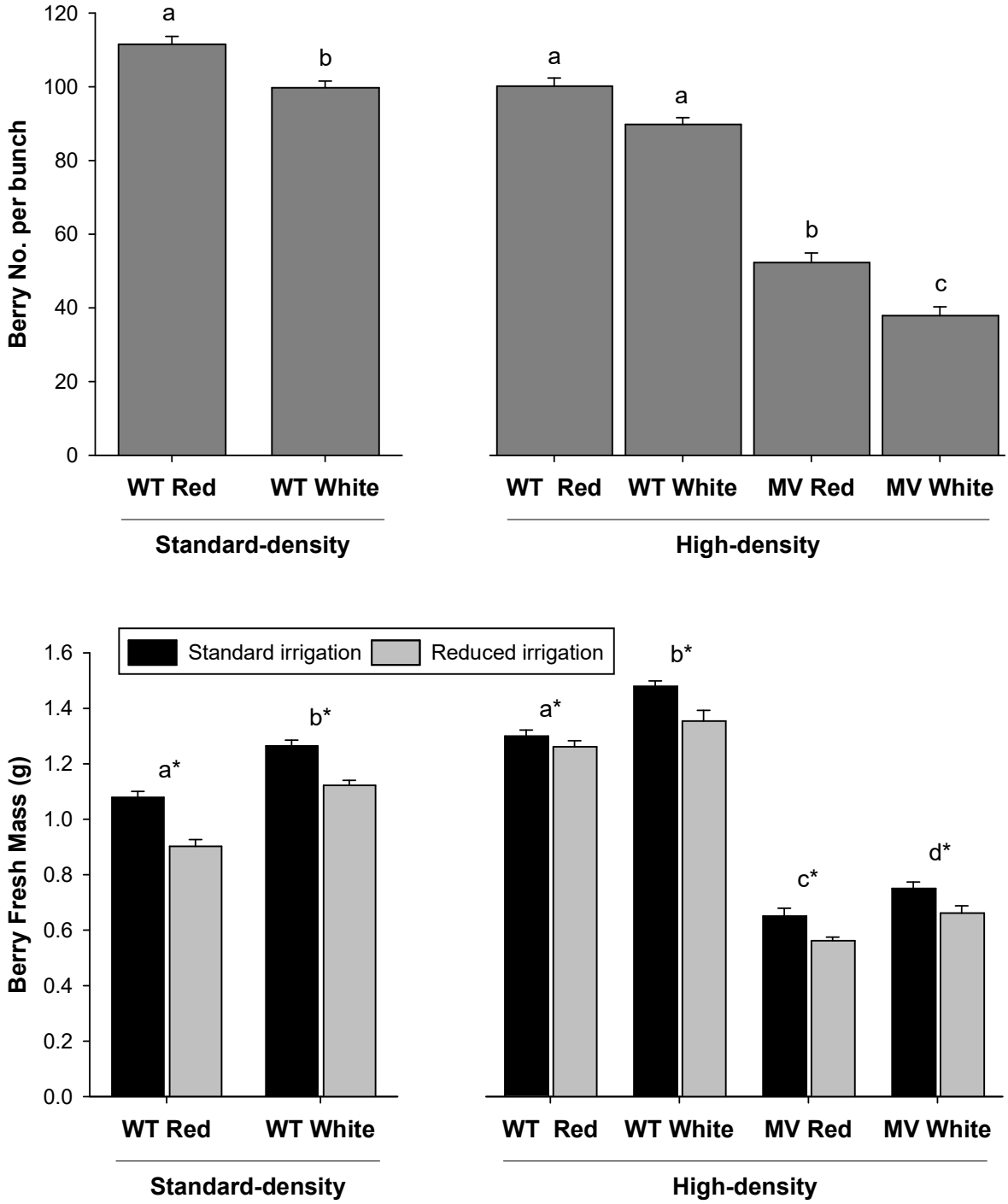


*Figure 24: the effects of density, irrigation and scion choice on yield components: berry no. per bunch (top) and berry fresh mass (bottom). Data are means + SE, letters denote significant scion differences (p<0.05) and an * denotes a significant effect of irrigation (p<0.05).*

The most commonly used measure of this relationship – usually termed vine balance – is the Ravaz index, or mass of yield per mass of fresh prunings. This index could not be calculated for the 'no-prune' MV vines, due to the lack of pruning. For the WT vines, there were

significant effects of scion, planting density and irrigation on the Ravaz index (Figure 25). The index was lower for the WT White variety in all treatments and lower for both genotypes in the high-density planting than the standard-density plot. Reduced irrigation also reduced the Ravax index for all plots except the WT White variety at high-density.

In general, a high Ravaz Index suggests a more efficient production system, but at very high values it might not be possible to mature the crop (Kliewer & Dokoozlian 2005, Edwards et a. 2017). This suggests that the WT White variety may require canopy management or other management decisions not employed in this mixed trial to maximise efficiency. The lower index under reduced irrigation is a surprise, but is due to the lower yield, without a corresponding reduction in canopy in the standard-density planting and the higher vigour vines under reduced irrigation in the high-density plot. As noted above the high vigour of vines in the high-density plot may be a function of the irrigation management used (per vine) and carry over from that, even once irrigation was matched to row length.

There was also an effect of rootstock on the Ravaz Index, where M6262 had the highest value in both standard- and high-density plots (Figure 26). M6262 reduced yield in WT vines, but vigour was reduced still further; M6262 is known for low conferred vigour and was chosen for this reason. The effect of M6262 was still present under reduced irrigation, but the relative differences between rootstocks did not change.

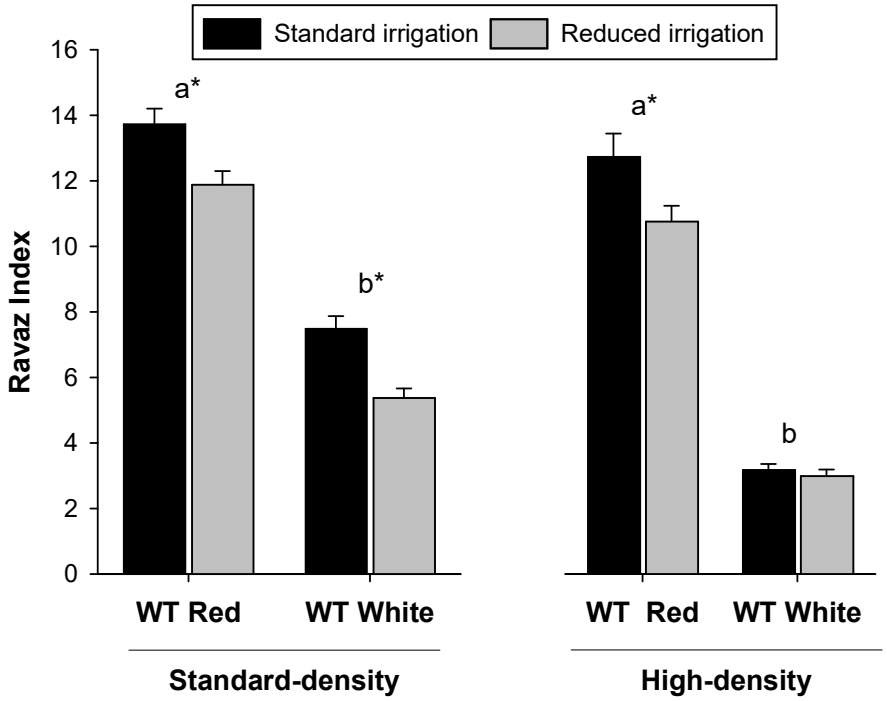


*Figure 25: the effects of density, irrigation and scion choice on four year mean of Ravaz index in WT vines. Data are means + SE, letters denote significant scion differences (p<0.05) and an * denotes a significant effect of irrigation (p<0.05).*

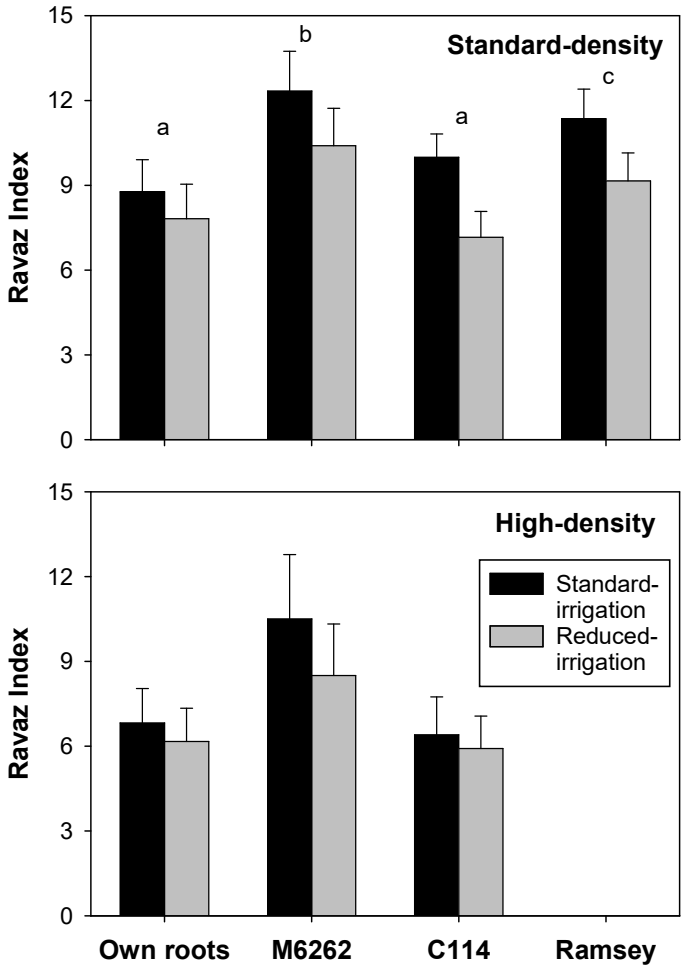


Figure 26: the effects of density, irrigation and rootstock choice on four year mean of Ravaz index in WT vines. Data are means + SE, letters denote significant scion differences (p<0.05.

Ultimately, it is canopy size and structure which determines the in-season productivity of the vine as the canopy is the site of photosynthesis. The Ravaz index is a retrospective measure of vine balance and can be difficult to compare year-to-year as the canopy size:pruning mass relationship can vary. Further it can't be used with vines that don't require pruning! In order to provide a comparison of vine balance between all the treatments, including the 'no-prune' MV vines canopy size was estimated as LAI_{app} and vine balance calculated as yield per unit canopy area. Canopy area was calculated as LAI_{app} multiplied by the vineyard floor area represented by a single vine, i.e. 3*2.12 m for standard-density and 1.5*1.27 m for high-density.

In contrast to the Ravaz index, this measure of vine balance was higher for the WT Red variety under standard irrigation than the standard-density and the WT White variety was unaffected by planting density (Figure 27). Despite the yield penalty of the 'no-prune' MV vines in

comparison with the WT vines the yield:canopy size relationship was equal to that of the WT vines and there was less effect of reduced irrigation.

This suggests that the 'no-prune' vine were as efficient in their production as the WT vines, but would require careful irrigation and other management to match the reduced yield with reduced inputs.

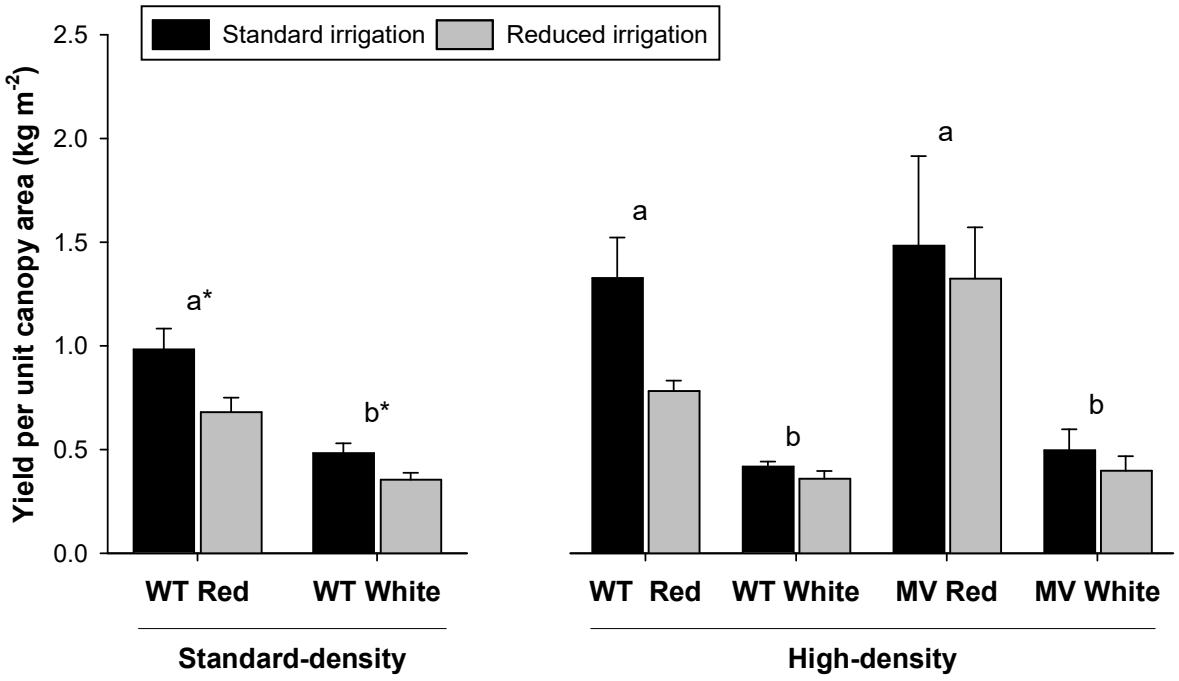


*Figure 27: the effects of density, irrigation and scion choice on the yield:canopy size relationship in the 2019/20 season. Data are means + SE, letters denote significant scion differences (p<0.05) and an * denotes a significant effect of irrigation (p<0.05).*

3.2.4 Irrigation use efficiency

A more direct way of looking at the efficiency of production, in reference to water as an input, is to estimate the irrigation water use efficiency (IUE); calculated as the yield per unit of water applied (kg kL^{-1}). There were large differences between seasons in the results, partly due to changes in the way irrigation was determined (per vine vs per row length), partly due to the carry-over effect of past damage on the 'no-prune' vines discussed above and likely a direct impact of different weather conditions between seasons. Figure 28 provides an overview of these changes, with the data averaged across two seasons according to the irrigation calculation method in the high-density plot. There was a change in the WT vines under standard irrigation in the standard-density plot, despite no change in irrigation (an average 4.5 kL per panel for 2020 & 2021 vs 4.9 kL per panel in 2018 & 2019), with an improvement of 31%. This was higher in the reduced irrigation treatment, a difference of 53%. However, the irrigation changes to the high-density plot overshadowed these, with an increase of 56

and 41% under standard irrigation for WT and MV vines respectively. Under reduced irrigation the changes were higher still, 103 and 83%.

When standard and reduced irrigation treatments were compared for other treatment combinations, the reduced irrigation treatment invariably had a higher IUE as any yield penalty observed was relatively less than reduction in irrigation applied. For the WT vines, the high-density planting resulted in a better IUE under reduced irrigation, but a poorer IUE under standard irrigation. This suggests improved water stress resilience in high-density plantings, but could be due to carry over effects from the previous high irrigation.

It is difficult to draw conclusions about IUE for the scion & rootstock genotypes as irrigation was applied the same, irrespective of potential demand and not optimised to the scion:rootstock combination. Under the irrigation applied, however, the WT Red scion had a better IUE than WT White, there was little difference between MV scions and the M6262 rootstock had the lowest IUE, followed by C114.

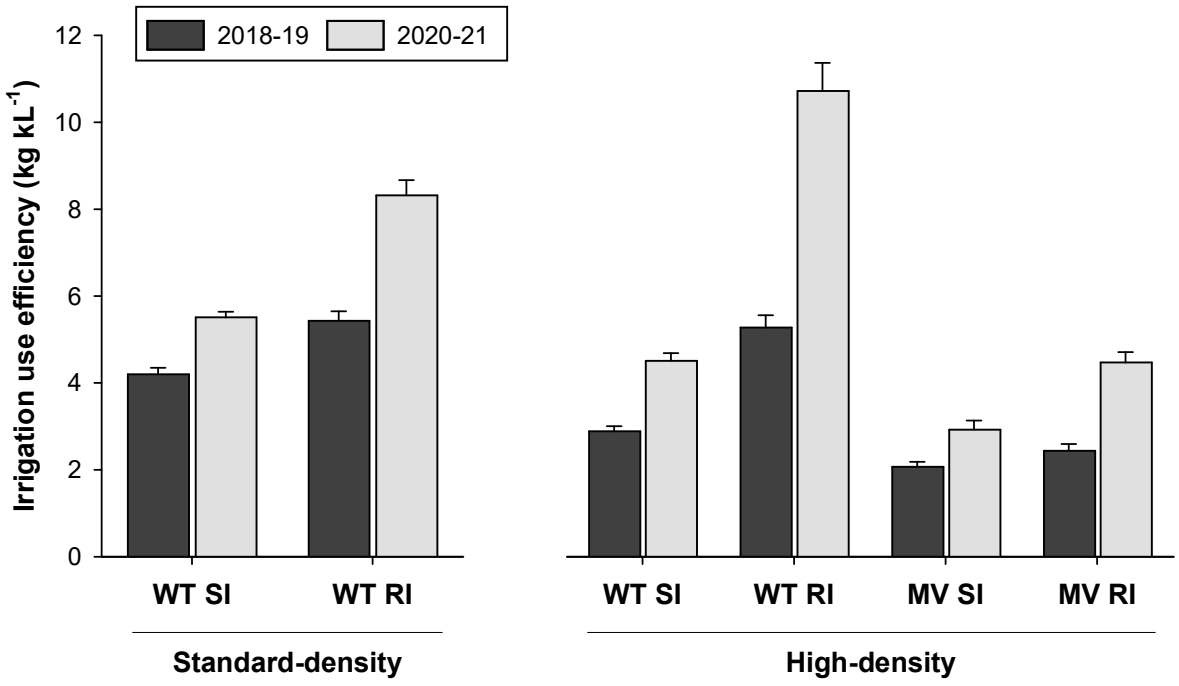


Figure 28: change in irrigation use efficiency between the first two seasons and the second two seasons of the trial for WT and MV vines under standard irrigation (SI) or reduced irrigation (RI). Data are means + SE.

3.3 Conclusions

Vine vigour and yield were affected by scion genotype, rootstock genotype, planting density and irrigation. However, the there were complex interactions with effects on vigour not

necessarily leading to concomitant changes in yield. This was particularly noticeable in the high-density planting, where higher vigour was not matched by higher yield. On the other hand, yield in the high-density planting was more resilient to reduced irrigation – although it is unclear if this was due to the higher irrigation provided.

The ‘no-prune’ MV vines had far lower vigour than the WT vines, as anticipated and far lower yield. However, irrigation and other management was not specifically matched to the MV growth habit (demonstrated by the higher soil water content) and when yield:vigour relationships were examined the ‘no-prune’ MV vines had similar or better production than the WT vines. This offers the prospect of a radical low-input vineyard with fruit production potentially at a cost-effective level with appropriate management.

Chapter 4: The effect of low input strategies on fruit and wine composition

A significant aim of the project was to assess the fruit produced from the various treatment combinations, both to demonstrate the suitability of the novel varieties for winemaking and to determine any potentially beneficial or deleterious effects of the treatments or their combinations for wine quality. Micro-vinification was for the first two seasons of the project, with small-lot winemaking used in the third, allowing sensory analysis to be undertaken as well as chemical analysis.

4.1 Fruit composition

Fruit were deemed to have reached maturity when juice TSS reached 22°Brix (24°Brix for small-lot winemaking in 2020). Due to the large number of treatment/genotype combinations and small scale of the individual plots this was only practical by taking a small sample of individual berries. Further, harvesting had to be undertaken in tranches, with groups of treatments at a similar level of maturity harvested together. Finally, maturation was slower in the 'no-prune' MV vines, meaning full maturity was not always reached before harvest was required for logistical reasons. As a result there were small differences in TSS in the harvest samples (Figure 29). The two white varieties achieved a little over 22.5°Brix on average during the four vintages of the trial, irrespective of planting density. The WT Red variety averaged around 20.5°Brix, but the MV Red averaged only 18.9°Brix, even when the 2018 vintage was excluded due to the sunburn problems described above.

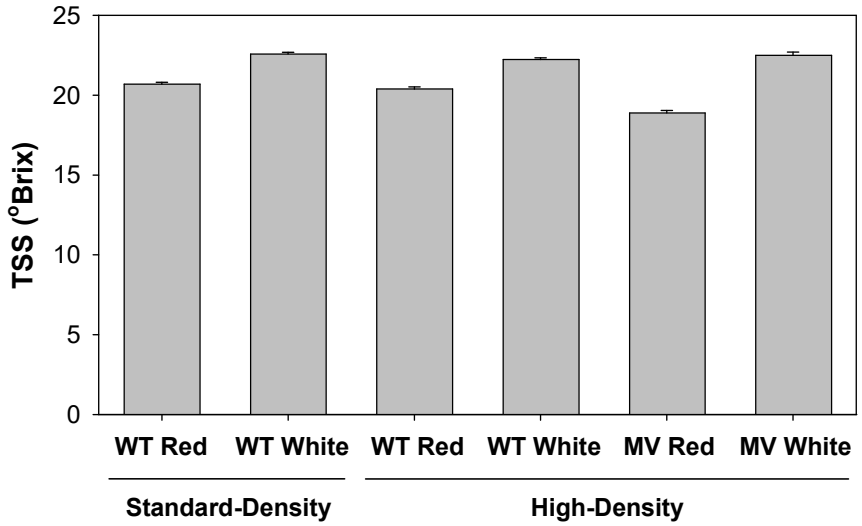


Figure 29: Four vintage mean (2018-2021) of total soluble solids concentration of berry samples at harvest for each scion variety. Data are means+SE.

There were interactions between scion genotype and other treatments on maturity at harvest, but these were not large. For example, planting at high density resulted in a mean decrease of 0.40°Brix for the WT White variety and 0.53°Brix for the WT Red variety relative to planting at standard density. Further, reduced irrigation caused a drop of 0.63°Brix on the WT Red variety, but had no impact on the WT White variety. In contrast, reduced irrigation resulted in a TSS 1-2°Brix higher in the 'no-prune' MV varieties.

A possible concern with the differences in TSS at harvest was that this would impact other aspects of fruit composition and suggest differences relevant for commercial winemaking that were not inherent, but due to different degrees of maturation at sampling. In particular, the concentrations of organic acids and anthocyanins are often correlated with TSS and are important considerations for wine quality. To test for this, TA:TSS and anthocyanin:TSS correlations were performed (data not shown). In the case of anthocyanins, no statistically significant correlation with TSS existed in any dataset, except where shaded and non-shade MV Red vines in 2020 were compared, so it is reasonable to conclude that the berry maturity between treatments was close enough that any differences were not caused by differences in maturity. For the TA:TSS relationship, there was only significant negative correlations for the two MV varieties. These explained only 37% and 28% of the variation in TA for red and white respectively and had a slope of approximately 0.5 g/L per °Brix. Consequently, whilst berry maturity may have had some effect on measured TA in the MV vines it would be fairly limited and there was no evidence for an effect on the WT varieties.

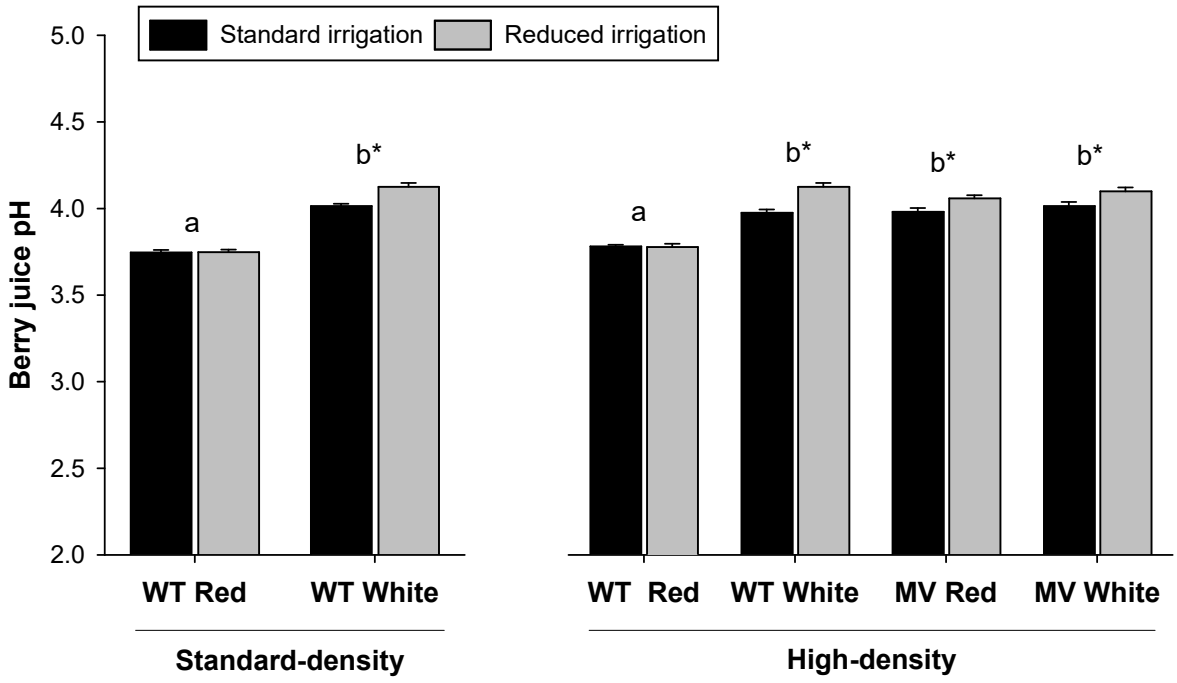


*Figure 30: Four-season mean of berry juice pH at harvest for each scion/management treatment combination. Data are means + SE, letters denote significant scion differences (p<0.05) and an * denotes a significant effect of irrigation (p<0.05).*

Juice pH at harvest had a range of only 3.7 to 4.1 across the entire data set. There was no effect of density on the WT scions, whereas reduced irrigation resulted in high pH for the 'no-prune' MV varieties and the WT White, but not WT Red (Figure 30). These effects did not match effects on TSS, so were unlikely to be maturity related. There was a significant effect of rootstock in the high-density plot, but not the standard-density plot, with own-roots having a lower pH than the other rootstocks. However, this was only 0.05 pH units and not likely to be meaningful.

Juice TA was highly inversely correlated to pH and exhibited the same treatment effects, albeit in reverse. Interestingly the WT Red variety appeared to have a different relationship to the others, with TA declining more rapidly with increasing pH (Figure 31). There was little overlap between the datasets, so a non-linear 'broken-stick' model was also possible.

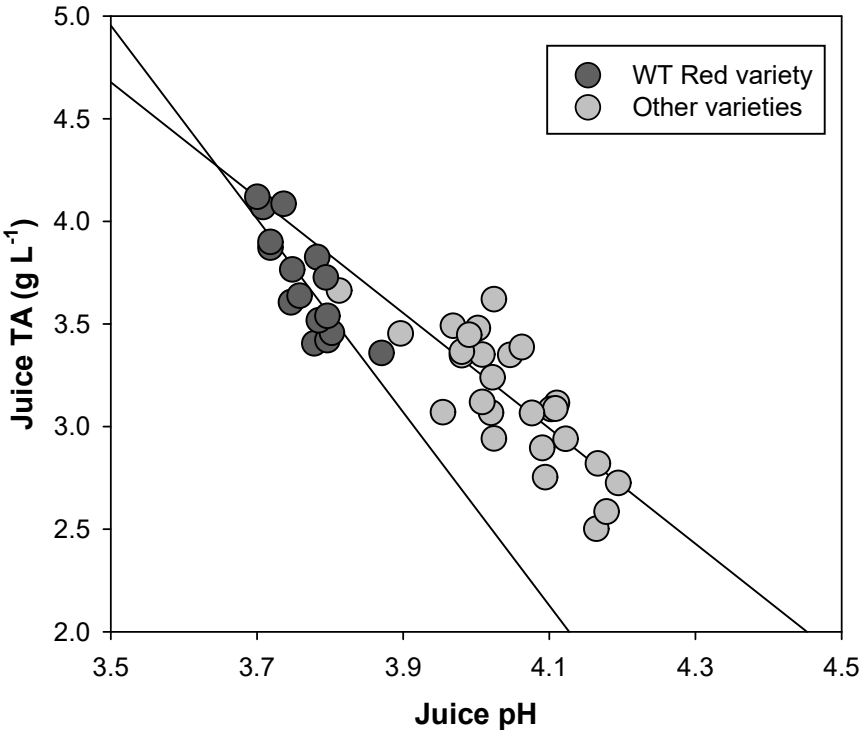


Figure 31: Relationship between berry juice pH and TA. Data are four-season means for each panel in each scion variety/management treatment combination. Lines denote separate regression fits for WT Red and all other data.

YAN was within recommended concentrations for low-risk ferments in all cases (AWRI 2022), with fairly complex interactions between the genotype*treatment combinations (Figure 32). For instance, the WT vines had lower YAN when planted at high-density than at standard-density, but the 'no-prune' MV vines had higher YAN than the WT vines. Reduced irrigation increased YAN in WT White vines, but only increased YAN in WT Red vines in the high-density

planting. The high-density planting would have received more fertiliser application per unit of row length (or ground area) than the standard density plot and both standard and reduced irrigation vines received the same fertiliser application, so this may play a part in some of the results. Petiole or blade nutrients were not examined so it is difficult to speculate further. There was also a rootstock effect, with vines at standard-density grafted to M6262 having about 10% lower YAN than vines grafted to other rootstocks. There was no significant effect at high-density however, possibly because of other limitations indicated in the lower YAN in WT vines at high-density.

In the standard-density planting the WT Red vines had higher anthocyanins with reduced irrigation, as often observed previously (e.g. Edwards & Clingeleffer 2013), but there was no significant effect of irrigation in the high-density plot (Figure 33). The 'no-prune' MV Red variety had higher anthocyanin concentration than the WT variety. There was also a rootstock effect under standard-density, but not high-density, planting, with own-rooted vines having about 15% lower anthocyanins than the C114 or Ramsey rootstocks (data not shown).

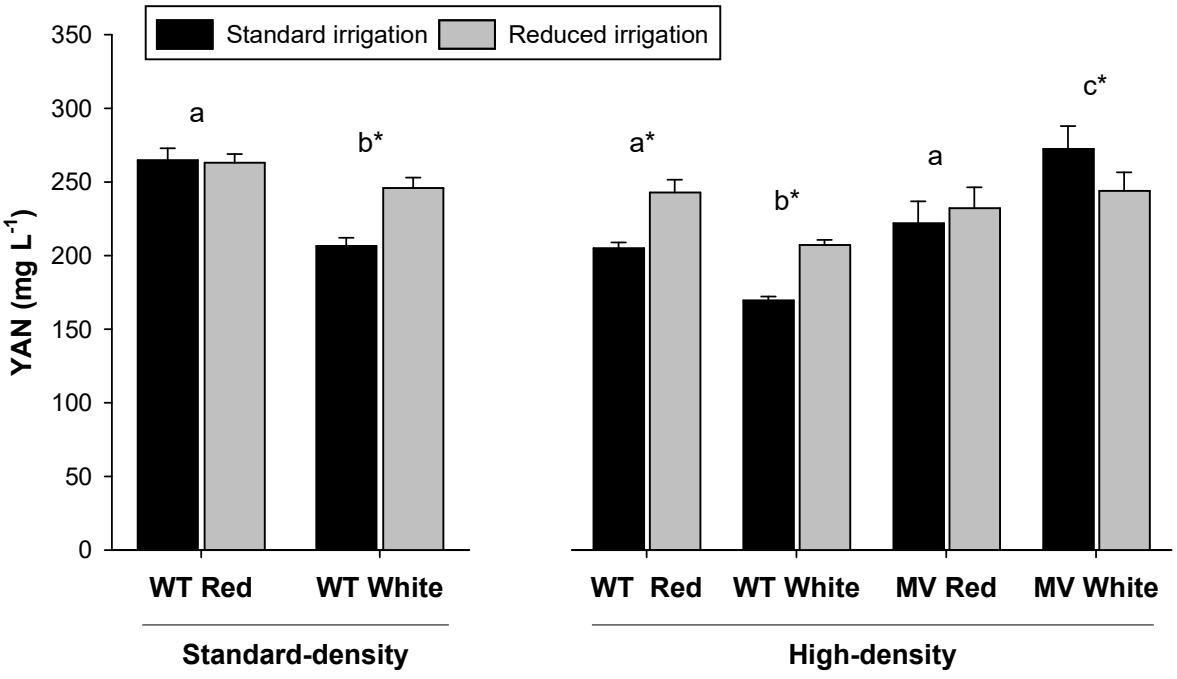


*Figure 32: Four-season mean of berry juice YAN at harvest for each scion/management treatment combination. Data are means + SE, letters denote significant scion differences ($p<0.05$) and an * denotes a significant effect of irrigation ($p<0.05$).*

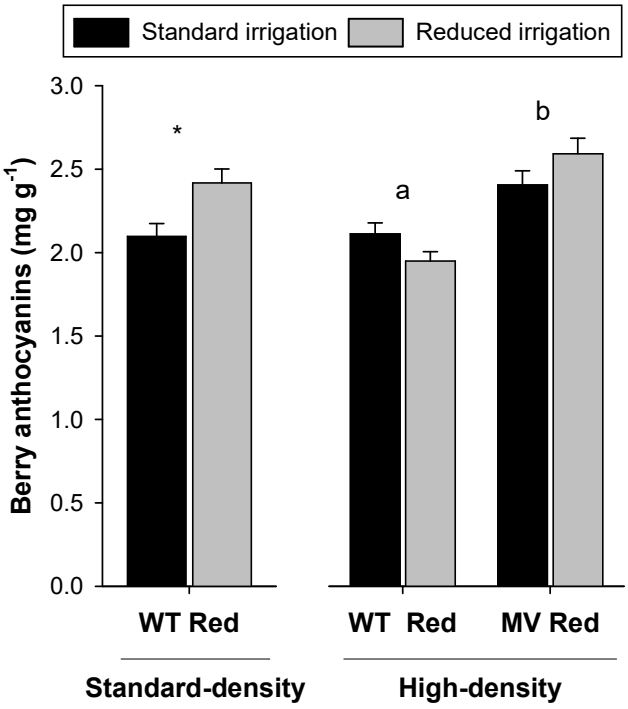


*Figure 33: Four-season mean of berry anthocyanins at harvest for each red fruit scion/management treatment combination. Data are means + SE, letters denote significant scion differences (p<0.05) and an * denotes a significant effect of irrigation (p<0.05).*

4.2 Wine composition

Fruit for micro-vinification in 2018 and 2019 were bunches selected during the harvest yield estimates and taken from multiple vines within the central panel of each replicate. The exception to this was the 'no-prune' MV vines in 2018 that suffered significant damage, bunches for these vines were individually selected from the vines throughout the five replicate panels for each genotype/treatment combination to ensure that undamaged fruit could be used. As 2018 was the first season of reduced irrigation and the damage to the 'no-prune' MV vines was greatest in the reduced irrigation treatments, no wines were made from the reduced irrigation treatments in 2018. A single micro-ferment per genotype/treatment combination was undertaken, with the four rootstocks providing replication at the scion level.

The micro-vinification in both seasons were successful in producing consistent wines with appropriate basic properties that did not indicate any difficulties for larger-scale winemaking (Tables 5 & 6).

In 2020 the COVID-19 pandemic reached Australia during the harvest period for the trial site. This interfered with scheduling of harvests, meaning that the target TSS concentration was missed in some cases. Further, the 'no-prune' MV vines had to be harvested using remotely

Table 5: Properties of wines produced in 2018 by micro-vinification. Data are means±SE, n=4.

	Scion	Ethanol (%)	pH	TA (g L^{-1})	Malic acid (g L^{-1})	Residual sugar (g L^{-1})	VA (g L^{-1})
Standard-density	**WT Red**	11.98±0.43	3.47±0.05	5.98±0.14	0.38±0.05	3.10±0.17	0.31±0.03
	WT White	12.73±0.44	3.23±0.04	7.10±0.17	1.83±0.13	3.45±0.09	0.16±0.01
High-density	**WT Red**	12.33±0.36	3.64±0.06	5.40±0.08	0.35±0.05	2.48±0.23	0.36±0.02
	WT White	13.23±0.13	3.34±0.09	6.53±0.15	1.8±0.15	3.33±0.43	0.20±0.04
	MV Red	10.98±0.49	3.97±0.03	5.30±0.08	0.62±0.05	1.78±0.1	0.33±0.03
	MV White	12.93±0.16	3.35±0.02	6.23±0.08	1.23±0.06	2.52±0.16	0.16±0.01

Table 6: Properties of wines produced in 2019 by micro-vinification. Data are means±SE, n=4.

	Scion	Ethanol (%)	pH	TA (g L^{-1})	Malic acid (g L^{-1})	Residual sugar (g L^{-1})	VA (g L^{-1})
Standard-density & irrigation	**WT Red**	13.78±0.46	3.73±0.05	6.03±0.36	0.3±0.04	2.75±0.12	0.41±0.04
	WT White	14.25±0.5	3.44±0.01	6.6±0.12	1.85±0.13	3.03±0.35	0.19±0.02
Standard-density & reduced irrigation	**WT Red**	12.8±0.57	3.64±0.09	6.15±0.18	0.33±0.11	3.08±0.24	0.43±0.02
	WT White	14.38±0.84	3.57±0.08	6.48±0.13	1.88±0.23	3.55±0.62	0.25±0.02
High-density & standard irrigation	**WT Red**	14.1±0.28	3.85±0.05	5.55±0.09	0.25±0.06	2.28±0.11	0.44±0.01
	WT White	13.57±0.58	3.45±0.07	6.73±0.09	2.33±0.26	3.23±0.46	0.22±0.02
	MV Red	12.37±0.64	3.97±0.06	5.33±0.12	0.2±0.06	1.2±0.21	0.25±0.03
	MV White	13±0.29	3.49±0.06	8.48±0.41	3.78±0.34	1.38±0.46	0.32±0.01
High-density & reduced irrigation	**WT Red**	13.08±0.25	3.62±0.09	5.93±0.22	0.33±0.08	2.78±0.3	0.4±0.02
	WT White	13.63±0.7	3.47±0.1	6.5±0.12	2.03±0.18	2.93±0.52	0.22±0.02
	MV Red	11.9±0.36	3.93±0.01	5.3±0.06	0.2±0	1.43±0.12	0.32±0.01
	MV White	13.65±0.23	3.41±0.04	7.35±0.5	2.25±0.32	2.55±0.61	0.23±0.04

organised contractors when they were available. As a result samples weren't available (see above) and MV Red variety had to be harvested before the target TSS concentration was reached. The WT Red wines successfully achieved the intended winemaking outcome, but the

white varieties had excessive alcohol and the MV Red variety was under-ripe with low alcohol (Table 7).

The 2018 and 2020 red wines were also analysed for phenolics. The small-lot wines from 2020 had higher colour density (ionised anthocyanins) and higher total anthocyanins than the micro-ferment wines from 2018 (Figure 34), presumably due to better extraction during pressing. However, there was little evidence for major differences in colour with planting density or irrigation. Unfortunately in both 2018 and 2020 the 'no-prune' MV fruit used had not reached the target TSS and thus the wine colour is potentially an underestimate of what would be achieved at full maturation

The AWRI were engaged to assess the small-lot wines and undertook a preliminary tasting on 17-19th February 2021. The consensus was that the white wines were difficult to judge due to the high-alcohol content and atypical of the intended wine style as a result. The 'no-prune' MV wines were low alcohol and had a range of unripe flavours, with the lowest alcohol wines being fairly sour. Consequently, formal difference was only carried on the WT Red wines and compared

*Table 7: Properties of wines produced in 2020 with small-lot winemaking. Data are means±SE, n=2. * denotes n=1, nd = none-detectable*

	Scion	Ethanol (%)	pH	TA ($g\ L^{-1}$)	Malic acid ($g\ L^{-1}$)	Residual sugar ($g\ L^{-1}$)	VA ($g\ L^{-1}$)
Standard-density & irrigation	**WT Red**	13.95±0.05	3.45±0.03	5±0.1	0.06±0	0.2±0.2	0.63±0.02
	WT White	15.7±0.1	3.42±0	5.45±0.05	1.36±0.02	1.4±0.1	0.31±0.01
Standard-density & reduced irrigation	**WT Red**	13.3±0.8	3.37±0.03	5.7±0.1	0.08±0.02	nd	0.59±0.01
	WT White	15.5±0.2	3.43±0.02	5.35±0.05	1.08±0.05	0.9±0.1	0.27±0.01
High-density & standard irrigation	**WT Red**	14.3±0.1	3.46±0.03	5.15±0.15	0.03±0.03	0.2±0.2	0.57±0.01
	WT White	15.6±0.4	3.39±0.05	5.85±0.05	1.37±0.03	0.45±0.05	0.33±0.01
	MV Red	9.3±0.7	3.56±0.06	4.95±0.15	0.03±0.03	nd	0.45±0.04
	MV White	13.05±0.85	3.34±0.02	5.35±0.45	1.59±0.7	0.75±0.35	0.37±0.01
High-density & reduced irrigation	**WT Red***	13.9	3.43	5.25	0.06	0.2	0.55
	WT White	15.6±0.4	3.49±0.03	5.5±0	1.24±0.15	1±0.5	0.25±0.04
	MV Red	10.3±1.6	3.59±0.04	4.95±0.05	0.03±0.03	nd	0.51±0.06
	MV White	14.2±1.6	3.42±0.04	4.85±0.35	1.21±0.49	2.1±1.4	0.38±0.04

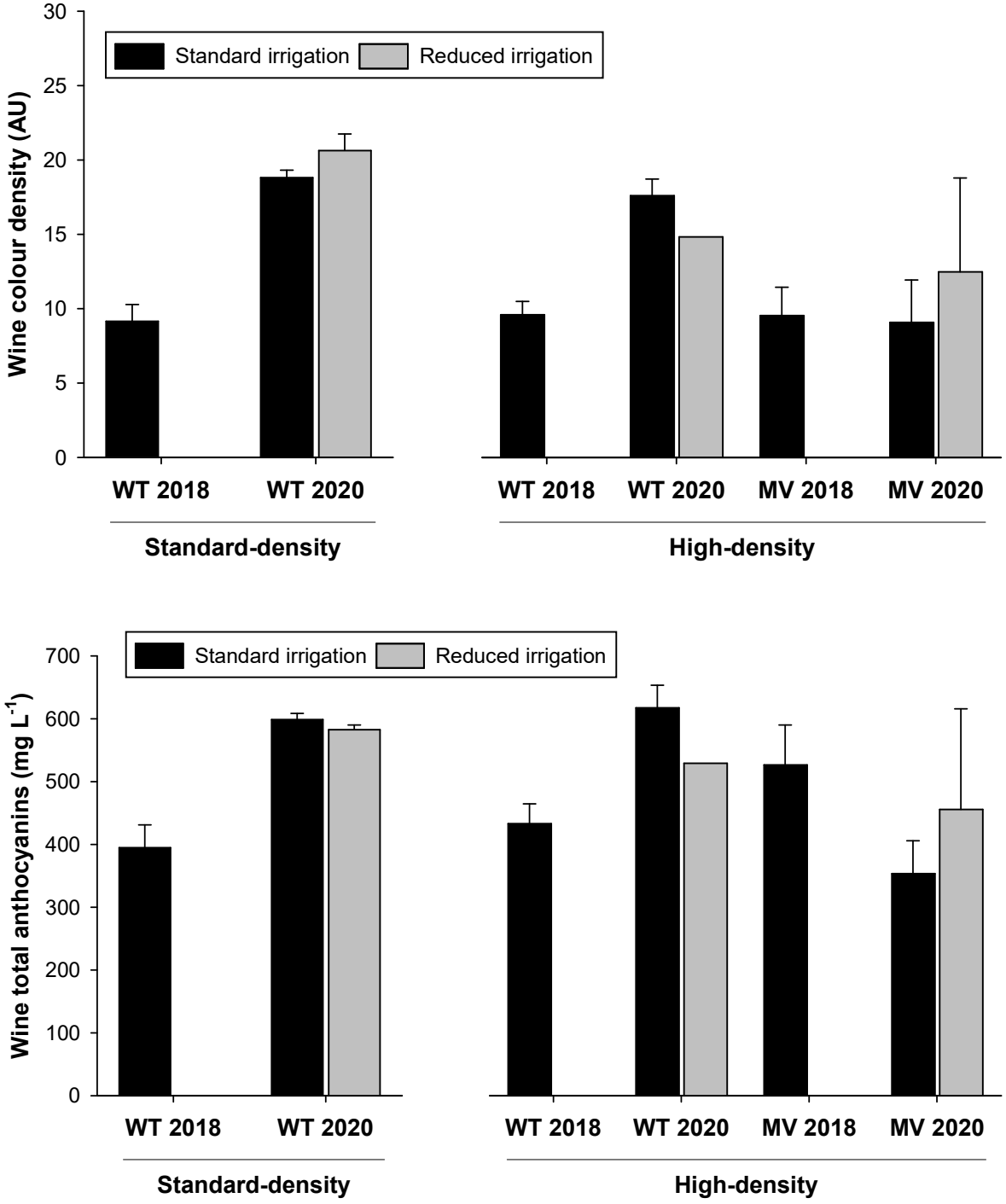


Figure 34: Wine colour density (top) and total anthocyanin concentration (bottom) for the WT and 'no-prune' MV wines from 2018 and 2020 for each management treatment combination.

the standard/reduced irrigation and standard/high-density planting using triangle testing (report is at Appendix 5.X).

The panel correctly differentiated the standard from the high-density planting at standard irrigation (p=0.01), but no other comparisons. Two comparisons were weakly significant

($p<0.1$), high-density standard irrigation vs reduced irrigation and high-density vs standard-density at reduced irrigation.

An informal ranking was undertaken at CSIRO, with three-quarters ranking the standard density reduced irrigation highest amongst the reds and the high-density, standard irrigation the lowest (data not shown). Within the whites, standard-density, full irrigation wine was ranked highest.

4.3 Conclusions

Overall differences in the fruit at harvest due to the treatments imposed were not large and it appeared even these weren't necessarily passed on to differences in the wines. Whilst it was difficult to get the 'no-prune' MV vines to the target TSS in all seasons, none of the varieties used had any problems producing wines with acceptable chemistry. The lack of significant differences in the wines suggests that any input cost savings made by using these varieties or the management strategies trialled are not likely to be lost through problems with vinification.

Chapter 5: Economic assessment of low input strategies

The trial site utilised for this project included four novel 'no-spray' scion varieties that are resistant to grapevine mildews and do not require fungicide sprays. The resistance is multi-genic and is due to having *Muscadinia rotundifolia* in the breeding background for these scions. Two of those varieties were also 'no-prune' varieties that do not require pruning due to their 'microvine' growth habit. This is the result of a single gene allele mutation which makes the vines insensitive to gibberellic acid, a plant hormone that influences cell expansion (Boss & Thomas 2002). Use of these varieties not only represents a positive environmental impact (less use of agrochemicals, fewer tractor passes), but also provides a significant cost saving for vineyard management.

This chapter examines those cost savings - together with savings from reduced irrigation and the impact of high-density planting on costs - comparing them with potential crop value and assessing the impact of the various management strategy/genotype combinations employed in this trial.

The input costs considered were:

- pruning,
- fertilizer,
- fungicidal sprays,
- weed and pest control,
- inter-row and vineyard floor management,
- irrigation,
- harvest.

Being a specifically established bespoke research trial plot most of these costs were atypical of regional industry costs, so in some cases the costs have been considered both as the actual costs incurred and as expected costs at a commercial scale. The establishment costs for the vineyard block were provided in a previous report to Wine Australia (Thomas & Hassan, 2017).

Pruning was undertaken by hand using local contractors at $30 per hour +GST. As prunings from each panel were also collected and weighed, the total cost was somewhat higher than would be expected for a commercial block. The time taken per vine was approximately five man-minutes and equated to $2.81 per vine; $6,000-$12,000 per hectare depending on planting density. Commercial spur pruning cost of $1 per WT standard-density vine and $0.75 per WT high-density vine were assumed, equivalent to $1,575 and $4,000 per hectare respectively.

Irrigation of the block actually used town water, with a cost of $3,410 per ML, but for the purposes of this chapter irrigation has been costed as if provided through Barossa Infrastructure Ltd (BIL) at the 2019 cost of $820 per ML. Irrigation volumes varied by season, planting density and irrigation treatment, ranging from 1.16 ML ha^{-1} for the reduced irrigation

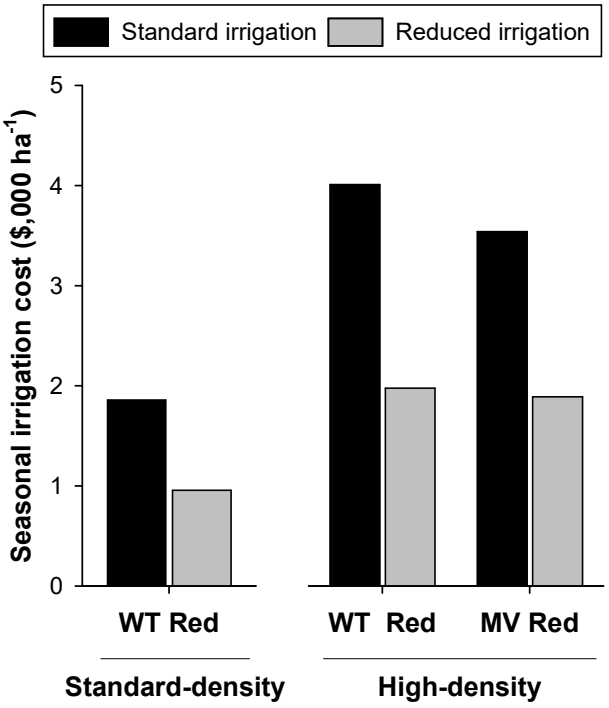


Figure 35: estimated cost of irrigation for the WT and 'no-prune' MV vines under the trial management combinations in 2019/20 using commercial irrigation water.

standard-density plot in 2019/10 to 8.98 ML ha^{-1} for the standard-irrigation high-density WT vines in 2017/18. This equated to an irrigation water cost of \$955 to \$7,400 ha^{-1}. Estimated cost in 2019/20, once irrigation in the two planting densities had been adjusted to the same volume per unit length of row (Figure 35), indicated savings under reduced irrigation of \$796 ha^{-1} for the standard-density WT vines, \$2,884 ha^{-1} for the high-density WT vines and \$2,129 ha^{-1} for the 'no-prune' MV vines.

Fertilizer application was through irrigation system, provided by the site management (SARDI) and charged only at the cost of the chemicals used. Fertilizer application rates were high during vineyard establishment to ensure success of the hand-grafted vines and reduced from 2018/19 onwards, equating to approximately \$0.02 per vine per season; \$30-80 per hectare, depending on planting density.

Fungicidal spray were not used at any time during the trial and no mildew was observed at any time. For consideration with commercial practice, spraying costs were considered at local contractor rates for the season including fungicidal, systemic, sulphur and copper sprays. This was estimated at \$532 per hectare (Alex Sas, pers. com.).

Weed and pest control was undertaken by the site management and required equipment that could navigate the high-density planting row width of 1.5m. Costs varied by season, varying between \$1,800 and \$8,000 per hectare. As with the pruning this was significantly higher than commercial practice due to the nature of the research trial planting.

The inter-row and vineyard floor management was also undertaken by the site management and again was higher than commercial practice for the aforementioned reasons. Costs equated to $5,000-6,000 per hectare per season.

Harvest was undertaken by hand using a local contractor was costed at $30 per hour. Each panel was harvested individually, weighed and in 2017/18 and 2018/19 individual panel bunch counts were also made. Time taken to harvest a single vine was approximately 19 minutes for the standard-density planting, 13 minutes for high-density WT vines and 15 minutes for 'no-prune' MV vines. This equated to between $15,000 and $40,000 per hectare depending on density and vine type. Clearly, this is higher than would be expected for hand-harvesting at a commercial scale and far higher than the cost of machine harvesting. Note that the 'no-prune' MV vines cannot be machine harvested as they would likely be severely damaged by the beater bars.

The value of the crop cannot be directly determined as these novel varieties are not yet commercially available. For comparison purposes typical fruit value in the region for Shiraz and Sauvignon Blanc were used for the red and white varieties respectively. These were $2,300 per tonne for Shiraz and $950 per tonne for Sauvignon Blanc (Alex Sas, pers. Com.). The per hectare three-season mean yield used for standard irrigation, standard-density WT vines was 12.3 t ha^{-1} for red and 11.1 t ha^{-1} for white, this is higher than the average yield per ha^{-1} in the Barossa for Shiraz, which would likely impact the potential value of the crop, but for this simple economic modelling that has been ignored. Figure 36 provides the three-season mean comparison crop value between 2017/18 and 2019/20.

When all of the actual costs of the research plot are used, including town water and all manual management, not surprisingly none of the genotype/management strategy combinations would have made a profit, with the high-density, reduced-irrigation WT Red variety making the smallest loss ($2,500 per ha^{-1}). The largest losses were made by the two white varieties in the high-density planting due to the lower crop value estimate for whites ($62,000 and $61,000 per ha^{-1} for the 'no-prune' MV and WT respectively).

A second estimate of margins was made using the same crop values, but with actual fertilizer costs, commercial costs for actual irrigation, and commercial costs for pruning (i.e. without including harvesting or floor management). This produced margins of $24,700 and $6,800 per ha^{-1} for red and white WT varieties respectively under standard conditions. Under standard density, the margin was lower with reduced irrigation as the water saving didn't make up for the crop reduction, but under high-density this was only the case with the 'no-prune' MV Red variety (Figure 37). The other varieties had much higher margins under high-density, but of course this doesn't take account of the doubled harvesting costs. Furthermore, whereas the WT vines could be machined picked in the high-density plot with an appropriate harvester, the 'no-prune' vines could not be and would necessarily have the higher cost of hand-picking.

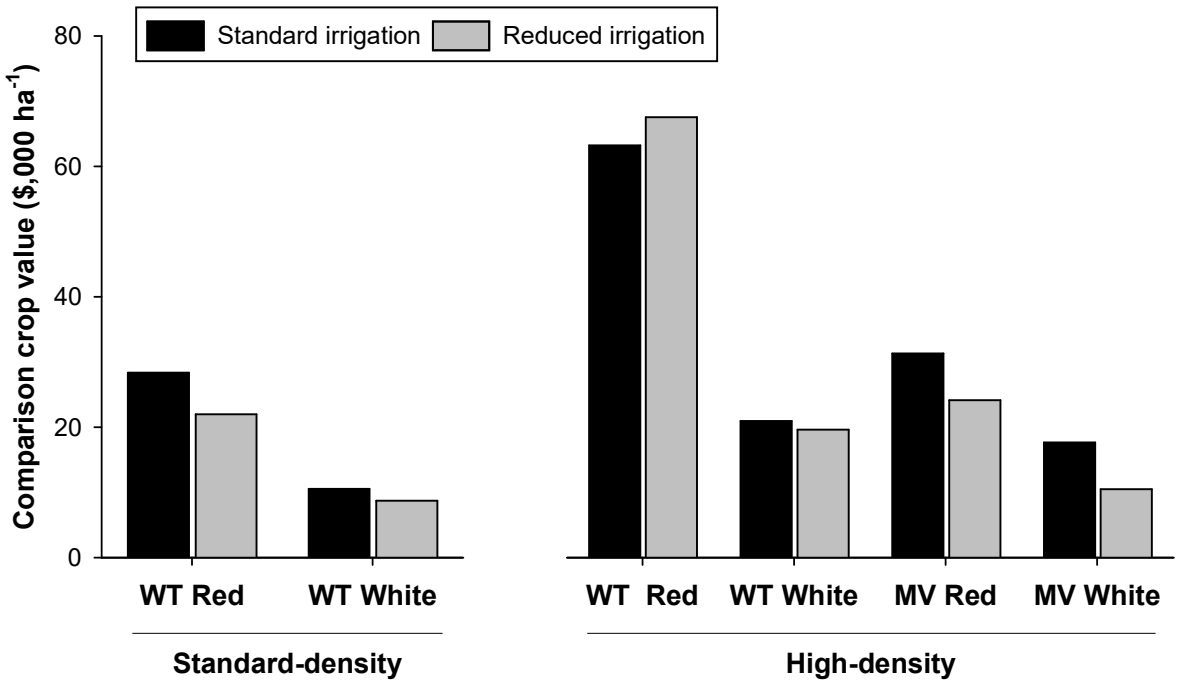


Figure 36: Comparison value of trial fruit based on typical Barossa red and white fruit prices and the three season mean yield results (2018-2020).

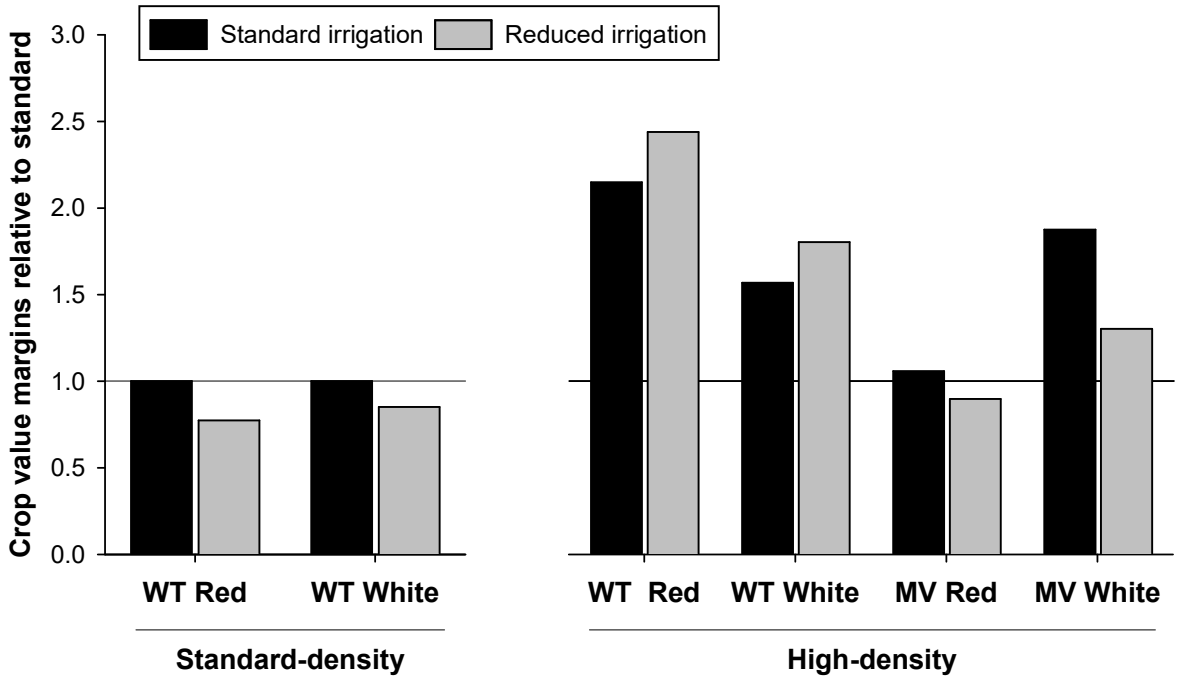


Figure 37: Estimated margin of production, excluding harvest and under vine management costs, relative to the standard management practice on typical Barossa red and white fruit prices and the three season mean input and production data (2018-2020).

The scale of the difference in margins for the WT Red and WT White varieties in the high-density plot leave a very significant window for the increased harvest costs and still generate higher profit. Whilst the crop values are admittedly nominal, the margin for the WT Red under high density was \$28,000 ha^{-1} under standard irrigation and \$41,000 under reduced irrigation. With those values, and assuming a doubling for high-density costs (i.e. the same harvesting cost per unit row length) harvesting and floor management would have to cost \$14,000 ha^{-1} under standard conditions to make the high-density less profitable than the standard density. Even with a fruit value of only \$700 t^{-1} and a harvesting cost of \$4,000 ha^{-1}, the high density WT Red fruit would have make a higher profit than under standard production conditions (data not shown).

Whilst these commercial production figures are clearly highly speculative, they do indicate that input efficiencies from higher density planting have the potential to increase growers profit margins. On the other hand, the reduced irrigation treatments would require the fruit value to be higher than under standard irrigation in order to increase profit margins. Berry and wine colour was improved with reduced irrigation under standard density, but not under high-density. Evidence that fruit composition was changed by reduced irrigation, which could potentially lead to more sought-after fruit.

Interestingly, the margin for the 'no-prune' MV Red vines, excluding harvest costs, was as good as the WT Red under standard conditions and the margin for MV White was improved, relative to WT White, despite the significantly lower yield of these vines. As irrigation application wasn't adjusted to their specific use (higher soil moisture) and those vines were yet to fully fill the cordon wire at the end of the project, it is likely that the potential margin of these vines would further increase with time.

Chapter 6: The use of canopy temperature sensors to assess irrigation need

The wide range of genotypes and vine management strategies, including irrigation differences, in the trial made it an ideal test-case for assessing the use of canopy temperature sensors in irrigation management. Canopy temperature is primarily a function of the air temperature, the received radiation (sunlight) and the rate of transpirational water loss from the leaf surface. If two vines are in the same environment (sunlight, air temperature), then any differences in canopy temperature will be the result of differences in transpiration. Leaf transpiration is itself a function of the evaporative demand of the air and the resistance provided by the stomatal pores on the leaf surface. Again, if two vines are in the same environment (evaporative demand of the air) then any differences in canopy temperature will be results of differences in stomatal opening. Whilst vine control of stomatal opening integrates a variety of factors, from day-to day a major factor will the water status of the vine. Consequently, by comparing leaf temperature differences to atmospheric characteristics (temperature, humidity), it is possible to infer information about vine water status. This can, in turn, be used to determine irrigation strategy.

Initially, this component of the work used leased 'ArduCrop' sensors from the High Resolution Phenomics Centre based within CSIRO in Canberra (Jones et al. 2018). The ArduCrop is a point-based non-contact long-wave infrared thermal sensor that can continuously log canopy temperature. A difficulty with this type of sensor is the sample size of canopy from which the temperature estimated. A sensor with a larger field of view will have a mixed signal that could include soil, trellis infrastructure, sky etc., whereas a sensor with a smaller field of view will sample only a very small section of canopy (possibly a single leaf), that is unlikely to be representative of the canopy as a whole. The compromise used with the ArduCrop still required significant post-processing of the data that was partly manual. Consequently, it was decided to develop a novel device that utilised a low cost, low-resolution thermal sensor in tandem with an RGB sensor and utilised data fusion and image segmentation to select canopy only pixels for the temperature measurement. The development of this sensor was transferred to Wine Australia project CSA1701-3.1 and will be reported on as part of that project.

Despite the difficulties with processing and assessing the ArduCrop data, successful results were obtained for the fruit maturation period in the 2017/18 season for which the devices were deployed. Three to four devices were set up in the trial block for each of the scion genotype/treatment combinations (Figure 38) and these recorded canopy temperature data at five-minute intervals from late December until mid-March.

The canopy temperature data were collated for each scion genotype/treatment combination and the average temperature per combination compared (Table 8). In all cases except the



Figure 38: ArduCrop devices set up in trial plot, 2018.

*Table 8: Mean canopy temperature during the maturation period of each scion/planting density combination and mean of each treatment relative to the standard irrigation vines in that planting density. *relative to standard-density mean temp.*

Density	Scion	Mean canopy temperature (°C)		Temperature differential (°C)	
		Standard-irrigation	Reduced-irrigation	Standard-irrigation	Reduced-irrigation
Standard-density	**WT Red**	21.8	22.2	--	0.46
	WT White	22.7	22.9	--	0.19
High-density	**WT Red**	20.9	22.0	-0.85*	1.04
	WT White	21.2	22.0	-1.43*	0.75
	MV Red	21.0	22.5	--	1.45
	MV White	21.5	21.2	--	-0.28

'no-prune' MV White scion, canopy temperature was high under reduced-irrigation, suggesting that vine water status was lower. Interestingly, when the standard and high-density vines were compared, the high-density canopy temperatures were lower, indicating less stress. Figure 39 demonstrates these differences for the WT Red variety treatments relative to the standard management.

Overall, each scion/treatment combination closely tracked air temperature and there was no difference between them in how they did this (i.e. the time between changes in air temperature and leaf temperature were the same for all treatments), consequently,

scion/treatment differences in canopy-air temperature difference matched the differences in absolute canopy temperature above (data not shown).

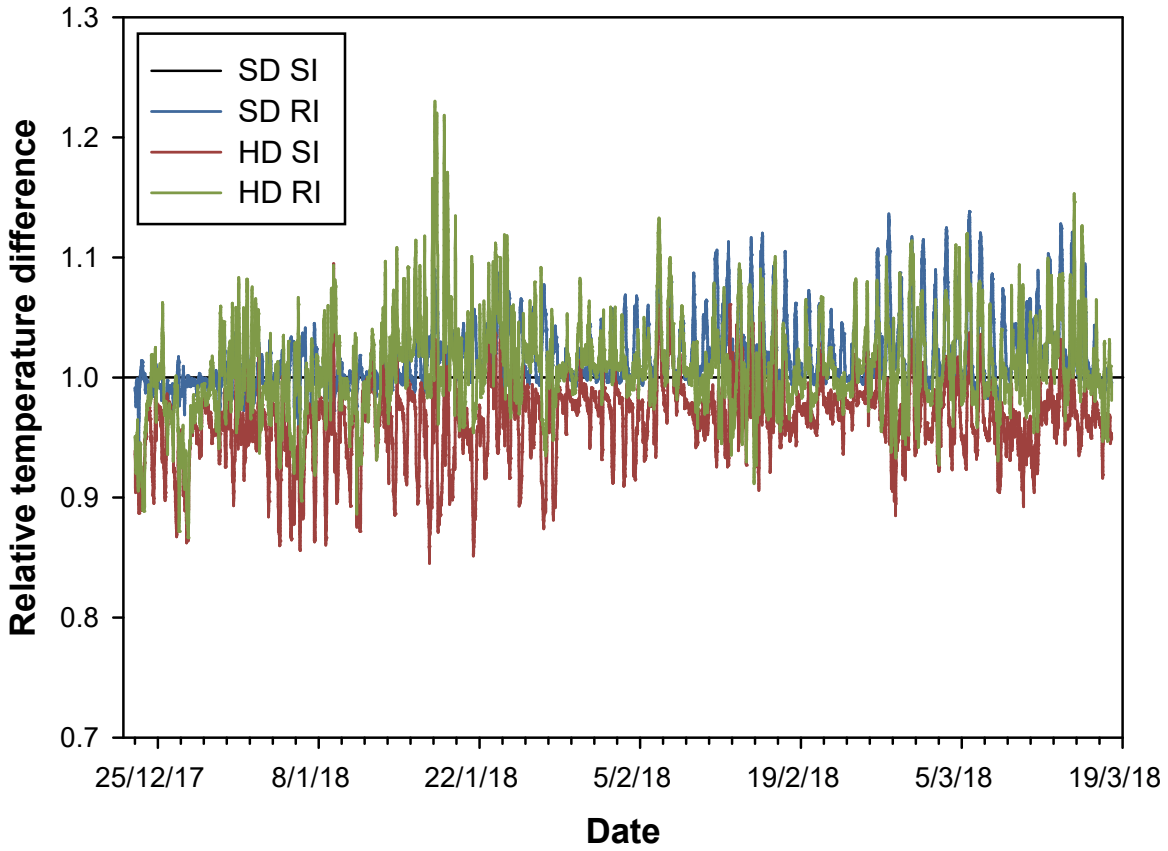


Figure 39: Canopy temperature relative to standard-density standard irrigation canopy for WT Red scion management treatment combinations. Data are plotted at 5 minute intervals and are means of four sensors.

As noted above, the canopy to air temperature difference depends on the evaporative demand of the air, low evaporative demand will result in low transpiration rates and thus a small difference between canopy and air temperature, high evaporative demand the reverse. Consequently, we would expect differences at night to be less than day and cool damp days to be different to hot dry days. It can be seen from Figure 39 that the treatment differences for the WT Red variety depend on time of day and vary between days. The same was true for the other varieties (data not shown). This doesn't mean that the vine stress necessarily varied in the same way or that vine irrigation requirements changed on the same time scale. In January 2018, there were extreme differences in weather conditions, just two days apart in time. No irrigation occurred between these dates, yet the canopy to air temperature and treatment to treatment relationships did not match (Figure 40). This illustrates the complexity in understanding how canopy temperature varies in relation to vine water status, but the data

also illustrates that, even over short timescale, leaf to air temperature differences do depend on vine water status (Figure 40 top).

In summary, even with the limitations of the sensors employed in this trial, the data support the potential for using canopy temperature to assess vine water status and thus inform irrigation scheduling.

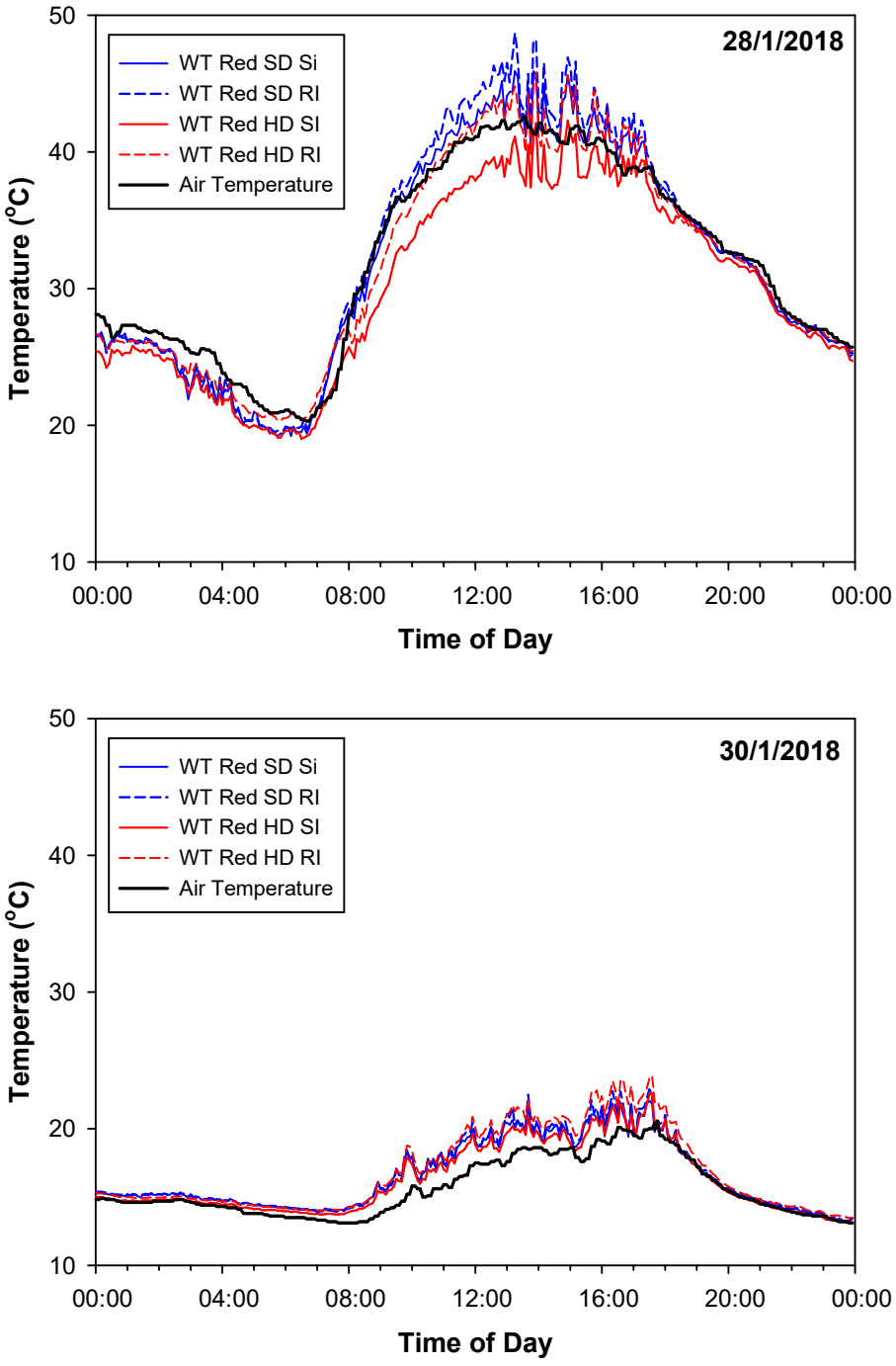


Figure 40: Canopy temperature plots for two contrasting days in January 2018 of WT Red scion canopies for each management treatment combination. Data are plotted at 5 minute intervals and are means of four sensors.

Appendix 1: Communication

This project has assessed CSIRO breeding material not available to the public and was ended prior to the originally contracted end date. As such communication has remained within CSIRO and Wine Australia.

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Appendix 2: Intellectual property

No patents were taken out during the term of this project. New CSIRO plant selections, rootstocks and scions, used in this project have not been released to the public.

Canopy temperature sensors used or developed during this project are protected CSIRO or project IP.

Information generated by this project will enter the public domain and will be accessible for future reference.

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Appendix 3: References

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Appendix 4

Project staff

Chief Investigators

Dr Everard Edwards from 2019

Dr Mark Thomas to 2019

Principal Investigators

Dr Mahmood Hassan

Dr Ian Dry

Administration

Mr Shane Wynn

Acknowledgements

CSIRO: Pat Corena is thanked for conducting the micro-vinification and assistance with Oenofoss measurements, Alex Lawlor is thanked for assisting with fieldwork in the 2020/21 season and Rosanna Powell is thanked for her assistance with processing berry samples.

SARDI: Mike McCarthy, Paul Petrie and particularly Roger Maywald are thanked for their assistance in establishing the project an maintaining the vineyard trial block. This research would not have been possible without SARDI providing land for the trial site and access to on-site facilities.

This research was supported by funding from Wine Australia. Wine Australia invests in and manages research, development and extension on behalf of Australia's grape growers and winemakers and the Australian Government.

Appendix 5: Other material

Appendix 5.1: AWRI report

The Australian Wine Research Institute

AWRI COMMERCIAL SERVICES
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Sensory Evaluation Difference Test Report

Attention:	**Everard Edwards**	
Samples Received:	16-04-2021	Report Date: 27-04-2021
Analysis Report:	Desireé Likos	

1. Introduction

The aim of this study was to determine whether there was a significant sensory effect for red wine made from either low or high density vines, or full or half irrigation, in a vineyard planted with a wild-type (WT) CAS grape variety. The samples were assessed to determine if there was a significant irrigation or density effect across the treatments.

2. Materials and Methods

The balanced reference triangle test was applied, following the Australian Standard: Sensory analysis of foods - Specific methods – Triangle Test AS 2542.2.2. The triangle test is a forced choice test and is not valid for determining preferences, nor the character or degree of any perceived difference.

Desireé Likos and Eleanor Bilogrevic were the test supervisors, and the tests were carried out on 23 and 30 April 2021.

There were two fermentation replicates of each treatment, and a preliminary sensory assessment of all replicates was conducted prior to the difference test, with a panel of eight experienced wine sensory assessors: four from the AWRI Technical quality sensory panel, two members of the CSIRO research team closely involved in the project, as well as two members of the AWRI sensory group. No winemaking faults or off-flavours were evident in any of the wines. All treatment replicates were found to be similar, except for the WT Low Density Half Irrigation R2 sample, which had lower than expected alcohol concentration. From this initial screening, a single replicate from each treatment was selected for the final difference testing assessment. The wines were considered suitable for an aroma and palate assessment, using sodium lighting to mask any slight colour differences. Details of the wines tested are outlined in Table 1.

3. Results

Tables 2 and 3 show the results from the triangle tests completed.

In the comparison assessing the irrigation effect (Table 2), there was weak evidence (*P*=0.06) that a difference existed between the High Density Half Irrigation R1 vs. High Density Full Irrigation R1 wines. There was no clear evidence that a difference existed between the Low Density Full Irrigation R1 vs. Low Density Full Irrigation R2 wines.

Table 2: Results of the triangle tests completed assessing the irrigation effect.

Comparison	No. of responses	Correct responses	Significance[1]
High Density Half Irrigation R1 vs. High Density Full Irrigation R1	31	15	ns (*P*=0.06)
Low Density Half Irrigation R1 vs. Low Density Full Irrigation R2	31	14	ns

[1] where ns = not significant.

In the comparison assessing the density effect (Table 3), there was weak evidence (*P*=0.07) that a difference existed between the High Density Half Irrigation R1 vs. Low Density Half Irrigation R1 wines. Contrastingly, there was strong evidence (*P*=0.01), that a difference existed between the High Density Full Irrigation R1 vs. Low Density Full Irrigation R2 wines.

Table 3: Results of the triangle tests completed assessing the planting density effect.

Comparison	No. of responses	Correct responses	Significance[1]
High Density Half Irrigation R1 vs. Low Density Half Irrigation R1	34	16	ns (*P*=0.07)
High Density Full Irrigation R1 vs. Low Density Full Irrigation R2	34	19	0.01**

[1] where ns = not significant, *=*P*<0.05, **=*P<0.01*.

There were no useful comments provided by the judges.

Table 1. Details of the WT CAS wines assessed.

Wine	Code
Low Density Half Irrigation R1	2016-01
Low Density Full Irrigation R2	2016-04
High Density Half Irrigation R1	2016-05
High Density Full Irrigation R1	2016-07

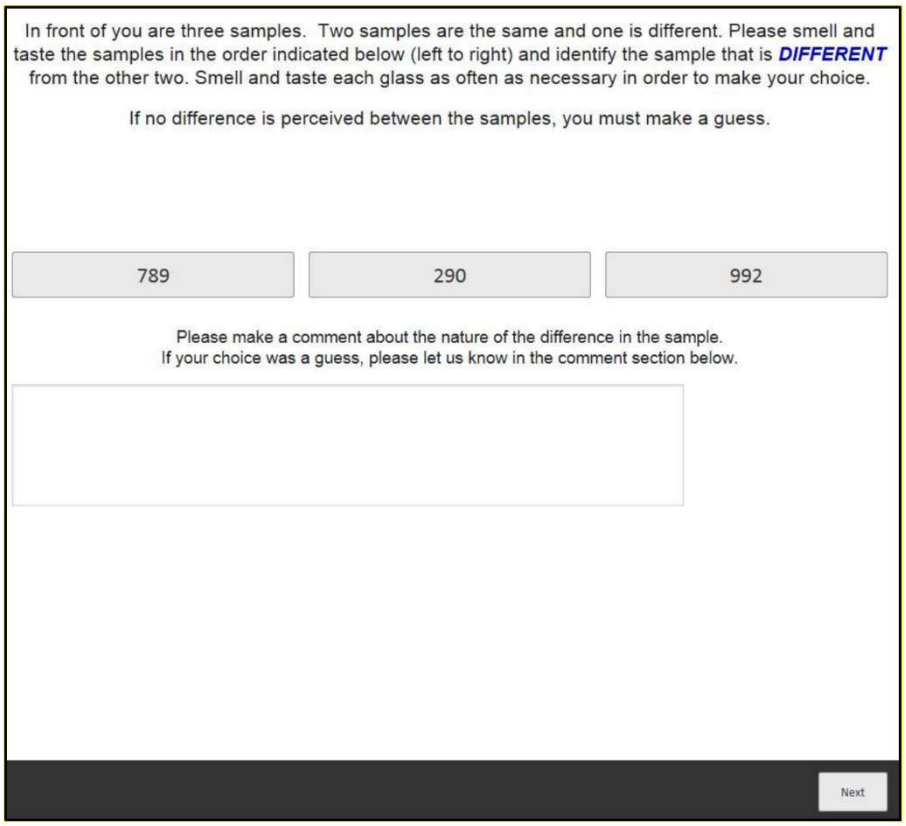
The samples were evaluated in two separate sessions, with thirty-one and thirty-four experienced, screened, and qualified assessors, respectively. In both sessions, the judges were presented with two triangle tests. Assessors were asked to select the sample in the set that was different from the other two. Panellists were also asked to comment on the nature of any difference between the samples if possible. The judges were forced to have a 30-second rest between the tests and were encouraged to rinse with water. An example of the instructions provided to the assessors and a test page for this session is presented in Appendix 1.

Samples were presented to panellists in 25 mL aliquots in 3-digit-coded, covered ISO standard wine glasses at 22–24°C, in isolated booths under colour-masking sodium lighting. There was a randomised presentation order across judges and tests. Data was collected using Compusense20 sensory evaluation software (Compusense Inc., Guelph, Canada).

Data analysis to determine statistical significance was carried out using the binomial model as specified in AS 2542.2.4.

4. Appendix

Screen shot of an example of the instruction and test pages provided to assessors.



PO Box 197 | Glen Osmond, SA 5064
T: +61 8 8313 6600 | F: +61 98 8313 6601; www.awri.com.au

Appendix 5.2: Planned Project Outputs

Outputs and activities from the original project application are in black, changes to these and additional outputs from the project variation imposed in September 2020 are marked in red.

Outputs and Activities 2017–18

Year 1	Output	Target Date	Activities
	Vine vigour data from the high density site	31/09/2017	Pruning weights collected from dormant FY1 vines and compared between selected treatments.
	Data from sensors and weather station.	30/06/2018	ArduCrop, or new sensors, modified based on FY1 results. Technology evaluated to improve precision of sensor temperature measurements Software improvements made for data collection and analysis.
	Data on vine performance for the different treatments.	30/06/2018	LiDAR or other technology used to estimate vine vigour based on canopy size and structure. Yield data collected from the different treatments at harvest.
	Fruit chemical composition data.	30/06/2018	OenoFoss data and anthocyanin measurements done on berries from treatments at harvest.
	Wine made and wine chemical composition data	30/06/2018	Small scale wine made from at least 16 treatments. OenoFoss data and anthocyanin measurements done on wine.
	Management costs and data from the	30/06/2018	Data collected on the management costs of the different experimental treatments. Crop water use index (kg/water used) calculated for the different treatments.

			Sensor data analysed and compared to data from soil moisture sensors. Differences between treatments analysed for vine performance and berry and wine parameters.

Outputs and Activities 2018–19

Year 2	Output	Target Date	Activities
	Data on vine vigour across the different treatments.	30/06/2019	Collect pruning weight data from previous seasons growth from dormant vines and compare with selected treatments. Use digital technology to collect data on canopy size and structure to estimate vine vigour.
	Dataset from sensors and weather station.	30/06/2019	Develop ArduCrop or new sensors based on FY2 results placed at the site and collect data for canopy temperature and soil moisture. Evaluate technology to improve precision of sensor temperature measurements. Make software improvements for data collection and analysis.
	Data on vine performance and fruit chemical composition for different treatments.	30/06/2019	Collect yield data from the different treatments at harvest. Collect OenoFoss data and anthocyanin measurements on berries from treatments at harvest.
	Small scale wine and wine chemical composition data.	30/06/2019	Make small scale wines from at least 16 treatments. Collect OenoFoss data and anthocyanin measurements on wine.

	Data from irrigation treatments.	30/06/2019	Compare irrigation, vine density and genotype treatments. for yield, canopy temperature and fruit and wine chemical composition.
	Data from irrigation and management comparisons.	30/06/2019	Collect data collected on the management costs of the different experimental treatments. Calculate crop water use index (kg/water used) for the different treatments.

Outputs and Activities 2019–20

Year 3	Output	Target Date	Activities
	Nuriootpa field trial maintained, vine growth and performance assessed and data available.	30/06/2020	Pruning weights from dormant vines to assess 2018/19 growing season vigour. Berry total soluble solids tracked during maturation to ensure all genotypes/treatments harvested at the same sugar maturity. Yield data and components (mean bunch weight, mean berry weight) collected at harvest (24°Brix). Berry composition at harvest assessed using OenoFoss and microplate anthocyanin assay.
	Small lot wines made from harvested fruit and available for subsequent sensory analysis.	30/06/2020	Wine made from small lots of fruit (30-50 kg fruit) from up to 16 treatments (depending on volume of fruit available), including 2-3 winemaking replicates.
	ProxiCrop thermal sensors and analytics further developed.	30/06/2020	Analysis improvements based on implementing colour segmentation algorithms.

			Assess the potential for using generalising segmentation algorithm and dual sensor calibration to crop rather than individual sensor hardware. Further develop python-based Dash GUI, including containerisation for version stability and deployment, increased ability for user to interact with data, improved visualisation, such as the display of segmented/masked overlays. Continued software and hardware improvements on ProxiCrop including power isolation of individual peripherals, matching power cycles to user requirements for data collection time and frequency, and further improvements to FTP server efficiency. Assess commercialisation potential and pathway, e.g. communication with "GoannaAg" for possible collaboration.
	ProxiCrop sensors field tested and used to assess irrigation status of vines at Nuriootpa field site.	30/06/2020	Existing sensors deployed at Nuriootpa. At a minimum, data collected and processed for the maturation period in high and low irrigation treatments. Comparison imaging with high-resolution hand-held thermal camera collected on at least two occasions for all treatments/replicates together with stem water potential measurements. Processed thermal image data compared with local climate data and assessed for sensitivity to irrigation

			treatment, genotype and stem water potential.
	Irrigation efficiency and vine management cost assessed.	30/06/2020	Irrigation Water use efficiency (IWUE) calculated for the different treatments. Data collected on the management costs of the different experimental treatments. Cost effectiveness of genotype/treatment calculated.

Outputs and Activities 2020–21

Year 4	Output	Target Date	Activities
	Nuriootpa field trial prepared for minimal 2020/21 season operations and long-term maintenance~~maintained, vine growth and performance assessed and data available~~.	30/6/2021	Pruning weights from dormant vines to assess 2019/20 growing season vigour. Irrigation treatments maintained for 2020/21 growing season. Prepared for long-term maintenance, shade and other structures removed, irrigation water changed from town to channel source, other activities undertaken after discussion with Nuriootpa site manager. Berry total soluble solids tracked during maturation to ensure all genotypes/treatments harvested at the same sugar maturity. Yield data and components (mean bunch weight, mean berry weight) collected at harvest (24°Brix). Berry composition at harvest assessed using OenoFoss and microplate anthocyanin assay.

	ProxiCrop thermal sensors and analytics further developed.	30/6/2021	Sensor data analysis improvements based on improvements in colour segmentation algorithms. Processed thermal image data compared with vine and climate data and assessed for development of novel or existing vine stress index to assist irrigation mangement. Continued software (and hardware if suitable) improvements to improve collection and processing of data. Further assessment of commercialisation potential and pathway.
	ProxiCrop sensors field tested and used to assess irrigation status of vines at Nuriootpa field site and in collaboration with Swan Systems.	30/6/2021	Existing sensors deployed at Nuriootpa. Five sensors built and deployed at commercial vineyards in collaboration with Swan Systems (Langhorne Creek or Barossa Valley). At a minimum, data collected and processed for the maturation period. Comparison imaging with high-resolution hand-held thermal camera and physiological measurements collected on at least two occasions.
	Irrigation efficiency and vine management cost assessed.	30/6/2021	Irrigation Water use efficiency (IWUE) calculated for the different treatments Data collected on the management costs of the

			different experimental treatments. Cost effectiveness of genotype/treatment calculated.
	Final report.	31/12/2020	Final report available on field site based work, including: relative performance of rootstock:scion combinations and assessment of wine produced, vine production efficiency in high/standard density and interaction with irrigation volume, assessment of cost effectiveness of no-spray vineyard.

Appendix 6: Budget reconciliation

A budget reconciliation will be provided separately.