ASSESSMENT OF VINEYARD PERFORMANCE TO PREDICT WINEGRAPE QUALITY

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A thesis submitted in fulfillment of the requirements for the degree of **Master of Philosophy**

July 2019

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Abstract

In many situations, winegrapes are grown by grapegrowers and then sold to winemakers to make wine. Developing quantifiable measures of winegrape quality is seen as beneficial to winemakers and grapegrowers to increase clarity and accountability between both parties. Currently vineyard performance in any given vintage can be assessed by price paid for the fruit at market, past performance, objective and subjective measures or a combination of these. Past vineyard studies have shown that defining winegrape quality is not a simple exercise and determining what vineyard measurements to take, when to take them and how to interpret their influence has been the subject of wide-ranging research.

One of the aims of this study was to develop models, on a commercial scale, for predicting winegrape quality from known vineyard performance measures. Two winegrape cultivars commonly grown in Australia; Shiraz and Cabernet Sauvignon were investigated. This research developed a methodology to assess winegrape quality in a commercial situation in the McLaren Vale, Langhorne Creek and Adelaide Hills wine regions using vineyard measures, assessments of canopy architecture and berry composition.

Known vine performance measures were taken at key phenological growth stages and then assessed for their ability to predict winegrape quality. Two models for predicting winegrape quality were developed - a growing season (GS) and a harvest (HRV) model.

The GS prediction model used image analysis of canopy architecture and vineyard observations taken up to 50% veraison (EL 35, Coombe 2004). This was done to assess if early measures could predict wine quality and therefore allow time for grapegrowers to adjust their practices before harvest. The HRV prediction model combined image analysis of canopy architecture with berry composition measurements (total tannin, anthocyanins and phenolics) up until the harvest period.

Results of the trial on Shiraz showed winegrape quality prediction by the HRV models were better than the corresponding GS models as measures of grape composition at harvest were good predictors of winegrape quality. When Cabernet Sauvignon was assessed by the same methodology the HRV models and the corresponding GS models had comparable predictive abilities.

This research showed that models of winegrape quality can be developed in commercial vineyards by combining canopy architecture measurements with grape berry composition. Based on the results with these grape varieties, using this methodology, winegrape quality modelling could be adapted for use in other regions and on other varieties.

Statement of works

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I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

James Hook Date: 9/7/2019

List of intended publications as part of this research

Hook, J., De Bei, R., Metcalfe, A., Collins, C. (2019) Assessment of vineyard performance to predict winegrape quality in *Vitis vinifera* L. (cv. Shiraz) (Prepared manuscript for submission to Australian Journal of Grape and Wine Research as a research article – presented as Chapter 3).

Hook, J., De Bei, R., Metcalfe, A., Collins, C. (2019) Assessment of vineyard performance to predict winegrape quality in Cabernet Sauvignon. (Prepared manuscript for submission to VITIS - Journal of Grapevine Research as a research article – presented as Chapter 4).

Hook, J., De Bei, R., Metcalfe, A., Collins, C. (2019) Assessment of canopy porosity at flowering and veraison and the influence on berry total anthocyanin in *Vitis vinifera* (cv. Shiraz) in Australian vineyards. (Prepared manuscript for submission to American Journal of Enology and Viticulture as a research note – presented as Chapter 5).

This thesis has been prepared under the University of Adelaide specifications for "publication format". Note that Australian English spelling and formatting is used for all publications included in this thesis.

Acknowledgements

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

All vineyards were located on private land with family ownership; thanks to the support and flexibility of all growers. Thanks to the Viticulture laboratory staff and interns at The University of Adelaide who assisted in laboratory work, and to DJ's Growers (Mr. Thomas Coleman, Mr. Nick Hillman and Mr. Joe Siebert) for assistance with data collection. Special thanks to Dr. Roberta De Bei whose input into the methodologies used was invaluable.

With gratitude to Assoc. Prof. Cassandra Collins and Assoc. Prof. Andrew Metcalfe for their supervision and guidance.

List of abbreviations

Abbreviation	**Full Term**
AUD	Australian Dollar $
cm	centimetre
cv.	cultivar
cvs.	cultivars
Brix	A means of expressing TSS as an estimate of juice sugar concentration
EL stage	Eichhorn Lorenz phenological stage
GHD	grape harvest dates
gm	gram
GS	growing season
HRV	harvest
p-value	probability
pH	a figure expressing the acidity or alkalinity of a solution on a logarithmic scale
m	metre
m^2	square metre
mg	milligram
TA	Titratable Acidity
TSS	Total Soluble Solids
R^2	coefficient of determination
RGB	Red Green Blue image
ºC	degree Celsius
%	percentage

Chapter 1: Introduction

Current commercial grapevine fruit production is aimed at producing the maximum return on investment from a given vineyard within sustainable means. Maximising the quality of fruit, using all the knowledge developed about what influences winegrape quality, is one method to increase the return of a vineyard, as opposed to maximising yield.

For example, the McLaren Vale, Langhorne Creek and Adelaide Hills wine regions are distinguished locations for red winegrape production in Australia. These regions produce a range of red wine styles which are sold at different price points in the marketplace (Appendix A, Wine Australia 2016/17). In these regions the value of the winegrapes purchased by wineries varies and winegrape prices per tonne range between below AUD $1,000 and above $5,000 per tonne (Appendix B, C, D, E). A direct relationship between the price paid per tonne for fruit and the resultant wine quality and the wines intended use has been shown (Hathaway 2013).

It is commonly believed that assessment of aspects of a vineyard by experienced practitioners can allow judgement of the likely quality of wine produced from the vines (Francis et al. 2005). Winemakers and other experienced practitioners spend time and resources assessing the quality of fruit into different grades before harvest. Identifying any flaws in fruit before winemaking begins is beneficial. Grading fruit is used to improve the efficiency of the winemaking process. After grading, fruit can be streamed in the winery so that processes specific to producing a certain wine style are undertaken.

The grape and wine industries peak research body, Wine Australia, has advocated using multivariate approach using most or all currently known potential measures of quality to define winegrape quality in their strategic plan (Gishen et al. 2002; Francis et al. 2005) and promoted studies into the targeted assessment of fruit quality. Selective harvesting and streaming of winegrapes is considered an important avenue by which grapegrowers can take a more active role in the winemaking process (Bramley & Trengrove 2013). Identifying sections of vineyards with better quality and harvesting accordingly improves harvest logistics, and profitability of the wine industry (Bramley et al. 2005).

1.1 Objectives of the research

Objectives of this research were to: i) investigate using vine performance measurements to predict winegrape quality ii) assess the relative influence of vine performance measurements on winegrape quality, and iii) investigate the effectiveness of using image analysis as a technique to assess canopy architecture. This research was focused on obtaining commercially relevant results using methodologies that could be adapted for use by grapegrowers and winemakers in their own vineyards.

Two commercially important varieties of *Vitis vinifera* L. were investigated (cvs. Shiraz and Cabernet Sauvignon) as they represent the two most widely planted red winegrape varieties in Australia and for their abilities to make wine styles that have high value in the marketplace. In the three wine regions chosen for the study their production is focused on producing a range of winegrape qualities including those intended for premium and ultra-premium wines. Wineries in these regions attempt to add value to their wine products along the production chain to improve their profitability.

1.2 Linking statement

The research in this thesis is presented in chapters including three research chapters which are presented as prepared manuscripts intended for publication.

Chapter 2 is a literature review outlining the history of vine performance measurements. Winegrape quality can be measured by the price paid for the fruit at market, a measurable outcome, but assessment methods for vineyard performance vary. The success of predictive studies using vineyard performance measures depends on what range of values are studied which can restrict the use of prediction to one region and whether the fruit was harvested at the same ripeness level, the use or not of similar winemaking methods and on how winegrape quality was assessed. When comparing winegrapes that differ from each other in region, winemaking methods or ripeness current practice is to assess vineyard performance by price paid at market, past performance, objective measures, and subjective appearance, or a combination of all four.

Chapter 3 describes an experiment to assess links between winegrape quality and vineyard performance in cv. Shiraz. A matrix approach, by taking multiple measurements at set phenological growth stages, investigated predicting winegrape quality using objective measurements. Methods were developed to allow vineyard assessment on a commercial scale. A system of image analysis was used to reduce the time and labour required to collect vineyard observations. Image analysis was used to assess a vines canopies for size by estimated leaf area index (LAIe) and light environment (canopy porosity).

The two models developed to predict winegrape quality were a growing season model (GS) and a harvest model (HRV). The GS prediction model was made at 50% veraison (EL 35) by combining canopy architecture measurements with vineyard observations. Early prediction of quality could then allow for potential management decisions to be made before harvest.

Chapter 4 describes an experiment assessing winegrape quality in Cabernet Sauvignon. This experiment used the same approach as Chapter 3. This study also developed two models for predicting cv. Cabernet Sauvignon winegrape quality from vineyard performance including a GS model that could allow grapegrowers to manipulate their practices.

Chapter 5 describes an experiment assessing links between canopy porosity and total berry anthocyanins (mg/g berry weight). Image analysis was used to assess the canopy porosity at two key growth stages as an efficient method of obtaining data for commercial use. This study demonstrates that the greater the canopy porosity at EL 25, the greater the total berry anthocyanin level at harvest. The relationship between canopy porosity at EL 35 and the colour level at harvest did not correlate as well. Vineyards with high porosity levels at EL 35 appeared to be at the upper limit of light exposure for the vineyard's climate.

The general discussion in Chapter 6 outlines overall findings. Differences between the performance of Shiraz in Chapter 3 and Cabernet Sauvignon in Chapter 4 are discussed. Future research into other varieties and other regions, linking winemaking trials with modelling, and taking image analysis from cameras fitted to vineyard equipment are discussed.

Chapter 2: Literature review

2.1 History of vine performance measures

Commercial winegrape production aims to produce the maximum return on investment, in a sustainable manner, from a given vineyard. There are two fundamental strategies to achieve this, firstly grapegrowers can aim to produce as much grape yield as they can, alternatively, grapegrowers aim to produce the highest quality grapes they can and receive a premium over the average market price. To attract a premium over the average market price winegrapes must be recognised for superior performance.

Modern viticulture can assess vine performance by objective measurements, however historically this has not been the case. There is a long history of winegrape quality being judged by subjective vineyard assessments made before winegrapes are harvested. Before the development of scientific instruments winemakers would have solely made judgements on whether winegrapes were fit for purpose based on their experience. These judgements were based on the taste of the fruit, time of the year, weather conditions and the appearance of grapevines before harvesting.

While objective measures of winegrape performance have now been developed they have not yet fully replaced subjective measurements. In modern viticulture winemakers may still use visual observations or their previous experience to determine when to pick and the quality of the fruit on the vine. Relying on subjective assessments to assess winegrape quality leads to inefficiencies in the wine supply chain and causes friction between grapegrowers and winemakers (Allan 2003).

2.2 Sugar level and hedonic price

Due to the inherent problems with relying solely on subjective measurements research studies into objective measures of winegrape quality have long been considered important. Even during the early stages of scientific discovery in Europe it was noted that the way the grapevine grew, in addition to its environment, influenced the resultant quality of wine (Jackson 2008). The scientific method, a procedure that has characterized natural science since the 17th century, consisting of systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses, has been applied to improve viticulture and winemaking. Improving viticulture by scientific methods was first achieved in France by French First Empire farming policies (Chaptal 1801, 1807). As such, objective measures of vineyard quality are some of the oldest scientific measures in agriculture. For example, one of the first scientific tools, the hydrometer, was widely used in viticulture to estimate juice sugar levels (TSS) in the early 19th Century (Paguierre 1828).

The estimate of the sugar level in juice soon became the first widely used objective measure of winegrape quality and it remains a measurement of vineyard performance. Sugar content increases during ripening and is therefore a function of berry maturity (Jackson 2008). Sugar content is relatively easy to assess. The use of hydrometers that measure sugar, formally called saccharometers, was complimented by handheld refractometers, known as Abbe refractometers, developed by the Carl Zeiss Company in the late 19th Century (Masters 2007). Both instruments made possible widespread assessment of fruit ripeness. From this gathering of data conclusions about the link between sugar and winegrape quality were drawn.

Historical price of grapes and wine was also used as a measure of quality in the 19th century. One of the most famous attempts to classify wine quality during the period was the exposition in Bordeaux in 1855 (Markham 1998). An international exposition was held in Paris and the organizers asked the Bordeaux Chamber of Commerce to rank their products in order of quality. With no objective system of wine measurement being available a ranking was developed based on historical prices. The Bordeaux classification of 1855 is still in place as a measure of quality with continued use as an indicator of wine quality (Thompson & Mutkoski 2011). However, it must be noted that the Bordeaux classification refers to the winery itself and not the direct quality of the vineyards the wine is produced from. Outside of the Bordeaux wine region’s specific example the use of historical price of wine and grapes remains commonly used as a measure of quality.

Vineyard assessment in the 20th Century moved away from simple sugar ripeness measurements and historical grading and saw the development of standardised measurements of vineyard performance. Objective measurements based on physical field measurements of the grapevines canopy and chemical measurement of fruit and wine were developed (Dry et al. 1998).

2.3 Vineyard Performance

The writings of AJ Winkler on the relation of leaf area and climate on vine performance and grape quality (1957) investigated links between plant physiology and production. Winkler noted that there were relationships between fruit physiology and production for other fruiting plants and conjectured that relationships should apply to grapevines.

There was little information on the response of the vine to pruning. Studies were initiated to determine the effect of pruning on vine growth, the effect of crop on vine growth and the effect of pruning on the capacity for production.

From this point the concept of vine balance and measuring grape yields as a measure of performance and quality was developed from studies across different regions, varieties and wine uses. A theory was established that vineyards can become unbalanced having high yields and are likely to produce lower quality wines than those in an optimal range for a given site (Smart & Robinson 1991). Also, if vineyards have too much canopy and not enough fruit they were classified as being in a vegetative state which is one where the vine grows leaves in preference for fruit (Smart & Robinson 1991). To maximise wine quality, grapegrowers tried to establish vine balance through pruning and management. Grapegrowers assessed their potential yield during the season and used management techniques to reduce the yield if above their desired range. Wines of premium quality may be associated with vineyards of low vigour and low yields (Smart & Robinson 1991) though it is not necessarily the reduced yield that is the causal factor (Dry et al. 1998) but more likely a balanced vine (Smart & Robinson 1991).

An index to represent the ratio of reproductive to vegetative growth was developed by Ravaz (1903). The yield of the grapevine was compared to the pruning weight (crop weight to pruning weight). This became widely known as the Ravaz index. In developing the index Ravaz suggested that the ratio of fruit to wood is the key to achieving both fruit quality and consistent production. Overcropped vines, or vines with excessive canopy, were referred to as “out-of-balance” and were generally associated with lower quality fruit. A vine is considered balanced when capable of ripening its fruit to the best compositional characteristics to produce high quality wines of a targeted style (Kliewer & Dokoozlian 2005).

Vine balance can also be defined as the amount of leaf area required to ripen a unit of crop weight. This is commonly expressed as cm^2 leaf area/gram (g), or m^2/kilogram (kg) fresh weight of fruit (Smart & Robinson 1991). In the early 1920s, vine balance was further defined. This was called the Growth-Yield Relationship (Partridge 1925). It was reasoned that a vine produced two forms of yield each growing season: reproductive yield and vegetative yield. Balance was achieved when yield of ripe fruit was maximized with no detrimental impact on vegetative growth. The weight of canes removed by pruning produced in Year 1 was an indicator of the upper limit of a vines capacity to produce and ripen a crop in Year 2.

The final configuration of a grapevine canopy is first influenced by the level of buds retained after pruning. In the latter half of the 20th Century methodology to prune grapevines into balance by evaluated pruning decisions based on the Ravaz Index and the Growth-Yield Relationship was developed (Shaulis 1966). The findings of this research, and other complimentary research (Winkler 1957), measured the relationship between vegetative and reproductive growth as one between pruning weight and yield. This concept allowed practical management of vine performance by manipulating the key grape growing operation of winter pruning.

2.4 Measures of vine canopy growth

Further measurements of vine performance were developed to measure the grapevines canopy growth rate, allowing monitoring of vine growth during the vines growing season. Measuring during the growing season (spring and summer) is considered advantageous compared to measuring pruning weight as it allows time for grapegrowers to make management decision to alter vine growth before harvest. Direct measurements of canopy fresh weight by stripping vines of their green tissue (leaves and shoots) or plucking leaves and then measuring their size as an area (as cm^2, or m^2) allowed a comparison with yield as a proxy for pruning weight. Alternatively, assessing canopy size and density by using the point-quadrat measure; passing a rod horizontally through the fruit zone and recording the number of contacts with leaves, fruit and shoots, is used as growing season measurement (Smart 1985; Grantz & Williams

1993). Both measurements (stripping leaves and point quadrat assessment) are limited in use in a commercial situation because they require time and labour to accomplish.

Field techniques such as canopy scoring were introduced as an aid to measuring canopies. A set of twenty-one numeric indices and descriptors to assess winegrape canopies was presented to define ideal winegrape canopy ideotypes (Smart et al. 2017).

Leaf Area Index (LAI) is a measurement that was widely used by researchers to describe canopy size after it was defined (Watson 1947). It is a dimensionless index, defined as the amount of one-sided leaf tissue in each section of ground area. Leaf Area Index on vine or tree canopies with overlapping leaves can be determined by using indirect measures, however this is time consuming and labour intensive (Chen, & Black 1992). At the end of the 20th Century image analysis was used to estimate LAI beginning in the forestry industry then adapted for use in vineyards (Fuentes et al. 2016). Image analysis of leaf area is based on a light sensitive scanner reading the amount or fraction of solar radiation transmitted through the canopy. Plants with dense canopies, have higher levels of leaf chloroform than plant canopies which are sparse, and will absorb more light than sparse ones and therefore will record a higher estimated LAI (Broge & Leblanc 2001).

2.5 The influence of light environment in ripening fruit

Research into winegrape quality during the growing season has focused on the light environment and microclimate inside grapevine canopies (Smart et al. 1988). Contemporary with research establishing links between nitrogen and canopy light levels (Keller et al. 1998), yield (Smart et al. 2017), pruning weight and winegrape quality (Kliewer & Dokoozlian 2005), links between grape composition, canopy shoot density and wine quality were investigated.

Fruit exposure to light was shown to influence grape and wine quality (Smart 1985). Grape berries exposed to sunlight have juice that is generally higher in sugars, anthocyanins, and phenolics, and lower in titratable acidity, malate, and pH, compared to berries ripened in canopy shade (Kliewer & Antcliff 1970; Kliewer & Lider 1968; Kliewer 1977; Morrison & Noble 1990; Reynolds & Wardel 1986). Light exposure also affects bud fruitfulness which is important for reproductive development and therefore the long-term viability of vineyards.

Shaded grapevine canopies produce less fruit over time (Dry 2000; May 2000) which can promote vegetative growth leading to vines becoming unbalanced under the definitions of the Ravax index.

Fruit exposure does not universally lead to better winegrape quality. A recent study has shown that the accumulation of anthocyanins is dependent on both low temperature and light through the regulation of flavonoid biosynthesis pathway genes (Azuma et al. 2012). Vineyards in hot climates have been noted to have poor anthocyanin levels if they have excessive direct sun exposure as anthocyanin production and accumulation is inhibited (Bergqvist et al. 2001, Dry et al. 1999, Kliewer 1970, Kliewer 1977). Direct sun exposure leads to high berry temperatures which are not conducive to optimal anthocyanin accumulation in berries (Haselgrove et al. 2000) and the synthesis of flavonoids (Downey et al. 2004).

A series of simple measurements were developed to assess vineyard microclimate and fruit exposure to allow different vineyards to be compared with each other (Smart 1985). The ability to compare vineyards across different regions, and countries was beneficial as it facilitated an exchange of techniques across the whole world (Jackson & Lombard 1993). Shoot counts were used to measure and compare canopies (Smart & Robinson 1991). The number of shoots growing were expressed as a number per meter of cordon. This is used as a measure of the density and therefore as an estimate of light exposure into the canopy as fruit ripens. Shoot density has been used as vineyard canopy measurement in numerous studies on different winegrape cultivars including Cabernet Sauvignon (Hunter et al. 1995), Chenin Blanc (Volschenk & Hunter 2001), Riesling (Percival et al. 1994), Shiraz (Peterson & Smart 1975) and Tempranillo (Vilanova, et.al 2012).

Shoot density was further defined with shoots being classed into two categories. Count shoots, also called primary shoots, which is a sum of shoots growing from the grapevine buds retained during dormancy (Wolpert et al. 1983). They are counted by a visual inspection. Non-count shoots, also called secondary shoots, are described as those that burst from older buds or from basal buds on the cordon or trunk (Wolpert et al. 1983). These are also counted and expressed as buds per meter of cordon. Typically, it is thought that these non-count shoots are less fruitful and have inferior quality fruit than count shoots (Wolpert et al. 1987).

Both count and non-count shoots contribute to the total shoot number of the grapevine. Within-canopy shading is promoted by high shoot numbers. Within-canopy shading leads to undesirable traits for winemaking, shading decreases berry juice TSS and increased wine pH at harvest (Smart 1985). For these reasons, the practical interpretation of shoot density research was to increase light exposure in the canopy by removing non-count shoots and to alter the arrangement of shoots to allow light exposure on inflorescences and bunches during spring and summer.

The practical implications of light exposure research influenced practices in commercial vineyards. The understanding of the role shoot density played in the canopy light environment saw the adoption of assessing canopy shoot density as a standard vineyard measure (Reynolds et al. 1994). Vineyards are commonly assessed with manual counting of shoot density and manipulated through shoot thinning or other canopy management techniques including wire-lifting and green pruning. These techniques can be undertaken at any point of the growing season, including early manipulation between grapevine bud burst (EL 5) and early capfall (EL 19), or as late as pre-harvest (EL 37). Canopy manipulation is designed to alter the level of light exposure onto developing inflorescences and berries as this is thought to lead to better quality fruit (Tardaguila et al. 2010).

2.6 Berry composition

Berry composition is vital to wine quality. Which compounds are present in the berry, and in what quantity determines the aroma and varietal characteristics of finished wine (González-Barreiro et al. 2015). Winegrape quality can be directly assessed by measuring grape berry composition. Grape berry composition levels can be benchmarked to rank vineyards by the concentrations of soluble solids, organic acids and pH in their berries (Mercurio et al. 2010).

During the 20th Century there was extensive research into how berry composition was influenced by the environment under which fruit ripened (Jackson & Lombard 1993). The development of berries and their composition is considered important because pH and sugar level are important for wine stability and specific grape substances such as phenols, anthocyanins and aroma compounds are mainly found in the berry skin (Conde et al. 2007). Research has shown that berry composition is driven by genes triggering the expression enzyme proteins after flowering (Boss et al. 2003; Vasconcelos et al. 2009). Gene expression of enzymes is associated with an increase in berry size (Davies et al. 2006). The size of a berry at harvest influences the ratio of skin surface to berry pulp volume. Phenolic, anothocyanin and aroma compounds give wine its unique qualities (Cordonnier & Bayonove 1978; Champagnol 1993). Berry pulp contains most of the water, sugars and acids present in the berry (Coombe 1976).

Gene expression of enzymes has also been linked to flavour components of finished wines (Bogs et al. 2005; Cohen et al. 2012; Dunlevy et al. 2016), and total anythocyanin levels (Azuma et al. 2012). Protein production during berry development is affected by light (Koyama et al. 2012) and temperature (Cohen et al. 2012).

Winegrape juice pH is one of the more important quality parameters as pH can affect fermentation rates (Ough et al. 1968). Also, wine pH levels above 3.6 are detrimental to wine quality as above this level there is increased likelihood of microbial spoilage or the production of hydrogen sulphide (H_2S), and lowered colour intensity in the wine (Jackson & Lombard 1993).

Grape berry development is classified as having two stages of growth, separated by a lag phase (Coombe 1976). During stage I berry pericarp growth is rapid, at first due to cell division and expansion, and later due to the expansion of cells alone (Harris et al. 1968). Berries accumulate organic acids but little sugar during stage I and remain green and hard. Stage II is referred to as the lag phase of development, as berry growth slows. Rapid berry growth, because of cell enlargement, resumes with the initiation of stage III. During stage III sugar and colour accumulate rapidly, and the concentration of organic acids declines.

Many studies have shown that different factors such as temperature (Hale & Buttrose 1974; Kliewer 1977), light (Dokoozlian & Kliewer 1995), plant water status (Hardie & Considine 1976; McCarthy 1997; Roby et al. 2004), and leaf area (Ollat & Gaudillere 1998) influence berry size.

Techniques to reduce berry size by reducing stage I pericarp growth by manipulating plant water status through withholding irrigation (Dry et al. 1998), altering the temperature and light environment by canopy manipulation (Gregan et al. 2012), competition for water and nutrients by covercrops and leaf area by green trimming or leaf plucking are common vineyard practices (Jackson & Lombard 1993; Tardaguila et al. 2010; Acimovic et al. 2016).

2.7 Physiological ripeness

Grape harvest dates (GHD) have been used historically as a measure of quality. Towards the end of the 20th century the concept of achieving physiological ripeness in the grapes was described as a more complete ripeness of tannins and other phenolic compounds in the grapes that contribute to the colour, flavour and aroma of wine (Robinson et al. 2014). As the development of the grapevine is mainly driven by temperature (Jones 2003), if the microclimate is the same for two vineyards, slow ripening is due to the ratio of cropload to canopy size (Smart & Robinson 1991). Higher crops take longer to ripen than lower crop levels. This reflects how balanced the grapevines cropload is to its leaf ratio.

2.8 Vineyard assessment by benchmarking in Australian vineyards

Common vineyard quantitative assessments used to assess vineyards include harvested yield, bunch size, bunch number, bunch weight, leaf area index, ripeness sugar level, total berry anthocyanins (colour) and grape tannin levels (Gishen et al. 2002; Francis et al. 2005). These techniques rely on field observations and samples of berry composition during the growing season. Commercial grapegrowers and researchers aim to minimise the number and size of field observations and berry samples taken to reduce labour and material costs (Vasconcelos & Castagnoli 2000; Meyers et al. 2011). Fruit and pruning weight measurements are tedious, yet easy to conduct, while estimating or measuring canopy size and architecture can be a complex and time-consuming exercise and this is considered a barrier to their usefulness and applicability (Marbrouk et al. 1997).

Finding simple and easy to collect objective measures that predict or represent winegrape quality, and thus can be managed by grapegrowers, is considered important, and has been the focus of vineyard quality benchmarking studies (Rolley 2003; Winter 2005; Lowe 2005). In commercial grape production subjective visual observations are still commonly used to make vineyard management decisions and assess winegrape quality because visual observation does not require any sampling procedures and minimal labour costs (D. Cameron [DJ's Growers Services & Supplies PL] 2019. pers. comm).

2.9 Image analysis as a method of vineyard assessment

The time and labour requirements needed to manually assess vineyard performance accurately, to a statistically relevant level, is a barrier to the use of vineyard performance data for predicting wine quality in the field (De Bei et al. 2016). In response, new technologies have been developed to remotely assess the vines canopy using image analysis as an alternative to manual assessment (Sinoquet et al. 1998). In recent years the development of accurate, inexpensive tools including smartphone applications for use in the vineyard have become available. Methods using image analysis has been proposed to assessing pruning weight (Dobrowski et al. 2003), shoot density (Dobrowski et al. 2002), leaf area (Drissi et al. 2009), yield estimation (Dunn & Martin 2004; Diago et al. 2012), flowering and bunch assessments (Diago et al. 2013) and grape phenolics and colour at harvest (Lamb et al 2004) all of which are mostly preformed manually.

Leaf area index can be also be assessed by image analysis or hyperspectral image acquisition, or two-dimensional red, green, blue (RGB) photographs, and/or three-dimensional crop surface models (Kalisperakis, et al. 2015). Grapevine canopy porosity can be also be assessed by image analysis using digital photography and gap size assessment algorithms (Fuentes et al. 2014). Fuentes et al. (2014) developed an automated method for leaf area estimation and porosity estimation on grapevine which uses cover photography and MATLAB® (Mathworks Inc., Matick, MA, USA) programming language. This method estimates LAI and other canopy architecture parameters according to the algorithms developed by Macfarlane et al. (2007).

The obvious benefit of using image analysis to assess grapevines is the time and labour saving. Potentially, one of the most powerful tools in viticulture is the use of image analysis, as entire vineyards can be assessed rapidly (Hall et al. 2002) and spatial variability in fruit composition and yield can be determined (Hall et al. 2011). Image analysis provides a benefit of increased capacity (because image capture requires less time than sampling or counting) and precision (reproducibility), but not necessarily the accuracy of the analysis. Its potential for improving vineyard practice will rely on being able to define useful relationships between these canopy descriptors and winegrape quality and yield (Hall et al. 2002).

2.10 Conclusions

Currently vineyard performance in any given vintage can be assessed by price paid for the fruit at market, past performance, objective and subjective measures or a combination of these. Vineyard studies have shown that defining winegrape quality is not a simple exercise and determining what vineyard measurements to take, when to take them and how to interpret their influence has been the subject of wide-ranging research. Vine canopy size, the light environment and temperature as berries ripen influences berry chemistry. Investigating the light environment and temperature inside grapevine canopies is difficult since they are characterised by large spatial and temporal variations (Smart et al. 1985; Schultz 1995). Recent research has investigated using image analysis to compliment traditional observation, manual count and sample-based assessments to overcome barriers in data collection.

Chapter 3: Prepared manuscript

Assessment of vineyard performance to predict winegrape quality in *Vitis vinifera* L. (cv. Shiraz)

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Keywords: *winegrape quality, vineyard performance, canopy architecture, berry composition, veraison*

Statement of Authorship

Title of Paper	Assessment of vineyard performance to predict winegrape quality in *Vitis vinifera* L. (cv Shiraz)
Publication Status	☐ Published ☐ Accepted for Publication ☑ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Hook, J., De Bel, R., Metcalfe, A., Collins, C., (2019) Assessment of vineyard performance to predict winegrape quality in *Vitis vinifera* L. (cv Shiraz) (Prepared manuscript for submission for Australian Journal of Grape and Wine Research – presented as Chapter 3).

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Contribution to the Paper	Performed analysis on all samples, interpreted data, and wrote manuscript as lead author.
Overall percentage (%)	80%
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 28/1/2019

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Abstract

Background & Aims: Vineyard performance in any given vintage can be assessed by past performance, objective measures, and subjective appearance. In many wine growing regions winegrape quality is measured by the price paid for the fruit at market. The aim of this study was to develop models for predicting winegrape quality from vineyard performance measures including early season prediction models that allow grape growers to adjust their practices.

Methods & Results: A three-year study was conducted in 35 Shiraz vineyards in the McLaren Vale and Langhorne Creek wine regions of Australia. To assess vineyard performance, vineyard attributes, and berry composition measurements were taken at key phenological growth stages. Additionally, image analysis was used to assess the development and properties of the grapevines canopy architecture at the same key phenological growth stages. Winegrape quality was assessed by the commercial value of grapes ascribed to the vineyard. Regression analysis was used to identify the relationships between vineyard performance measures and winegrape quality. Two models for predicting winegrape quality were developed. A growing season model (GS model), using measures collected up to 50% veraison (EL 35), and a harvest model (HRV model). The GS model showed that soil readily available water (RAW) and canopy architecture up to veraison had the greatest influence on winegrape quality. The HRV model showed that canopy architecture and berry composition had the greatest influence on winegrape quality. The HRV model had better predictive performance than the GS model with the inclusion of harvest berry composition data to compliment canopy architecture measures.

Conclusion: Vineyard canopy image analysis, together with other vineyard attributes including canopy architecture, provide effective early season predictions of Shiraz winegrape quality from regression models. Models of winegrape quality prediction can be augmented with berry composition at harvest to give more precise predictions of Shiraz winegrape quality at harvest.

Significance of Study: This study showed the importance of assessing vine performance through monitoring canopy architecture and how this monitoring gives insight into winegrape quality. Image analysis is a cost-effective technique for monitoring canopy architecture. These techniques enable the prediction of Shiraz winegrape quality early in the growing season. Growers can then modify their management strategy to optimize the combination of yield and quality. The improved predictions of winegrape quality that can be made at harvest allow

growers to plan for the next year. Similar models can be developed for other grape varieties in other wine growing regions.

Introduction

Commercial vineyards can produce a range of different winegrape quality levels each harvest. Winegrape grading before grapes are harvested is the process of ranking different vineyards by quality levels (Winter 2005). Vineyards can have similar vine ages, be situated on similar vineyard soil types, trellis and training systems, latitude and mesoclimates, yet produce grapes of differing perceived qualities (Patic, et al. 2009). In commercial production subjective assessments can be made on berry size, canopy size and shoot density. Finding objective measures that predict or represent winegrape quality has been the focus of vineyard quality benchmarking studies (Rolley 2003; Winter 2004; Lowe 2005). These studies aimed to objectively define and measure winegrape quality, beyond the basic parameters of sugar, acid and colour by ranking vineyards using score card assessments of canopy architecture.

Having objective winegrape quality measures allows for improved vineyard management, as grape growers can target their practices to maximise winegrape quality in a timely manner (Allan 2003). Grapegrowers must interpret seasonal conditions to achieve the expected quality and quantity of grapes they produce at harvest. Grapevine quality is managed throughout the grapevine growing season. Grapegrowers actively manage their vineyards to produce grapes with desirable traits by controlling the way that grapevines grow through each season. Decisions are made on the vineyard operations, including irrigation and canopy management, with the aim of producing grapes of a desired outcome and often of the highest possible quality. For example, reducing grapevine canopy growth and berry size by altering the timing or amount of irrigation is used to maximise winegrape quality (Dry & Loveys 1998) by increasing desirable berry traits like total anthocyanins (Cook et al. 2015).

There are many factors which determine winegrape quality and hence the quality of the resultant wine. Relying on visual appearance to assess vineyards is unreliable because wine production cannot be adequately described by one selected variable without the risk of serious misrepresentation (Cozzolino et al. 2009). Significant efforts have shown that defining and measuring quality is not a simple exercise and suggest that focusing on selected key measurable attributes and developing a matrix approach to assessment is more likely to be successful than attempting to broadly define ‘quality’ in a single measurement (Gishen et al. 2002; Francis et al. 2005).

One of the currently used methods to assess quality in-season is using previous wine performance as a prediction of current season quality (Golan & Shalit 1993). The concept of vine performance from one season influencing the next is the basis of hedonic market pricing (Oczkowski 1994). Hedonic grading is defined as the current value of the current season’s grapes being ascribed based on the previous quality of wine produced.

There are a series of objective measures of quality that can be taken based on measuring vineyard growth and canopy density and grape composition at harvest (Dobrowski et al. 2002). For example, vineyard canopy architecture, including light exposure, shoot number, shoot vigour, canopy density, and vine leaf size, have been correlated to winegrape quality (Smart 1985; Dokoozlian & Kliewer 1995; Cartechini & Palliotti 1995). Therefore, assessing grapevine canopy architecture and manipulating vine growth, vigour and light transmission through the canopy has potential for maximising winegrape quality. Vineyard canopy measurements include shoot length, internode length, visual estimate of light exposure and point quadrat assessment (Dry et al. 1998; Gladstone & Dokoozlian 2003; Vargas et al. 2016).

One objective measure that is used in the classification of grapevine canopies, particularly in field research, is leaf area index (LAI). LAI is commonly defined as the total one-sided area of leaf tissue per unit ground surface area (Watson 1947). LAI can be either measured directly using destructive methods or indirectly using dedicated and expensive instrumentation, both of which require a high level of know-how to operate equipment, handle data and interpret results. The complexity involved in collecting LAI measurements has been prohibitive. But, recently the automated estimation of LAI using image analysis has been developed (De Bei et al. 2016) and offers a commercially viable measurement.

The aim of this project was to assess whether different grapevine performance measurements assessed during the growing season could predict winegrape quality. The performance measurements used were adapted for commercial practice, so that they were non-destructive and repeatable over multiple vineyards, allowing for efficient data collection. This paper describes the development of two models, a growing season model (GS model), with measurements taken up to 50% veraison (EL 35) and a harvest model (HRV model) with measurements taken up to the growth stage of berries EL 37 as defined by Coombe (2004). This study also investigated the relative contribution of the various vineyard performance measures to the prediction of winegrape quality.

Materials and Methods

Experimental design and vineyard details

Thirty-five commercial Shiraz vineyards in the McLaren Vale and Langhorne Creek wine regions were selected for this experiment. Twenty-eight vineyards were in the McLaren Vale wine region. Seven vineyards were in the Langhorne Creek wine region. The experiment took place over three seasons, 2014, 2015 and 2016. Vineyards were chosen to represent a range of winegrape quality levels based on the value of the specific site, as assessed by the winemaker, in the previous season before the trial. A summary of site-specific vineyard details is provided in Tables 1 and 2.

Vineyards varied in vine age, planting material (clone), trellis, planting density, row orientation and canopy management. Vineyard sizes ranged from one hectare to six hectares. All vineyards were under drip irrigation and irrigation volume ranged from dry grown (no irrigation applied via the drip irrigation system) to 2.5 ML/ha. Soil types are defined by Fairburn et al. (2010) and Carosone & Cobb (1975) for the McLaren Vale and Langhorne Creek regions respectively. The soil readily available water holding capacities (RAW) were estimated for each vineyard using methods described in Gupta et al. (1979). Vineyard harvest dates ranged from late February (end of summer) to late March (mid-autumn) for all years of the study.

Table 1. Site specific details of cv. Shiraz vineyards in the McLaren Vale Wine Region included in study.

Historical Grading	Vine age (years)	Clonal material	Soil Type	Readily available water (RAW mm)	Vineyard floor mgmt.	Under vine mgmt.	Soil Moisture monitoring	Water source	Water usage band (ML)	Area (ha)	Row Orientation	Vine planting density (vines/ha)	Cordon Number	Trellis style	Shoot thinned
A	15-20	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	Bore[1]	1.0-1.5	3.79	E/W	1852	Double	Sprawl	Yes
A	15-20	1127	Black clay	75-100	Permanent sward	Herbicide	Yes	Recycled[2]	0.5-1.0	2.20	N/S	1852	Single	Catch wires	No
B	15-20	n/a	Red clay loam	125-150	Permanent sward	Cultivate	Yes	Bore	1.0-1.5	4.49	N/S	1667	Single	Catch wires	No
B	15-20	1654	Red clay loam	125-150	Permanent sward	Herbicide	No	Bore	1.0-1.5	5.00	N/S	2084	Single	Catch wires	No
B	15-20	1654	Red clay loam	125-150	Annual cereal	Herbicide	Yes	Bore	0.5-1.0	5.64	N/S	2084	Single	Catch wires	No
A	15-20	1654	Red clay loam	125-150	Permanent sward	Herbicide	No	Bore	0.5-1.0	4.05	N/S	1667	Single	Catch wires	No
B	10-15	R6v28	Red clay loam	50-75	Permanent sward	Herbicide	Yes	Recycled	0.5-1.0	4.15	E/W	2222	Single	Catch wires	No
A	>20	n/a	Red clay loam	100-125	Permanent sward	Herbicide	Yes	Bore	0.5-1.0	2.24	N/S	1667	Single	Catch wires	Yes
A	15-20	BVRC30	Black clay	75-100	Permanent sward	Cultivate	Yes	Recycled	0.5-1.0	0.79	N/S	2272	Single	Catch wires	No
A	15-20	BVRC30	Black clay	75-100	Permanent sward	Cultivate	Yes	Recycled	0.5-1.0	1.93	E/W	2272	Single	Catch wires	No
C	10-15	R6v28	Red clay loam	100-125	Permanent sward	Herbicide	Yes	Bore	1.0-1.5	0.9	E/W	2222	Single	Catch wires	No
B	10-15	1654	Red clay loam	75-100	Annual cereal	Herbicide	Yes	Recycled	0.5-1.0	4.27	N/S	2084	Single	Catch wires	Yes
C	10-15	1654	Red clay loam	100-125	Annual cereal	Herbicide	Yes	Recycled	0.5-1.0	1.74	N/S	2084	Single	Catch wires	Yes
A	15-20	1127	Red clay loam	75-100	Permanent sward	Cultivate	No	Recycled	0.5-1.0	3.25	E/W	2084	Single	Catch wires	No
C	10-15	1654	Red clay loam	75-100	Permanent sward	Herbicide	Yes	Bore	0.5-1.0	1.11	N/S	2222	Single	VSP	No
B	>20	1654	Red clay loam	50-75	Cultivate	Herbicide	Yes	Bore	0.5-1.0	1.25	E/W	2222	Single	Catch wires	No
B	>20	n/a	Sand	150-175	Permanent sward	Herbicide	No	Bore	<0.5	3.24	E/W	1515	Single	Sprawl	No
B	5-10	SAVII 13	Red clay loam	75-100	Permanent sward	Cultivate	Yes	Recycled	1.0-1.5	0.97	E/W	2272	Single	Catch wires	No
B	10-15	1654	Red clay loam	125-150	Permanent sward	Herbicide	Yes	Recycled	1.0-1.5	5.05	N/S	2222	Single	Catch wires	No
C	10-15	1654	Black clay	125-150	Permanent sward	Herbicide	Yes	Recycled	1.5-2.0	5.05	N/S	2222	Double	Catch wires	No
B	10-15	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	Recycled	1.0-1.5	4.78	N/S	2222	Single	Catch wires	Yes
A	>20	n/a	Red clay loam	100-125	Permanent sward	Herbicide	No	Bore	1.0-1.5	1.17	N/S	2222	Single	Sprawl	Yes
B	15-20	n/a	Red clay loam	100-125	Permanent sward	Herbicide	No	Bore	1.0-1.5	3.70	N/S	2222	Single	Catch wires	Yes
B	15-20	1654	Red clay loam	125-150	Permanent sward	Herbicide	No	Bore	1.0-1.5	2.88	N/S	2222	Double	Catch wires	Yes
C	15-20	1654	Black clay	150-175	Permanent sward	Herbicide	Yes	Bore	1.0-1.5	3.56	N/S	2222	Double	Catch wires	Yes
A	15-20	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	Bore	1.0-1.5	3.50	N/S	2222	Double	Catch wires	Yes
A	15-20	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	Bore	1.0-1.5	3.50	N/S	2222	Double	Catch wires	Yes
A	15-20	1654	Red clay loam	100-125	Permanent sward	Herbicide	Yes	Bore	1.0-1.5	4.17	N/S	2222	Single	Catch wires	Yes

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[1] Bore = underground aquifer water source

[2] Recycled = Recycled water from Willunga Basin Water Company irrigation scheme.

Table 2. Site specific details for the cv. Shiraz vineyards in the Langhorne Creek Wine Region included in study.

Historical Grading	Vine age (years)	Clonal material	Soil Type	Readily available water (RAW)	Vineyard floor mgmt.	Under vine mgmt.	Soil Moisture monitoring	Water source	Water usage band (ML)	Area (ha)	Row Orientation	Vine planting density (vines/ha)	Cordon Number	Trellis style	Shoot thinning
A	15-20	1654	Red clay loam	100-125	Permanent pasture	Herbicide	Yes	Lake water[3]	1.5-2.0	4.56	N/S	1852	Single	VSP	Yes
C	15-20	1127	Sand	125-150	Permanent pasture	Herbicide	No	Lake water	>2.5	5.70	N/S	1852	Single	Catch wires	No
B	15-20	n/a	Red clay loam	125-150	Permanent pasture	Cultivatie	No	Lake water	>2.5	6.00	N/S	1667	Single	Catch wires	No
C	15-20	1654	Red clay loam	100-125	Permanent pasture	Herbicide	No	Lake water	>2.5	4.56	N/S	2084	Single	Catch wires	No
D	15-20	1654	Red clay loam	175-200	Annual cereal	Herbicide	No	Lake water	1.5-2.0	4.50	E/W	2084	Single	Catch wires	No
A	15-20	1654	Red clay loam	100-125	Permanent pasture	Herbicide	Yes	Lake water	1.5-2.0	5.59	N/S	1667	Single	Catch wires	No
C	>20	BVRC 30	Red Clay loam	100-125	Annual cereal	Herbicide	No	Lake water	1.5-2.0	4.22	N/S	1852	Single	Catch wires	No

At each site, six panels of four vines were randomly selected to give a total of 24 sample vines from each vineyard. The rows, and the position of the panels within selected rows, were chosen using random digits generated by Excel (version 1812). These panels were used to assess vineyard performance during the growing season. In all three years the measurements described in Table 3 were taken from the same sample panels.

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[3] Lake = Langhorne Creek region irrigation water supplied from Lake Alexandrina/Murray River.

Table 3. List of vineyard performance measures and timing in the cv. Shiraz vineyards study.

Growth Stage	Measurements
EL 4	bud number retained at pruning, soil readily available water (RAW), row orientation, previous seasons winegrape quality grade
EL 17	count shoots per metre, non-count shoots per metre, total shoots per metre
EL 25	leaf area index (LAIe), light environment (canopy porosity), inflorescence count
EL 35	leaf area index (LAIe), light environment (canopy porosity), irrigation usage (ML/ha)
EL 37	Berry and juice composition: tannin concentration (mg/g berry weight), phenolic level (mg/g), total berry anthocyanin (mg/g), sugar content (°brix), total soluble solids (TSS), pH and titratable acidity (TA), berry weight (g), Canopy measurements: leaf area index (LAIe), canopy density (porosity),
EL 38	yield per metre of cordon (kg)

Collection of vineyard data and vine performance measures

The vineyards previous season grading was obtained by a survey of the grape growers.

Vineyard row orientation was given a score. If rows were oriented East/West they were given a score of 1, if they ran North/South they were scored 0. At the beginning of the growing season, the bud number retained after pruning was manually counted at the grapevine growth stage budburst (EL 4, Coombe 1995), and expressed as buds per metre of cordon. Manual counting of shoots per metre of cordon was repeated at EL 17 (10-12 leaves separated). Shoots were classified into two categories: count shoots (shoots growing from the grapevine buds retained during pruning) and non-count shoots (described as those that burst from buds not deliberately left at pruning or from basal buds on the cordon or trunk). The total number of shoots per metre was calculated as the sum of the number of count shoots and non-count shoots and was used as a measure of canopy shoot density. Bunch number was assessed by counting inflorescence number per metre of vine cordon at full flowering (EL 25).

The vineyard management practice of shoot thinning was given a score. If grape growers completed a pass of shoot thinning, they were scored as 1, if no pass was performed they scored 0.

Canopy architecture was measured using the VitiCanopy application (De Bei et al. 2016). Images were collected from the assessment panels in each vineyard using an iPad Air, or iPhone 5S, 6 and 7 (Apple, Cupertino, CA) and analysed using the VitiCanopy App. All canopy photos were taken with the device positioned at 70 cm below the cordon. Images were acquired at key phenological growth stages: 80% capfall (EL 25), 50% veraison (EL 35) and before harvest (EL 37).

VitiCanopy calculated the following canopy architecture parameters using algorithms described in Fuentes et al. (2008, 2014) which were calculated from Macfarlane et al. (2007):

- Leaf area index (LAIe): total one-sided area of leaf tissue per unit ground area corrected by the clumping index.
- Canopy porosity: percentage of gaps within the image (spaces), which can be related to the light penetration through the canopy.

The average value of the six reference panels sites was used to produce a value for LAIe and canopy porosity.

At harvest, yield was estimated by counting the number of bunches per vine and weighing the fruit to then estimate bunch weight from the six reference panels in each vineyard. The average of the six reference panels was used.

Grape berry and juice composition

Bunch samples were collected at EL 37 from all vineyards. Ten bunches were collected from each panel and then mixed to form three replicates of 20 bunch samples from each vineyard. From each of the three replicate samples 100 berries were randomly collected and stored at -20°C for berry composition measures.

Berry samples were assessed for TSS, pH, TA, and Brix according to Iland et al. (2007). Total anthocyanins and phenolics were measured using methods described in Mercurio et al. (2007). Winegrape berry tannin were assessed using the methyl cellulose precipitable (MCP) tannin assay measuring the total grape tannin in red grape homogenate extracts (Sarneckis et al. 2006) the results provide tannin concentration expressed in epicatechin equivalents (mg/g berry weight). The values of berry and juice composition used for statistical analysis were an average of the three replicate samples.

Winegrape quality assessment/grade

An original approach was used in this study to ascribe winegrape quality. In commercial practice and alphanumeric system (A1, A2, A3… D) is often used to differentiate winegrape qulaity, however often this system is not transferable across different regions and varieties. To assist comparison this study used the value of the winegrapes in terms of money per tonne as way of differentiating quality level. Winegrape purchase price was expressed in Australian dollars (AUD) per tonne of grapes. The price obtained for the winegrapes was then graded into bands of $500 AUD increments, starting at a level below $1000 and ending at greater than $5000 (Table 4a). The band that the winegrapes were assigned was termed the winegrape quality grade and used as the response variable in this experiment.

Table 4a. Matrix of winegrape pricing used in the cv. Shiraz vineyard performance study.

Grading Level	Alphabetical Grading	Price Range per tonne (AUD)
10	A	>$5000
9	A	$4500-$4999
8	A	$4000-$4499
7	A	$3500-$3999
6	A	$3000-$3499
5	B	$2500-$2999
4	B	$2000-$2499
3	B/C	$1500-$1999
2	C	$1000-$1499
1	D	<$999

Statistical analysis

Multiple regression was used to model the relationship between winegrape quality grades, the response, and the vineyard performance measures, predictor variables, which can be classed into three categories: grapevine management variables; environmental variables; and grape characteristics. Models were fitted for the growing season and at harvest, within each of the three years and for the three years combined. The regressions were analysed using the XLSTAT statistical software (version 2015.1, developed by Fahmy and Aubry (2003) and the R statistical programme (version 2.15.3) R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Predictor variables were selected so that their measurement would be compatible with standard vineyard practice, and so that they would be representative of the three categories. Grape characteristics included were berry composition analysis (tannin, colour, phenolics) and berry weight. Grapevine management variables included trellis type, row orientation, water regime and canopy management techniques. The environmental variable used described the soil water holding capacity. Canopy architecture was assessed by shoot density, LAI and canopy porosity measures.

The general form of the regression models fitted to data from a single year as:

$$\begin{aligned} &Y_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki} + \varepsilon_i \\ &i = 1, \ldots, 35 \end{aligned}$$

where *i* is an identifier for vineyard, Y_i is the winegrape quality grade, $x_{i1}, x_{2i}, \ldots, x_{ki}$ are the values of *k* predictor variables, $\beta_0, \beta_1, \ldots, \beta_k$ are unknown coefficients to be estimated, along with their standard errors, and ε_i is random error. The random error is assumed to be independently and identically distributed with mean 0.

The overall model included all the measurement variables and the additional term 'Previous Year Grading' which was the quality grade the vineyard achieved in the season before the measured season. The overall model had the random effects, τ_j, to allow for the different years and random effects, α_i, for vineyards to allow for the three repeated sets of measurements taken over the three years from the vineyards. This model has the form:

$$Y_{ij} = \beta_0 + \tau_j + \alpha_i + \beta_1 x_{1ij} + \cdots + \beta_k x_{ij} + \varepsilon_{ij}$$
$$i = 1, \ldots, 35 \; , \; j = 1,2,3$$
$$\tau_j \sim 0, \sigma_j^2$$
$$\alpha_i \sim 0, \sigma_i^2$$

where all the components of variance are independently distributed.

Development of models

An initial regression model of winegrape quality was fitted with all the variables measured in the study up to the growth stage of EL 35. The predictive performance was assessed by the coefficient of determination, R^2 (defined as the proportion of the variance in quality explained by the model). Variables were selected based on their contribution to the model based on R^2.

The GS model used measurements either related to vineyard design, establishment, management practices, soil water holding capacity or canopy architecture, all of which were measurable up to EL 35. The measurement of vineyard set up and management were, irrigation volume (ML) up to EL 35, row orientation (north/south or east/west) and the undertaking of shoot thinning (yes or no). An estimate of soil water holding capacity was taken as soil RAW. Measurements of canopy architecture were taken at two growth stages EL 25 and EL 35. Canopy architecture measurements were related to canopy size (leaf area index) and light environment (canopy porosity).

A HRV model regression of winegrape quality was fitted with all the variables measured in the study. The model was refined by retaining those variables that had lower p- values. The HRV model used the measurements LAIe and canopy porosity at EL 35 and EL 37 with additional grape berry composition measures taken at EL 37 (berry size, colour, tannin and phenolics).

Results

Range of LAI at EL 25, 35, 37

LAIe can be used as an estimate of vine size. Over the course of the trial vineyards in McLaren Vale (Table 4b) has lower values of Leaf Area Index than those in Langhorne Creek (Table 4c).

Table 4b: Range of Leaf Area Index (LAIe) at key growth stages in cv. Shiraz in the McLaren Vale Wine Region, South Australia, vintages 2014-2016.

Vintage	EL 25 lowest LAIe	EL 25 highest LAIe	EL 35 lowest LAIe	EL 35 highest LAIe	EL 37 lowest LAIe	EL 37 highest LAIe
2014	1.29	2.11	1.39	2.25	1.58	2.27
2015	1.51	2.92	1.59	3.31	1.54	3.79
2016	1.89	3.10	1.78	3.01	1.76	3.19

Table 4c: Range of Leaf Area Index (LAIe) at key growth stages in cv. Shiraz in the Langhorne Creek Wine Region, South Australia, vintages 2015-2016.

Vintage	EL 25 lowest LAIe	EL 25 highest LAIe	EL 35 lowest LAIe	EL 35 highest LAIe	EL 37 lowest LAIe	EL 37 highest LAIe
2015	2.39	4.22	2.59	4.64	2.19	4.11
2016	2.19	4.24	2.28	4.62	2.59	4.46

Combined growing season model

Standardised coefficients of variables were generated from the growing season linear fixed effect model shown in Figure 1. Coefficients of the predictor variables are presented in standardised form, meaning they are multiplied by the standard deviation of the predictor variable and are non-dimensional. This makes variables directly comparable and predictor variables with larger coefficients have a more significant effect on winegrape quality. Analysis of the standardised coefficients of variables allowed the weighted effect of each measurement variable to be determined.

The previous vintages grading was seen to be a predictor of the current season grading indicating previous season winegrape quality had an influence on the quality of the present season. A vineyards previous season can influence the current season by many factors including carbohydrate storage (Vasconcelos & Castagnoli 2000), and the growth/yield relationship (Howell 2001).

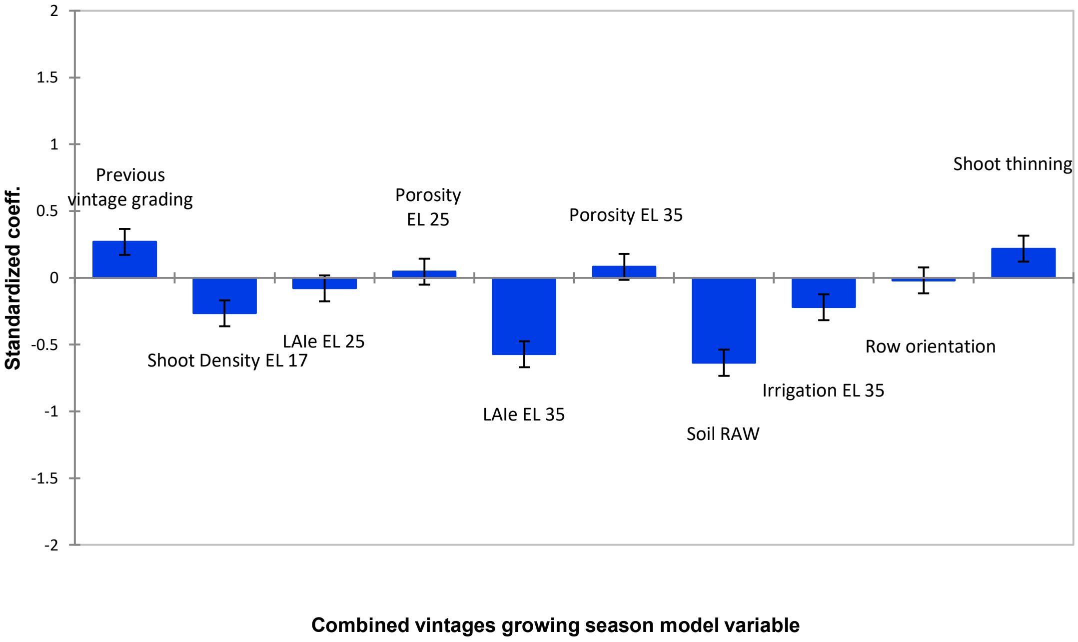

Figure 1. Standardised coefficients ± SE of variables in GS prediction model for cv. Shiraz in the McLaren Vale and Langhorne Creek wine regions, South Australia for the combined vintages 2014, 2015 and 2016.

Table 5. Summary table of standardised coefficients from combined vintages GS modelling of winegrape quality prediction of cv. Shiraz in the McLaren Vale and Langhorne Creek Wine Regions, South Australia.

Source	Standardised coefficient
Previous vintage grade	0.271
Shoot Density at EL 17	-0.265
LAIe at EL 25	-0.077
Canopy porosity at EL 25	0.048
LAIe at EL 35	-0.571
Canopy porosity at EL 35	0.082
Soil RAW	-0.636
Irrigation amount	-0.218
Row orientation	-0.019
Shoot thinning	0.217

In this study vineyards with high LAIe measures at EL 35 had a negative influence on quality, indicating that high leaf area measurements (i.e. larger measured canopy size) were a predictor of a low-quality grade. Higher shoot density at EL 17 is associated with lower quality. These variables can be influenced by vineyard practices. High soil readily available water (RAW) had a negative association with winegrape quality. Soil RAW is a constant measurement across all seasons as it cannot be significantly changed by vineyard practices.

Individual growing season models

A summary of each individual growing season model (GS models) is shown in Figure 2. The R^2 values for the individual growing seasons are summarised in Table 6. The 2015 and 2016 GS models were statistically significant with $p=0.017$ and $p=0.015$ respectively. The ability of the 2014 GS model to predict the winegrape quality grade was not significant (R^2 of 0.4, $p= 0.36$).

Table 6. Goodness of fit and analysis of variance of GS linear fixed effect prediction models for cv. Shiraz in the McLaren Vale and Langhorne Creek wine regions, South Australia.

Vintage	R^2	F	Pr > F
2014	0.401	1.192	0.363
2015	0.538	2.977	0.017
2016	0.544	3.052	0.015

The absolute magnitudes of the coefficients of the predictor variables in the growing season models (Figure 2b, 2d, 2f and Table 7) show the relative influence of the variables on winegrape quality. LAIe and canopy porosity measured at EL 35 were the most convincing predictors of winegrape quality because their coefficients were: consistently negative and positive respectively in all three years; consistently statistically significant at the 0.05 level (the null hypothesis is that the coefficient is 0) in all three years. These two variables were also found to be significant in the combined GS model. Vineyards with lower LAIe and higher canopy porosity at EL 35 i.e. smaller canopies, with greater porosity at EL 35 had a higher winegrape quality grade. Large vines with high LAIe and lower porosity led to lower winegrape quality grade in all seasons.

Other variables were shown to be significant depending on the season. Canopy measures taken earlier in the season at EL 25 had a significant influence on the GS model in 2014 and 2015. Porosity at EL 25 had a significant influence in the 2015 GS model with higher canopy porosity levels indicating a higher quality grade.

Soil RAW was a significant contributor to the GS models in 2015, 2016 and the combined GS model with lower soil RAW predicting a higher quality grade. Irrigation amount applied to EL 35 was a significant indicator in the 2016 GS model, with vineyards that applied lower irrigation volumes having a higher winegrape quality grade.

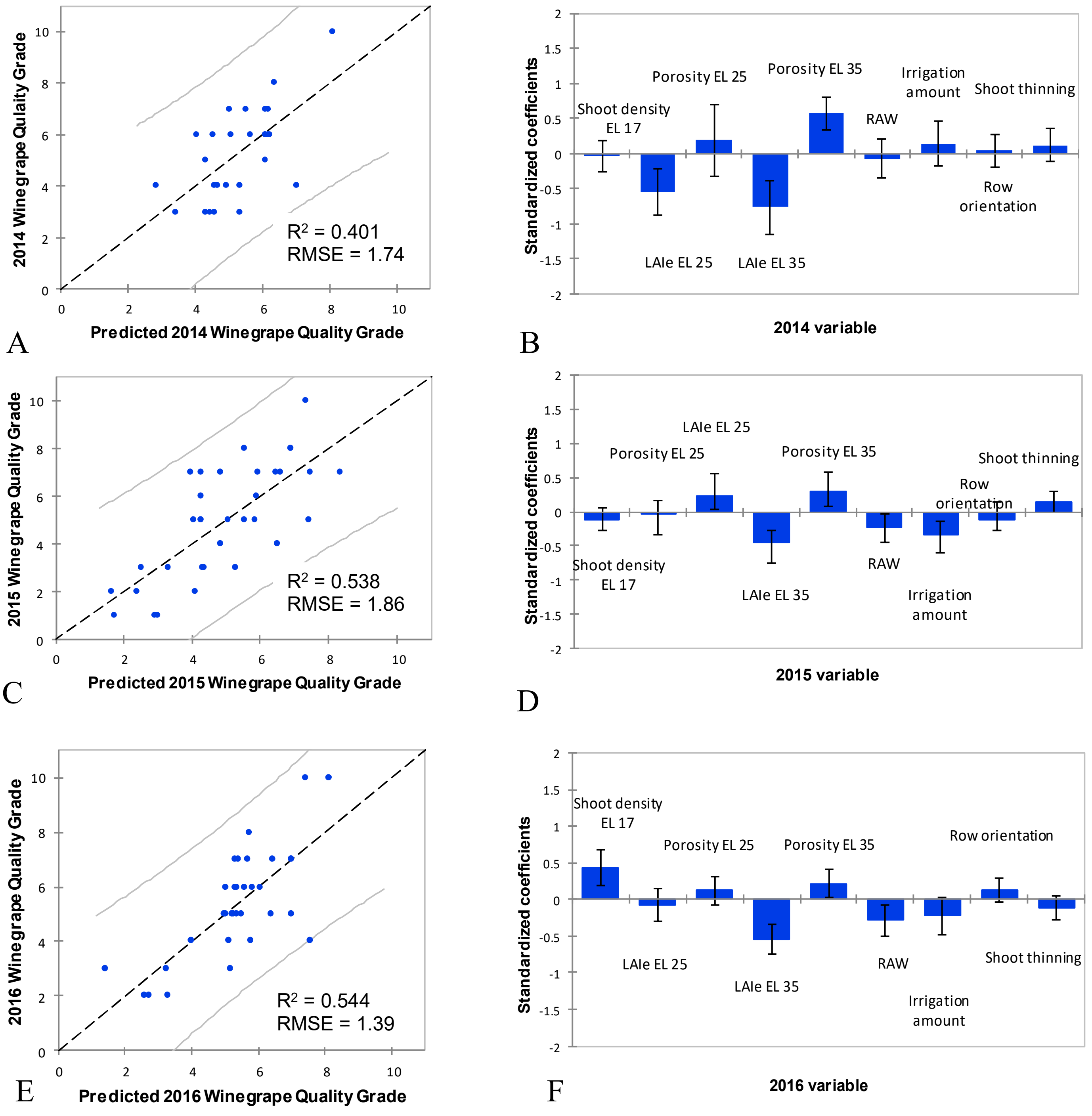

Figure 2. Graphical summaries of GS regression models of cv. Shiraz in the McLaren Vale and Langhorne Creek Wine Regions, South Australia. Left hand panels are plots of achieved winegrape quality grade against predicted quality (with 95% prediction intervals). Right hand panels are standardised regression coefficients, plus or minus standard errors. Rows correspond to vintage: 2014 (A,B), 2015 (C,D), 2016 (E,F).

Table 7. Summary table of standardized coefficients from GS modelling of winegrape quality prediction of cv. Shiraz in the McLaren Vale and Langhorne Creek Wine Regions, South Australia in vintage 2014, 2015 & 2016.

Source	2014	2015	2016
Previous vintage grade	-	-	-
Shoot Density at EL 17	-0.037	-0.108	0.426
LAIe at EL 25	-0.553	-0.011	-0.069
Canopy porosity at EL 25	0.191	0.236	0.125
LAIe at EL 35	-0.769	-0.453	-0.540
Canopy porosity at EL 35	0.575	0.288	0.218
Soil RAW	-0.072	-0.236	-0.282
Irrigation amount	0.141	-0.336	-0.224
Row orientation	0.039	-0.121	0.122
Shoot thinning	0.114	0.139	-0.120

Combined vintages harvest model

Standardised coefficients of variables were generated from the HRV model (Figure 3). Analysis of the standardised coefficients of variables allowed the weighted effect of each measurement variable to be determined.

The previous season grading had a positive influence on the following season (Figure 3 & Table 7). This was consistent with the results of the combined seasons GS model (Figure 1). Canopy architecture also had an influence on the HRV model (Figure 3) which was consistent with the combined GS model (Figure 1). Grape berry composition measurements taken at pre-harvest (total tannin, phenolics and anthocyanins) had a positive association with winegrape quality with higher measured levels of total tannin, phenolics and total anthocyanin predicting a higher winegrape quality grade.

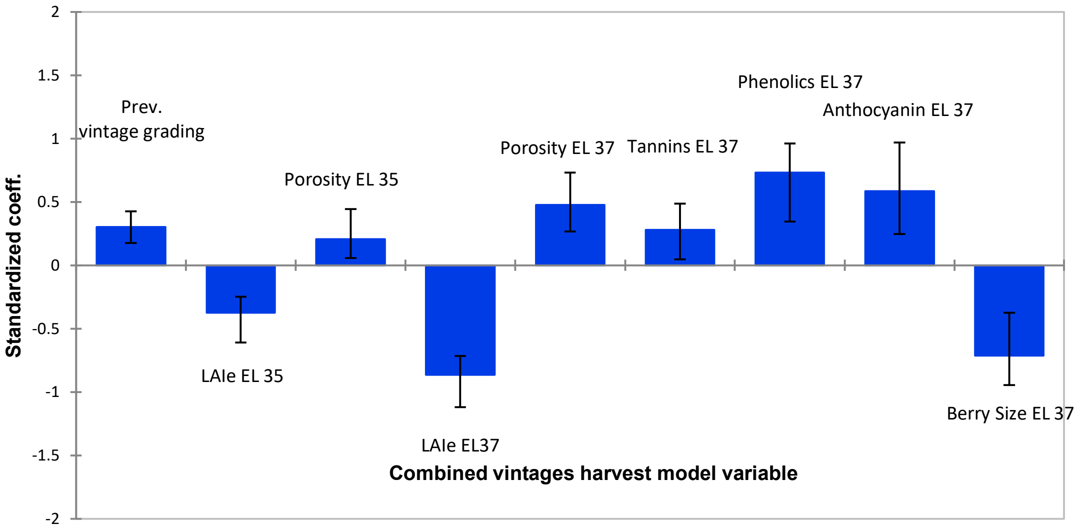

Figure 3. Standardised coefficients ±SE of variables in HRV linear fixed effect prediction model for cv. Shiraz in the McLaren Vale and Langhorne Creek wine regions, South Australia for the combined vintages 2014, 2015 and 2016.

Individual harvest models

HRV models were developed with measurements taken up to pre-harvest (EL 37) for each of the vintages studied (Figure 4). The R^2 values for the harvest models were statistically higher as might be expected because they used direct measurements of berry composition. Berry composition in grapes relates closely to the composition of the final wine. The R^2 values for the HRV models in each season were above 0.6 (Table 8) were statistically significant with p values of at the 0.05 level ($p=0.005$, $p= < 0.0001$ and $p= 0.001$ respectively).

Table 8. Summary table of standardized coefficients from HRV modelling of winegrape quality prediction of cv. Shiraz in the McLaren Vale and Langhorne Creek Wine Regions, South Australia in vintage 2014, 2015 & 2016.

Vintage	**R^2**	**F**	**PR > F**
2014	0.711	4.383	0.005
2015	0.707	7.244	< 0.0001
2016	0.642	5.388	0.001

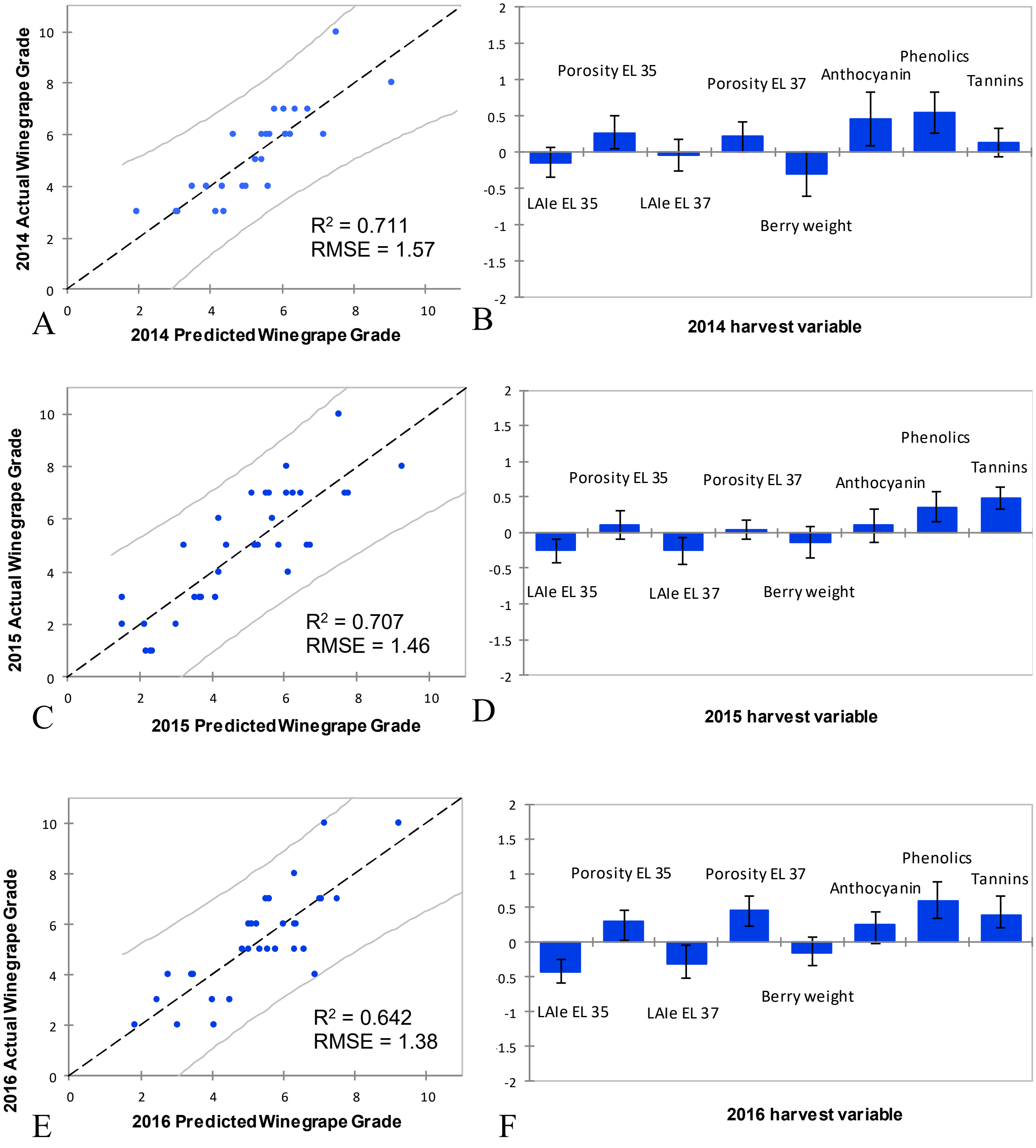

Figure 4. Graphical summaries of HRV regression models of cv. Shiraz in the McLaren Vale and Langhorne Creek Wine Regions, South Australia. Left hand panels are plots of achieved winegrape quality grade against predicted quality (with 95% prediction intervals). Right hand panels are standardised regression coefficients, plus or minus standard errors. Rows correspond to vintage: 2014 (A,B), 2015 (C,D), 2016 (E,F).

Analysis of the variables, (Figure 4b, 4d and 4f) showed the relative influence of the variables on the winegrape quality grade. Vineyards with higher berry phenolic levels had a higher winegrape quality grade. The absolute magnitude of the coefficients of phenolics, was statistically significant at the 0.05 level (the null hypothesis is that the coefficient is 0) in all three years, indicating that this variable was a consistent predictor of winegrape quality.

Other variables were shown to be significant influencers in specific seasons, and/or the combined HRV model. Anthocyanin was a significant predictor of quality in the 2014 GS model with vineyards with higher anthocyanin levels having a higher winegrape quality grade. Harvest tannins were significant in the 2015 and 2016 model. Vineyards that produced grapes with higher tannin levels were seen to have a higher winegrape quality grade. Measurements of canopy architecture taken at EL 35 were significant in the combined model. LAIe taken at EL 35 was significant in the 2015 and 2016 models with vineyards with a lower LAIe having a higher quality grade.

Discussion

This study developed models for predicting winegrape quality using in-season vine performance measurements that could be used in a commercial practice on a wide scale. Measurements that were taken up to EL 35 were used to create the GS model. The HRV model was not limited by timing and included measurements taken up to EL 37 including grape berry composition measures taken from bunch samples.

When comparing the GS models with the HRV models unsurprisingly the HRV models performed better at predicting the winegrape quality grade. The HRV model's R^2 values (Table 7) were statistically higher when compared to the corresponding growing season models (Table 5). As might be expected using berry composition measures as an assessment to model winegrape quality grade improved the accuracy of the harvest models compared to the growing season models. Including berry composition measures in assessing winegrape quality is consistent with previous studies linking ripeness of tannins and other phenolic compounds in the grapes that contribute to the colour, flavour and aroma of wine (Conde et al. 2007; Mercurio et al. 2010; Ristic et al. 2010). Anthocyanins in the grape berry are important contributors to wine quality (Somers & Evans 1974; Jackson et al. 1978; Freeman

1983; Glories 1988; Mazza et al. 1999). These studies support the link between berry composition and winegrape quality.

Analysis of the standardised coefficients of variables allowed comparison of the relative effect of each variable on the winegrape quality grade. This gave insight into which vineyard measures had the greatest influence on the prediction model. The results generally showed that the closer to harvest the measurement was taken, the greater the influence on the winegrape quality model.

Growing season models

Positive correlations were found between the predicted winegrape quality grade and the actual winegrape quality grade as modelled by the GS models (Figure 1). This would indicate that measurements of vineyard canopy growth, and the factors that affect vineyard canopy growth influenced by vineyard establishment and management (estimated soil RAW, irrigation ML and the presence or absence of shoot thinning) do influence the winegrape quality grade. Measures of canopy architecture were consistent predictors of winegrape quality which is consistent with previous research (Smart 1985; Dokoozlian & Kliewer 1995).

The GS models showed that measurement of canopy architecture (canopy size, density and porosity) had an influence on winegrape quality. LAIe and canopy porosity at veraison (EL 35) were significant across all GS models. Vineyards with lower estimates of LAIe had a higher winegrape quality grade. Canopy architecture has been correlated to yield, winegrape quality and productivity (Smart 1985), berry composition has been shown to be altered by light exposure levels on developing fruit (Smart et al. 1981; Coombe & Iland 1987; Haselgrove et al. 2000). These studies variously concluded that vineyard canopies produced fruit with higher quality if they were open to sunlight and had controlled vigour to limit the vines vegetative growth.

Shoot counts expressed as shoots per metre have been used to compare canopies across seasons and vineyards and provide an estimate of shoot density. Shoot density measurements have been used to indicate canopy porosity and light exposure into the canopy (Reynolds & Wardle 1989, Smart 1991; Dokoozlian & Kliewer 1995). In this study measures of shoot density were performed early in the growing season at EL 17. Shoot counts were not as good at predicting winegrape quality as measures obtained later in the growing season by image analysis (LAIe and canopy porosity). Not surprisingly, measures of LAIe and canopy porosity by image analysis are less labour intensive to perform than early season shoot counts and therefore may be more cost effective and of greater value in a commercial situation.

For the GS models, LAIe measurements taken at EL 35 were a consistent variable in the prediction of winegrape quality grade. LAIe measurements taken at EL 35 had a greater influence on winegrape quality compared to the same measurement taken at EL 25. This may be due to the important changes that occur at EL 35 inside the berry. The growth stage EL 35 corresponds with the onset of ripeness, where berry acidity decreases, and sugar accumulation and anthocyanin production begin (Hrazdina, et al. 1984; Cortell & Kennedy 2006; Conde et al. 2007). Specifically, low light intensity in the canopy is seen to produce a berry composition of lower quality for winemaking purposes (Ristic et al. 2007). A low light environment inside the vine canopy has been found to produce fruit with lower colour, lower amounts of phenolic compounds and lower tannin levels (Keller & Hrazdina, 1998; Smart et al. 2017).

Measurements of canopy porosity at EL 35 showed a significant positive affect on the winegrape quality grade across combined seasonal GS models (Figure 1). Increased porosity at EL 35 is associated with higher winegrape quality, over the range of porosity observed in the study. This indicates that a canopy with lower levels of shading at EL 35 were beneficial for winegrape quality grade at harvest across the three seasonal GS models.

Canopy porosity was measured as the percentage of gaps within an image and was used in this study as an estimate of light penetration through the canopy. Canopy porosity at flowering had a significant positive association on the 2015 GS model (Figure 2d), but for the other GS models it was not a reliable indicator. Early assessment of canopy porosity from image analysis may not be a consistent assessment across seasons as the vine is only part the way through its vegetative growth cycle. As with LAIe a clearer influence was shown with the measures at EL 35 and EL 37 when vines were more advanced in their growth cycle. Weather conditions, including cloud cover and wind direction and speed, between EL 35 and EL 37 are likely to influence the light environment in the canopy. Rainfall during the growing season will increase soil moisture levels. Vines are shown to grow additional lateral shoots and new leaves if they are supplied with an abundance of water (Intrigliolo & Castel 2010; Cramer et al. 2013).

Alternatively, if water is withheld by drought conditions or deficit irrigation vines are shown to have lower values of total leaf area at harvest, leaf layer number, and lateral shoot number, allowing a higher light interception for bunches (Matthews & Anderson 1988; Hunter et al. 1995; Dry et al. 1998; Van Leeuwen, et al. 2009). Additionally, other weather factors including wind speed, air and soil temperature, will influence the light environment in the canopy by influencing the extent to which leaves senesce earlier in the growing season, including if hey senesce before harvest.

Canopy management often aims to increase light exposure and change grape biochemistry. Previous research has shown that low levels of shading were beneficial for winegrape quality grade at harvest (Reynolds & Wardle 1989; Dokoozlian & Kliewer 1995). However, there is likely an upper limit to light exposure, where too much light exposure reduces winegrape quality through sunburn or heat damage caused by direct sunlight as demonstrated by Haselgrove et al. (2000). The upper limit of light exposure was not established in this study and including methods to monitor vineyards for heat damage and assess the influence on sunburn on winegrape quality is recommended for future research.

In addition to the measures of canopy growth being used in the GS model, factors that affect vineyard canopy growth influenced by vineyard establishment and management (soil RAW, irrigation before veraison and shoot thinning) also influenced the winegrape quality grade. The GS models showed that a low soil RAW, a factor in limiting vegetative growth and therefore preventing shaded canopies, was positively correlated with quality in the 2015 and 2016 GS models. High soil RAW values have been linked to high plant vegetative growth rates in grapevines (Kasimatis 1957; Veihmeyer & Hendrickson 1957) and to lower winegrape quality (Bravdo et al. 1985).

It is known that vine water deficits generally lead to smaller berries, increased light exposure to fruit and to several changes in berry composition (Bravdo et al. 1985; Kennedy et al. 2000; Kennedy et al. 2002) and reducing plant vegetative growth by using water deficit is linked to favourable grape chemistry characteristics, higher tannin, higher phenols and increased colour for winemaking (Intrigliolo & Castel 2010). These changes are considered to produce fruit with better grape berry composition for winemaking, tannin levels, phenolic structure and colour (Dry et al. 1998; De la Hera et al. 2007; Acevedo-Opazo et al. 2010). The levels of irrigation applied in this study varied from dry grown (nil irrigation) to over 2.5ML/ha. Irrigation amount (ML) has been linked to plant growth, with the amount of irrigation applied influencing the amount of plant vegetative growth (Boland et al. 1994). In the combined GS model (Figure 1) the higher the amount of irrigation applied up until veraison the more negative the effect on grapevine quality grade. Although the negative coefficient of irrigation is consistent with the scientific explanation, that the greater the amount of irrigation applied the lower the grapevine quality grade, results were not statistically significantly different from 0 at a p value of 0.10 level.

The number of shoots per vine can vary each season and can be manipulated through shoot thinning as this is thought to lead to better quality fruit through changes to the grape berry biochemistry (Smart et al. 1985; Dry et al. 1998; Downey 2004; Chapman, et al. 2004; Dunlevy et al. 2013) as protein production inside the berry is affected by light exposure (Koyama et al. 2012) and temperature (Cohen et al. 2012). Shoot thinning was used as a canopy management technique to alter the level of light exposure on developing inflorescences by many of the sites included in the experiment (Table 3 & 4) which is why it was included as an indicator variable in this study. In this study shoot thinning had a positive association on the combined GS model, although not at a significant level. This study used the presence or absence of shoot thinning as a factor in the GS model without any assessment of the effectiveness of the canopy manipulation. Solely assessing the presence or absence of shoot thinning did not assess the effectiveness of this shoot thinning. Grape growers shoot thinning practices may not have significantly altered the vine canopy because the amount they were removing was not measured. Quantifying the level of shoot thinning and measuring its changes to the light environment in the canopy is recommended for future research.

Harvest models

HRV models of winegrape quality used vineyard measurements taken up to pre-harvest (EL 37). Additionally, berry size, total anthocyanins, tannin and phenolic levels at EL 37 were used because this is consistent with existing knowledge where a relationship was found between berry composition at harvest, total production, and quality in France (Jones & Davis 2000), California (Jackson & Lombard 1993; Jones & Goodridge 2007) and Australia (Winter et al. 2004).

As seen in the GS models canopy architecture measures influenced the winegrape quality grade. Large canopies, as measured by LAIe at EL 35 and EL 37, had a negative influence on the winegrape quality grade in the combined harvest model (Figure 3). This would indicate a canopy with low levels of shading at EL 35 and EL 37 was beneficial for winegrape quality. Therefore, vineyards that control canopy size through veraison to harvest were more likely to have better winegrape quality grades than those vineyards where the canopy size was relatively larger. Previous studies have shown that low bunch exposure in Shiraz grapes negatively alters wine colour, tannin and sensory properties (Krstic et al. 2007) and canopy shade has been shown to be detrimental to berry composition in numerous other cultivars (Kliewer & Lider 1968; Kliewer & Antcliff 1970; Kliewer 1977; Reynolds et al. 1986; Morrison 1988; Krstic et al. 2010). Monitoring vine growth and undertaking management practices during the growing season with the aim of controlling canopy size and porosity may be beneficial to achieve this. These findings also support previous research where canopy manipulation techniques were used to change grape biochemistry by increasing light exposure (Smart et al. 1985; Dry et al. 1999, Downey 2004; Chapman, et al. 2004; Dunlevy et al. 2013).

Vineyards in this study did not struggle to ripen the fruit, although some sunburn was reported by vineyard owners. The lower limit of leaf area per kg of fruit could be tested in the future to see if a low leaf area reduces fruit quality as has been shown in studies that assess vine balance (Smart et al. 2017).

Large berry size at EL 37 was also found to have a negative effect on winegrape quality. In each of the harvest models there was a link between berry size and winegrape quality end use (Figure 4). Berry size has been recognized as an important factor in determining winegrape quality because it influences the concentration of berry flavour compounds and phenolics, tannins and anthocyanin (Roby et al. 2004). However, berry size has some provisions to consider when used to assess winegrape quality. For example, vines can produce small malformed berries that are associated with excessive water stress during critical phases of vine development (McCarthy 1997). Malformed berries have negative characters for winemaking (Ferreyra et al. 2004). Therefore, placing emphasis on berry weight alone may not be valuable when predicting fruit quality. Future assessments of winegrape quality using berry weight as a measure should establish if malformed small berries impact on fruit quality.

Colour measured as the level of total anthocyanins was shown to positively correlate to winegrape quality grade. In this study higher anthocyanin levels at EL 37 were a predictor variable of higher winegrape quality. This supports previous studies that linked anthocyanin and wine quality in red grape varieties (Somers & Evans 1974; Jackson et al. 1978; Freeman 1983; Mazza et al. 1999).

Total tannin and phenolics were both predictor variables in the harvest model. This was expected as statistical analysis of Australian wine by Mercurio et al. (2010) revealed a positive trend toward higher wine grade allocation and wines that had higher concentrations of both total phenolics and tannin, respectively. Mercurio et al. (2010) also demonstrated that in general, Cabernet Sauvignon and Shiraz wines allocated to higher market value grades had higher total phenolics and higher tannin concentrations. Other studies have also found a positive relationship between total tannin level and projected bottle price as a measure of wine quality (Kassara & Kennedy 2008). Previous studies on the effect of light exposure on specific phenolic compounds of berries from Shiraz vines grown in a hot climate (Haselgrove et al. 2000) showed that berries which had developed on bunches receiving high levels of ambient light generally had the highest relative levels of phenolics. Harvest modelling in this study was consistent with these studies; higher tannin and higher phenolics were predictors of a higher fruit quality grade. However, it must be noted that there have been studies where high berry anthocyanins, total phenolics and tannin concentration measures were not good indicators of wine quality grades (Holt et al. 2012) as other vintage influences (disease, and/or ripeness level) overrode berry composition as a quality factor.

Limitations and suggested improvements

This study used the value ascribed to the grapes as a measure of winegrape quality which assumes that this is accurate and not without bias. To eliminate the possibility of bias in vineyard grading future studies could use small batch winemaking to produce wine from each trial vineyard for direct measurement of quality using wine sensory descriptive analysis to compliment field assessment of winegrape quality.

In practice winegrape quality grades can be based on other factors than canopy characteristics and berry composition. Market forces affect winegrape value. High prices are paid for batches of grapes that have intrinsic value, examples including having an old vine age or a scenic vineyard location, in the market. Low prices for grapes can also be offered for winegrapes that are affected by disease, pest damage or have high material other than grape (MOG). Future studies need to account for the external factors that lead to a reduction in the price paid for fruit at market.

Berry composition measures could be taken early in the season. In this experiment higher levels of anthocyanin, and tannin phenolics were predictors of a higher fruit quality grade. Early assessment of berry composition could be included with the GS modelling of winegrape quality to improve its accuracy.

Measures of vineyard performance could be further simplified for use in winegrape quality prediction. Leaf area index and porosity are strongly correlated as they are both generated from image analysis. One of these measures could be used, instead of both, as a single measure may be enough as an indicator. Measures of tannin, colour and phenolics are correlated and a single measure of these could be taken as a predictor of vineyard performance.

The influence of temperature inside the canopy was not measured in this study. Given that berry composition measures were predictors of winegrape quality, and that berry composition is driven by temperature (Haselgrove et al. 2000; Downey et al. 2006; Azuma et al. 2012) temperature should be monitored for its influence on winegrape quality. Additionally, the upper limit of light exposure and the minimum size of LAIe should be investigated to determine how much light exposure, and how small a canopy can be, before fruit quality is reduced.

Conclusion

This study showed the importance of assessing vine performance through monitoring canopy architecture and how this monitoring gives insight into winegrape quality. Taking benchmarking data, via vineyard canopy image analysis and grape chemical composition, has merit as a quantitative assessment of vineyard performance.

In commercial practice measurement of canopy architecture beyond simple shoot density counts are limited. Some of the commercial vineyards used in this study had previously collected limited or no data on the light environment inside their canopy, canopy size or leaf area index due to the time commitment involved and the lack of established benchmarks.

Measurements of canopy porosity and LAIe, and grape berry composition were seen to be predictors of quality with EL 35 and EL 37 being key growth stages at which to take measurements. This study highlights the potential gains/insights from using simple, cost-effective and accurate objective methods to model winegrape quality.

Early assessment models of winegrape quality which used image analysis of canopy architecture measured up to EL 35 could be developed. Measurements of winegrape performance that predict wine quality early in the season have a greater value to the wine industry as management decisions can be made during the growing season to maximise quality. Early assessment allows the time to manipulate the light environment of grapevine canopies to achieve desired berry compositional outcomes and hence quality. Early assessment of colour, tannin and phenolic levels from berries can help identify high quality fruit before it is harvested.

Harvest models of winegrape quality could be developed by combining canopy architecture measurements with grape berry composition in commercial vineyards. Demonstration of winegrape quality benchmarking is valuable to compliment subjective assessment. Being able to objectively define and measure grape and wine quality, beyond the basic parameters of sugar, and acid, allows more transparency and clarity in vineyard grading.

Improving the accuracy and efficiency of vineyard assessments could assist in vineyard profitability through savings and better prediction of quality to meet desired outcomes.

Having good information on vineyard performance allows targeted manipulation and canopy management interventions, targeted to produce desired winegrape quality. The assessment of shoot density as a measure of vine performance is a common practice in the wine regions used in this study but it has limitations as in this this study as it was not a consistent predictor of winegrape quality.

Acknowledgements

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.

All vineyards were located on private land with family ownership; thanks to the support and flexibility of all growers. Thanks to the Viticulture laboratory staff and interns at The University of Adelaide who assisted in laboratory work, and to DJ's Growers for assistance with data collection.

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Chapter 4: Prepared manuscript

Assessment of vineyard performance to predict winegrape quality in *Vitis vinifera* L. (cv. Cabernet Sauvignon)

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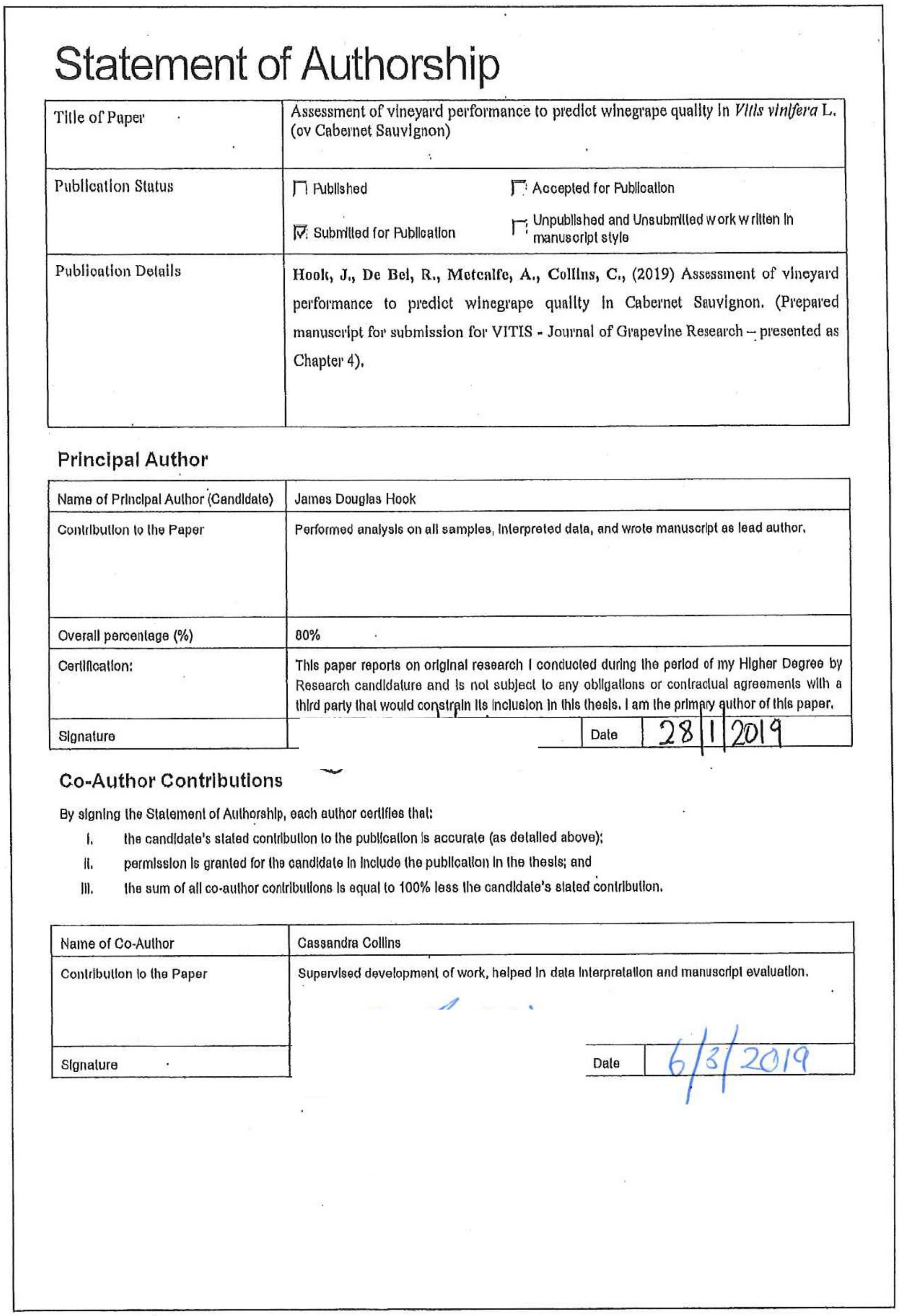


Statement of Authorship

Title of Paper	Assessment of vineyard performance to predict winegrape quality in *Vitis vinifera* L. (cv Cabernet Sauvignon)
Publication Status	☐ Published ☐ Accepted for Publication ☑ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Hook, J., De Bei, R., Metcalfe, A., Collins, C., (2019) Assessment of vineyard performance to predict winegrape quality in Cabernet Sauvignon. (Prepared manuscript for submission for VITIS - Journal of Grapevine Research – presented as Chapter 4).

Principal Author

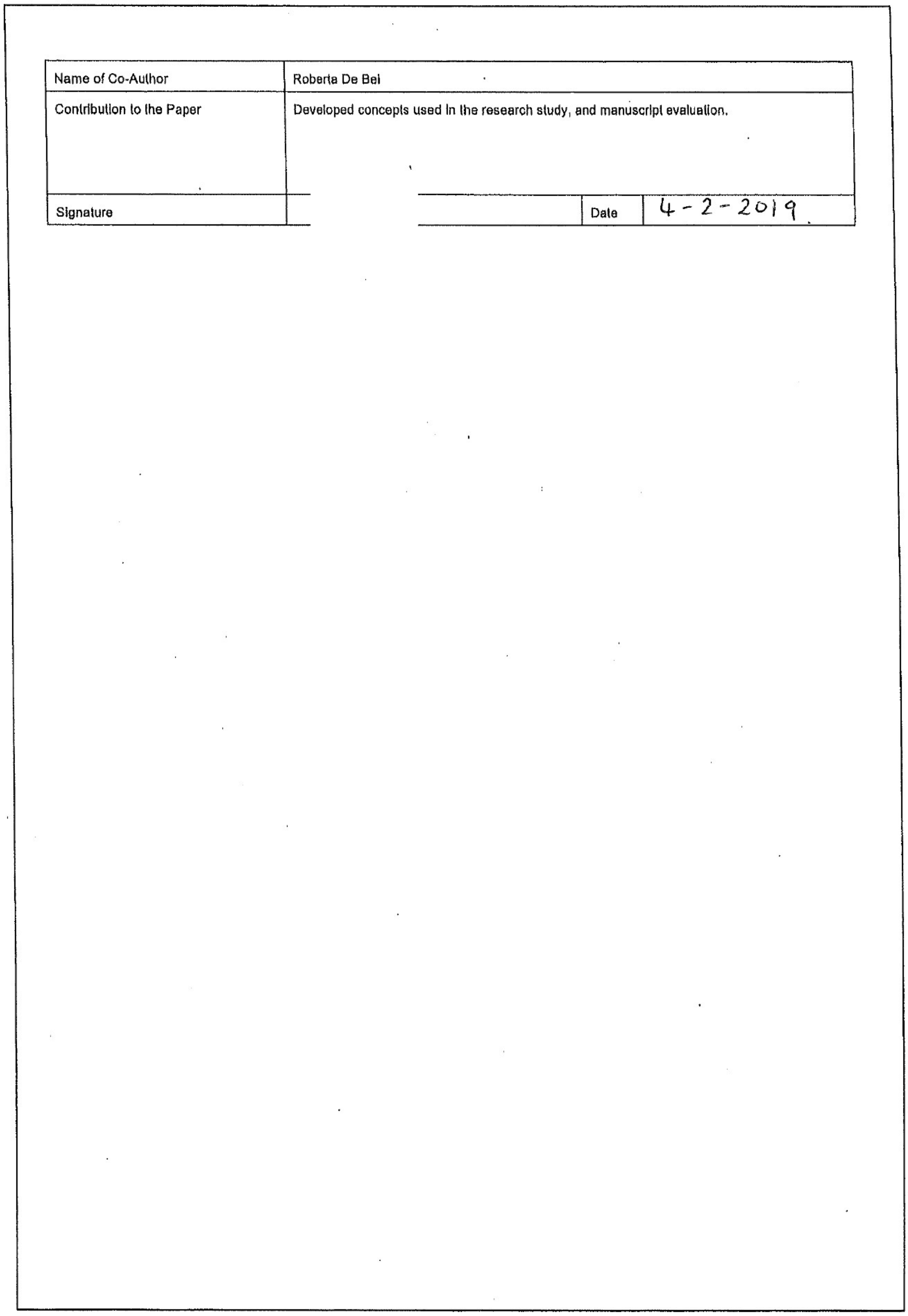
Name of Principal Author (Candidate)	James Douglas Hook
Contribution to the Paper	Performed analysis on all samples, interpreted data, and wrote manuscript as lead author.
Overall percentage (%)	80%
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 28/1/2019

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Cassandra Collins
Contribution to the Paper	Supervised development of work, helped in data interpretation and manuscript evaluation.
Signature	Date 6/3/2019



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Contribution to the Paper	Developed concepts used in the research study, and manuscript evaluation.		
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Introduction

Vineyard performance in any given vintage can be assessed by past performance, objective measures, and subjective appearance. In many wine growing regions winegrape quality grade is measured by the price paid for the fruit at market. Objective measures of quality based on measuring vineyard growth and canopy density during the growing season (Dobrowski et al. 2002), and grape composition at harvest for vineyard quality assessment have been studied (Conde et al. 2007; Mercurio et al. 2010; Ristic et al. 2010). The main physical field measurements include shoot length, internode length, visual estimate of light exposure and point quadrat assessment (Dry et al. 1998; Gladstone & Dokoozlian 2003; Vargas et al. 2016). In recent years automated estimation of LAI using image analysis has been developed (De Bei et al. 2016). This method of analysis has the potential to be a more commercially viable practice.

Cabernet Sauvignon is an important winegrape in Australian viticulture. The aim of this study was to assess whether different grapevine performance measurements during the growing season could predict winegrape quality grade in Cabernet Sauvignon. Three different regions were included in the study, Langhorne Creek, the Adelaide Hills, and McLaren Vale, which have different climates. These regions all produce Cabernet Sauvignon wines across a range of different styles and corresponding wine grape price points.

The performance measurements used were adapted for commercial practice, so that they were non-destructive and repeatable over multiple vineyards allowing for efficient data collection. As such, this paper describes the development of two models, a growing season model (GS model), with measurements taken up to 50% veraison (EL 35) and a harvest model (HRV model) with measurements taken up to the growth stage of EL 37 as defined by Coombe (2004). This study also assessed the relative contribution to quality of vine performance measures in order to show which variables had the best predictive ability to determine winegrape grade.

Materials and Methods

Site selection and measurement methodology

During the 2015 vintage an experimental trial was conducted to predict the winegrape grade of Cabernet Sauvignon. Seventeen Cabernet Sauvignon vineyards were surveyed across McLaren Vale, the Adelaide Hills and Langhorne Creek wine regions (Table 1).

Three vineyards were in the McLaren Vale wine region. Six vineyards were in the Langhorne Creek wine region. Eight vineyards were in the Adelaide Hills wine region. These sites have different soils and geologies, climatic conditions, management regimes and irrigation strategies, and represent a varied sample of viticultural techniques used in Cabernet Sauvignon production across these regions.

Table 1 Site specific details of the cv. Cabernet Sauvignon vineyards in the McLaren Vale, Adelaide Hills and Langhorne Creek wine regions of Australia included in study.

Region (GI)	Historic Grading	Vine age (years)	Soil Type	Readily available water RAW	Vineyard. floor mgmt.	Soil moist.monit.	Water source	Water usage band (ML)	Area (ha)	Row Orient	Planting density (vine/ha)	Cordon Number	Trellis style	Shoot thinned
McLaren Vale	A	15-20	Black clay	100-125	Sward	Yes	Recyc[4]	1.0-1.5	3.79	N/S	1852	Double	SWCW[5]	Yes
McLaren Vale	A	15-20	Red clay loam	75-100	Sward	Yes	Recyc	0.5-1.0	2.20	N/S	1852	Single	SWCW	No
McLaren Vale	B	15-20	Red clay loam	125-150	Sward	Yes	Bore[6]	1.0-1.5	4.49	N/S	1667	Single	SWCW	No
Langhorne Creek	B	15-20	Red clay loam	125-150	Sward	No	Lake[7]	2.0-2.5	5.00	N/S	2084	Single	SWCW	No
Langhorne Creek	B	15-20	Red clay loam	125-150	Annual cereal	Yes	Lake	2.0-2.5	5.64	N/S	2084	Single	SWCW	No
Langhorne Creek	A	15-20	Red clay loam	125-150	Sward	No	Lake	2.0-2.5	1.05	N/S	1667	Single	SWCW	No
Langhorne Creek	B	10-15	Red clay loam	150-200	Sward	Yes	Lake	2.0-2.5	1.15	E/W	2222	Single	SWCW	No
Langhorne Creek	A	>20	Red clay loam	100-125	Sward	Yes	Lake	2.0-2.5	2.24	N/S	1667	Single	SWCW	No
Langhorne Creek	C	15-20	Black clay	75-100	Sward	Yes	Lake	<3.0	3.79	N/S	2272	Single	SWCW	No
Adelaide Hills	A	15-20	Black clay	75-100	Sward	Yes	Lake	0.5-1.0	1.93	E/W	2272	Single	SWCW	No
Adelaide Hills	C	10-15	Red clay loam	100-125	Sward	Yes	Lake	1.0-1.5	0.90	E/W	2222	Single	SWCW	No
Adelaide Hills	B	10-15	Red clay loam	75-100	Annual cereal	Yes	Bore	0.5-1.0	4.27	N/S	2084	Single	SWCW	Yes
Adelaide Hills	C	10-15	Red clay loam	100-125	Annual cereal	Yes	Bore	0.5-1.0	1.74	N/S	2084	Single	SWCW	Yes
Adelaide Hills	A	15-20	Red clay loam	75-100	Sward	No	Bore	0.5-1.0	3.25	E/W	2084	Single	SWCW	No
Adelaide Hills	C	10-15	Red clay loam	75-100	Sward	Yes	Bore	0.5-1.0	1.11	N/S	2222	Single	VSP	No
Adelaide Hills	B	>20	Red clay loam	50-75	Sward	Yes	Bore	0.5-1.0	1.25	E/W	2222	Single	SWCW	No
Adelaide Hills	B	>20	Sand	150-200	Sward	No	Bore	<0.5	3.24	E/W	1515	Single	Sprawl	No

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[4] Recyc = Recycled water from Willunga Basin Water Company irrigation scheme.
[5] SWCW = Sprawl canopy with catch foliage wires
[6] Bore = underground aquifer water source
[7] Lake = Langhorne Creek region irrigation water supplied from Lake Alexandrina/Murray River.

All vineyards were drip irrigated with irrigation water volume applied up to EL 35 ranging from <0.5ML/Ha to 1.5ML/Ha. Trellis systems and canopy management varied across the sites including examples of both single and double cordons. Some sites had lifting foliage wires to manipulate the canopy, while others were left to sprawl. Some of the sites were shoot thinned or green trimmed as part of the grape grower's standard practices.

The vineyard management practice of shoot thinning was given a score. If grape growers completed a pass of shoot thinning, they were scored as 1, if no pass was performed they scored 0.

The trial vineyard sites represented a range of historical winegrape qualities based on their winegrape quality grade performance over the last three seasons (Table 2). The historical fruit quality ranged from below district average, to superior fruit purchased for the highest winegrape price as defined by figures supplied by Vinehealth Australia, formerly the Phylloxera and Grape Industry Board of South Australia (2013 Winegrape Crush).

Table 2. Matrix of winegrape pricing used in the Cabernet Sauvignon vineyard performance study.

Grading Level	Alphabetical Grading	Price Range per tonne
10	A	>$5000
9	A	$4500-$4999
8	A	$4000-$4499
7	A	$3500-$3999
6	A	$3000-$3499
5	B	$2500-$2999
4	B	$2000-$2499
3	B/C	$1500-$1999
2	C	$1000-$1499
1	D	<$999

The vineyards previous season grading was obtained by a survey of the grape growers. At the beginning of the growing season, the bud number retained after pruning was manually counted at the grapevine growth stage budburst (EL 4, Coombe 1995), and expressed as buds per metre of cordon. Manual counting of shoots per metre of cordon was undertaken at the growth stage of EL 17; 10-12 leaves separated.

Randomly selected assessment panels in each vineyard were sampled for leaf area index (LAIe) and light environment (canopy porosity) at key growth stages, 80% capfall (EL 25), 50% veraison (EL 35) and immediately before harvest (EL 37). Images were collected from the assessment panels in each vineyard using an iPad Air, or iPhone 5S, 6 and 7 (Apple, Cupertino, CA) and analysed using the VitiCanopy App (De Bei et al. 2016). Six images per vineyard were taken at each phenological stage. An average of each assessment panel measurement was used.

Inflorescence number was counted at EL 25. Bunch samples were collected at EL 37 from all vineyards. Ten bunches were collected from each panel and then mixed to form three replicates of 20 bunch samples from each vineyard. From each of the three replicate samples 100 berries were randomly collected and stored at -20ºC for berry composition measures.

Berry samples were assessed for TSS, pH, TA, and Brix according to Iland et al. (2007). Total anthocyanins and phenolics were measured using methods described in Mercurio et al. (2007). Winegrape berry tannin were assessed using the methyl cellulose precipitable (MCP) tannin assay measuring the total grape tannin in red grape homogenate extracts (Sarneckis et al. 2006) the results provide tannin concentration expressed in epicatechin equivalents (mg/g berry weight). The values of berry and juice composition used for statistical analysis were an average of the three replicate samples.

At harvest (EL 38), yield and yield components were measured by counting the number of bunches per vine and weighing the fruit to then estimate bunch weight from the six reference panels in each vineyard.

Table 3. List of vineyard performance measures taken and timing in the cv. Cabernet Sauvignon vineyard performance study.

Growth Stage	Measurements
EL 4	bud number retained at pruning, soil readily available water (RAW), row orientation, previous seasons winegrape quality grade
EL 17	count shoots per metre, non-count shoots per metre, total shoots per metre
EL 25	leaf area index (LAIe), light environment (canopy porosity), inflorescence count
EL 35	leaf area index (LAIe), light environment (canopy porosity), irrigation usage (ML/ha)
EL 37	Berry composition: tannin concentration (mg/g), phenolics (per g berry weight), anthocyanin colour (mg/g), sugar content (°brix), total soluble solids (TSS), pH and titratable acidity (TA), berry weight (g), leaf area index (LAIe), canopy density (porosity),
EL 38	yield per metre of cordon (kg)

Development of general model of winegrape quality grade

Multiple regression was used to determine the performance variables included in the model. The regressions were analysed using the XLSTAT statistical software (version 2015.1, developed by Fahmy and Aubry (2003).

The general form of the regression models fitted to data is:

$$Y_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki} + \varepsilon_i$$
$$i = 1, \ldots, 35$$

where i is an identifier for vineyard, Y_i is the winegrape quality grade, $x_{i1}, x_{2i}, \ldots, x_{ki}$ are the values of k predictor variables, $\beta_0, \beta_1, \ldots, \beta_k$ are unknown coefficients to be estimated, along with their standard errors, and ε_i is random error. The random error is assumed to be independently and identically distributed with mean 0.

Development of the growing season model

An initial regression model was fitted with all the variables measured in the study up to the growth stage of EL 35. The predictive performance was assessed by R^2 (defined as the proportion of the variance in quality explained by the model). Variables that had a negligible effect on R^2 were removed from the model.

The growing season (GS) model used measurements either related to vineyard design, establishment, management practices or canopy architecture, that were measurable up to EL 35. The measurement of vineyard set up and management were, soil RAW, irrigation volume up to EL 35 expressed as megalitres applied per hectare (irrigation ML). Irrigation use up to EL 35 was used as a measurement, rather than up to harvest, so that irrigation amount could be included in the GS model. Measurements of canopy architecture were included as an assessment of canopy size (LAIe), and light environment (canopy porosity).

Development of the harvest model

A harvest (HRV) model regression was fitted with all the variables measured in the study. The predictive performance was assessed by R^2 (defined as the proportion of the variance in quality explained by the model). Variables that had a negligible effect on R^2 were removed from the model.

The harvest model (HRV Model) included measurements from the GS Model of LAIe and canopy porosity taken at EL 35, with repeated measures taken at EL 37. Additionally, berry size, and berry composition measures of colour, tannin and phenolics taken at EL 37 were included.

Results

Results of the GS prediction model

A growing season model comparing predicted winegrape quality grade with the actual winegrape quality grade was performed (Figure 1). The 2015 Cabernet Sauvignon GS model regression predicted winegrape grade with an R^2 of 0.678; p=0.083. Analysis of variance of the growing season model is shown as Table 3.4.

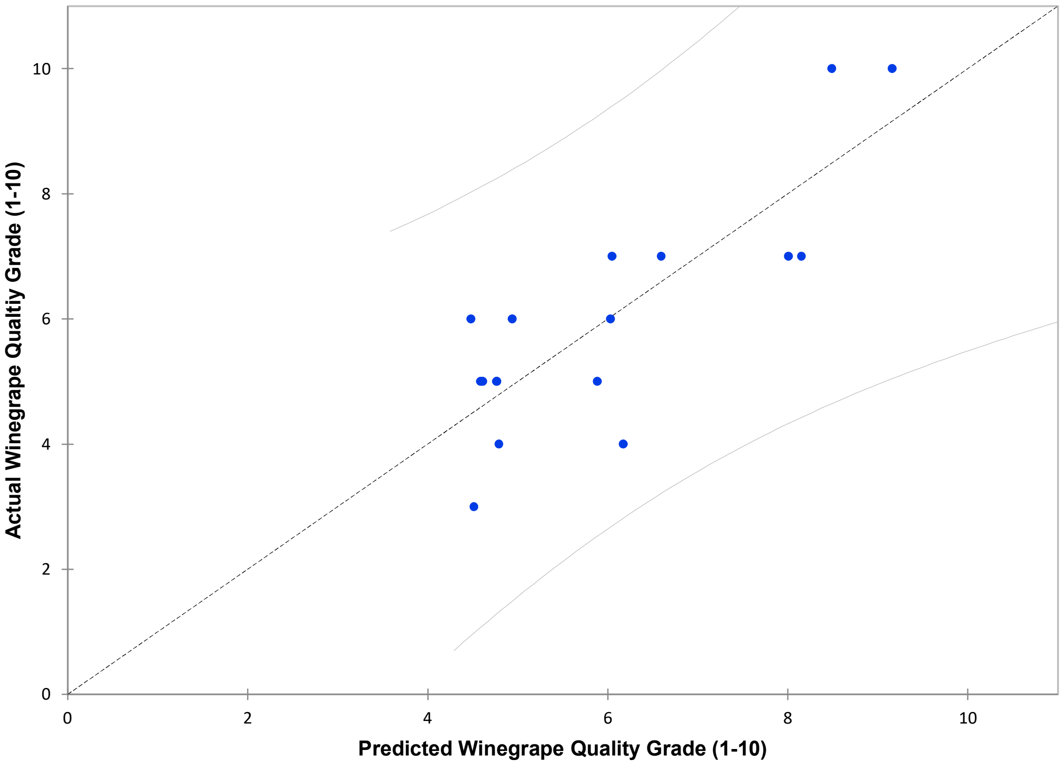

Figure 1. GS regression modelling of winegrape quality grade prediction (95% confidence interval) cv. Cabernet Sauvignon in the McLaren Vale, Adelaide Hills & Langhorne Creek Wine Regions, South Australia in vintage 2015 ($R^2 = 0.678$; RMSE = 1.44)

Table 4. Analysis of variance of the GS regression modelling of cv. Cabernet Sauvignon in the McLaren Vale, Adelaide Hills & Langhorne Creek Wine Regions, South Australia in vintage 2015.

Source	**DF**	**Sum of squares**	**Mean squares**	**F**	**Pr > F**
Model	7	39.323	5.618	2.707	0.083
Error	9	18.677	2.075		
Corrected Total	16	58.000			

Standardised coefficients of variables were generated from the GS linear fixed effect model shown in Figure 2 & Table 5. Coefficients of the predictor variables are presented in standardised form. Meaning they are multiplied by the standard deviation of the predictor variable and are non-dimensional. Variables are directly comparable and predictor variables with larger coefficients have a more significant effect on winegrape quality grade.

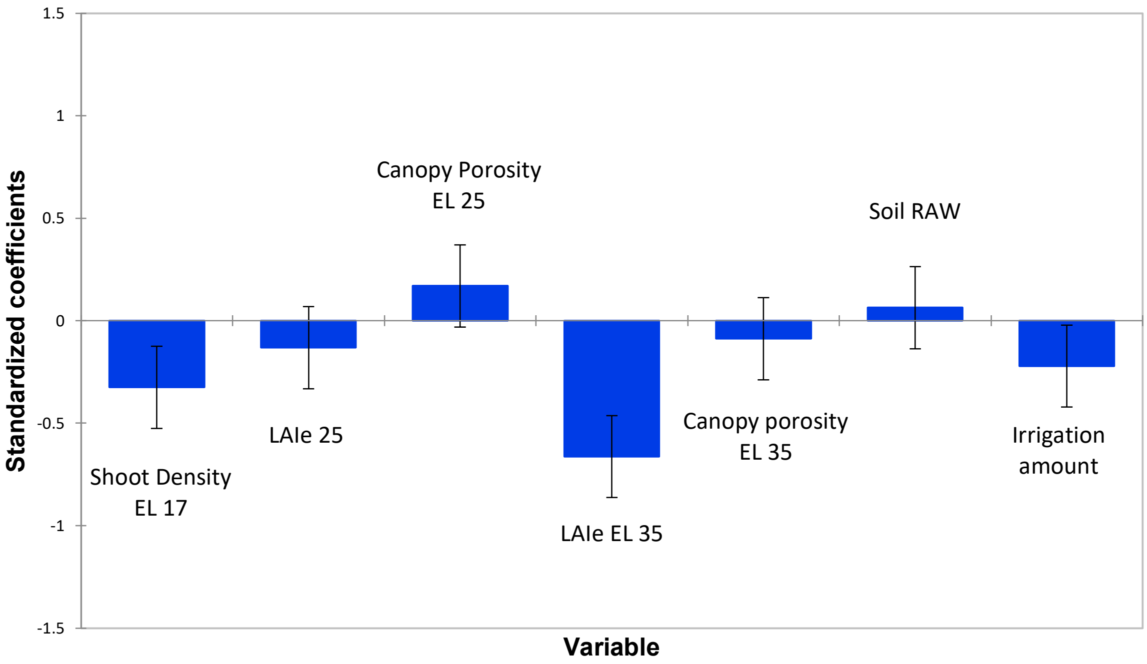

Figure 2. GS modelling of winegrape performance standardised coefficients cv. Cabernet Sauvignon in the McLaren Vale, Adelaide Hills & Langhorne Creek wine regions, South Australia in vintage 2015.

Table 5. Standardised coefficients of variables for the GS prediction model of cv. Cabernet Sauvignon in the McLaren Vale, Adelaide Hills & Langhorne Creek wine regions, South Australia in vintage 2015.

Source	**Value**	**Standard error**	**t**	**Pr > |t|**	**Lower bound (95%)**	**Upper bound (95%)**
Shoot Density EL 17	-0.325	0.200	-1.625	0.139	-0.128	-0.778
LAIe EL 25	-0.131	0.217	-0.607	0.559	-0.621	0.358
Canopy Porosity EL 25	0.170	0.206	0.822	0.432	-0.297	0.637
LAIe EL 35	-0.662	0.227	-2.912	**0.017**	-1.177	-0.148
Canopy Porosity EL 35	-0.087	0.232	-0.375	0.716	-0.612	0.438
Soil RAW	0.064	0.278	0.230	0.823	-0.565	0.693
Irrigation amount ML	-0.221	0.287	-0.769	0.462	-0.870	0.429

The absolute magnitudes of the coefficients of one variable, LAle at EL 35 was large enough to be statistically significant at the 0.05 level (the null hypothesis is that the coefficient is 0) indicating that this variable was a significant predictor of winegrape grade.

Results of the HRV prediction model

An analysis of the HRV model comparing predicted winegrape grade with the actual winegrape grade was performed (Figure 3). The 2015 Cabernet Sauvignon GS model was statistically significant with an R^2 of 0.646; p=0.022. Analysis of variance of this model is shown in Table 6.

Standardised coefficients of variables were generated from the HRV model (Figure 4). Analysis of the standardised coefficients of variables allowed the weighted effect of each measurement variable to be determined.

The absolute magnitudes of the coefficients of three variables, LAle at EL 35, colour at EL 37 and phenolic level at EL 37, were large enough to be statistically significant at the 0.05 level (the null hypothesis is that the coefficient is 0) indicating these variables were a significant predictor of winegrape quality grade.

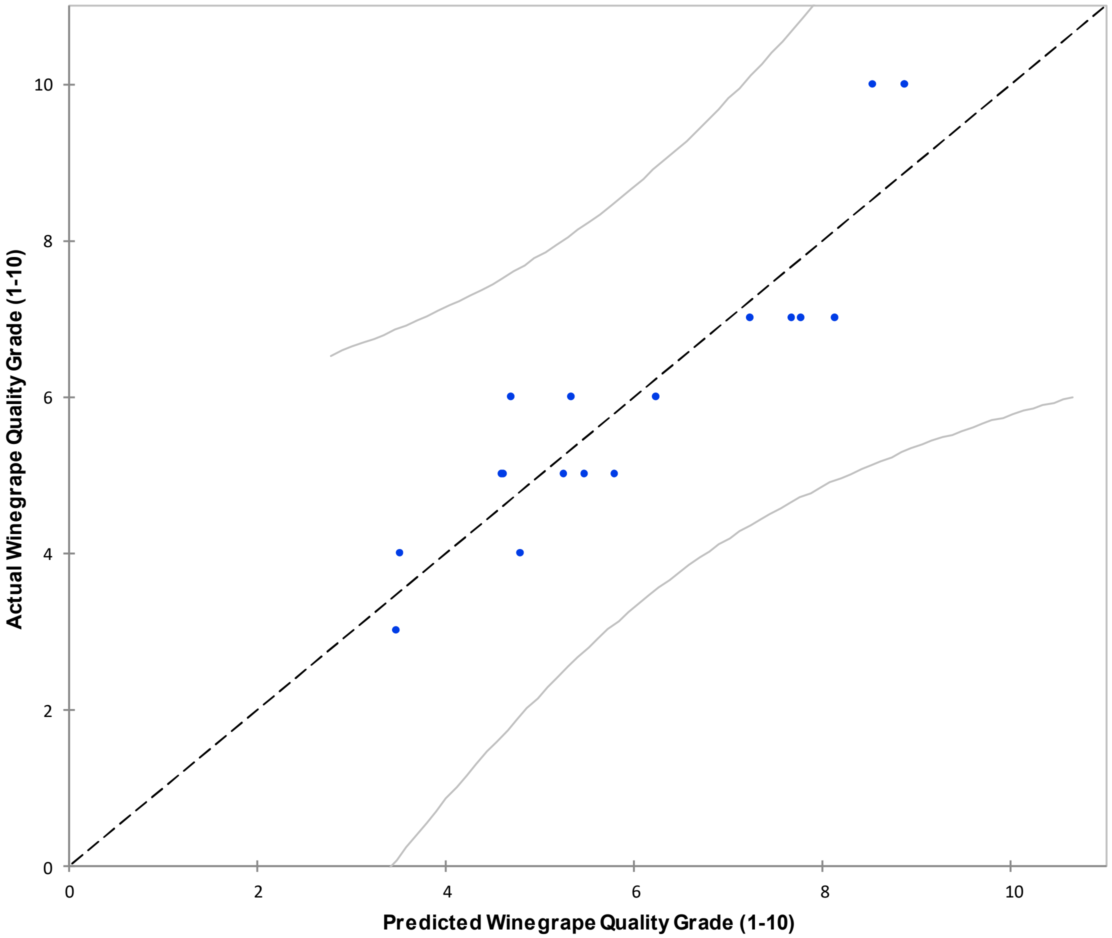

Figure 3. HRV linear regression modelling (95% confidence interval) of cv. Cabernet Sauvignon in the McLaren Vale, Adelaide Hills & Langhorne Creek wine regions, South Australia in vintage 2015 ($R^2 = 0.823$; RMSE = 1.13).

Table 6. Analysis of variance of the HRV regression modelling of cv. Cabernet Sauvignon in the McLaren Vale, Adelaide Hills & Langhorne Creek wine regions, South Australia in vintage 2015.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	8	47.721	5.965	4.643	**0.022**
Error	8	10.279	1.285		
Corrected Total	16	58.000			

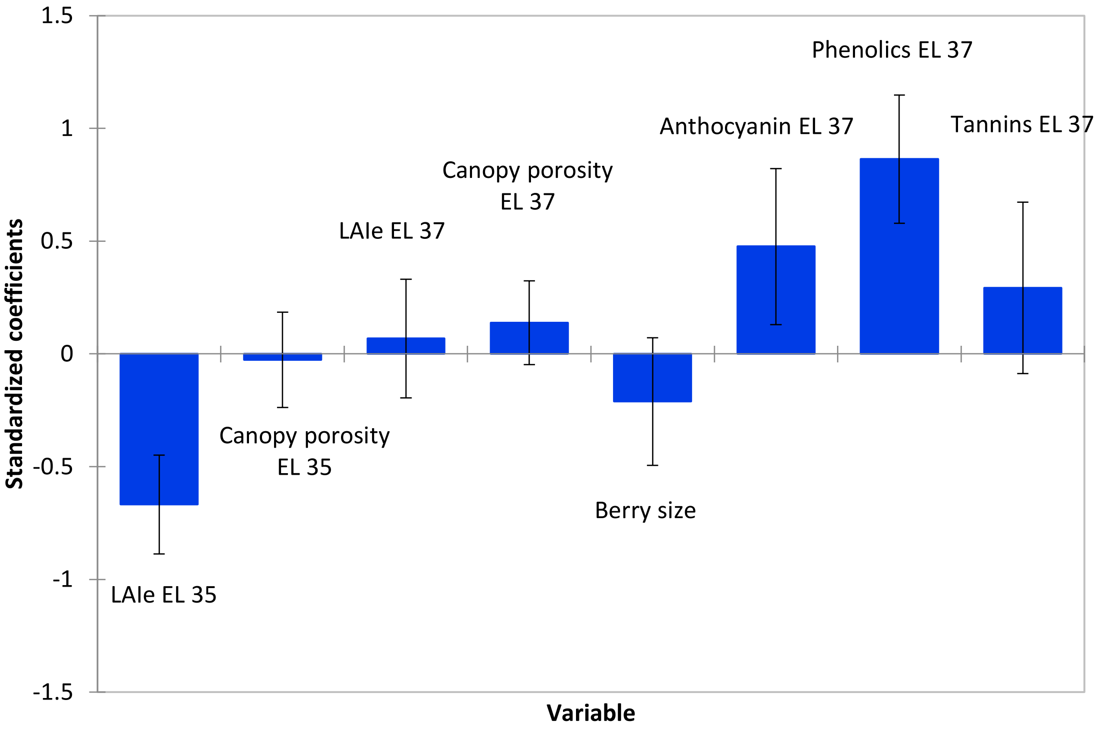

Figure 4. HRV linear regression modelling of vineyard performance standardised coefficients cv. Cabernet Sauvignon in the McLaren Vale, Adelaide Hills & Langhorne Creek wine regions, South Australia in vintage 2015.

Discussion

This study aimed to develop models for predicting winegrape grade in cv. Cabernet Sauvignon using measurements that could be used in a commercial practice. Measurements that were taken up to EL 35 were used to create the GS model, while the other model, the HRV model, was not limited by timing and included measurements taken up to the point that grapes were picked, including grape berry composition measures taken from bunch samples.

Both models, GS model (R^2 of 0.678; p=0.083) and HRV model (R^2 of 0.646; p=0.022), could predict winegrape grade using measurements suitable for commercial application. The GS season model gave insight into the importance of canopy architecture in winegrape grade. In comparison the HRV model showed the influence and importance of berry composition on winegrape grade.

Analysis of the standardised coefficients of variables allowed comparison of the relative effect on the winegrape quality grade. This gave insight into which vineyard measures had the greatest influence on the prediction model.

Growing season model

For this study a positive correlation was found between the predicted winegrape quality grade and the actual winegrape quality grade as modelled by the GS model (Figure 1). This would indicate that measurements of the vine canopy (shoot density, canopy porosity and LAIe), and the factors that affect vineyard canopy growth (soil RAW, irrigation volume before 50% veraison) do influence the winegrape quality grade. That the structure of grapevine canopies in cv. Cabernet Sauvignon could be used as a predictor of winegrape quality is consistent with previous research and understanding on what influences winegrape berry quality (Smart 1985; Dokoozlian & Kliewer 1995).

Results of the GS models are consistent with concepts of monitoring canopy architecture to monitor vineyard performance. Canopy architecture has been correlated to yield, quality and productivity (Smart 1985). The measurement of canopy architecture has previously been shown to be important for the assessment of growth, vigour and light transmission to the fruit because of the known links between grapevine canopies and berry chemical composition (Haselgrove et al. 2000). Trellis system, canopy density, light exposure and vigour impact final wine quality by influencing grape chemistry. Grape chemistry is influenced by light exposure levels on developing fruit, temperature in the canopy, and leaf shading altering vine photosynthetic capacity (Smart et al. 1981; Coombe & Iland 1987).

In this study shoot density was shown as a measure that could predict winegrape quality grade. This was consistent with previous studies where shoot density was demonstrated to be a valuable measure of canopy porosity and an estimate of light exposure into the canopy (Reynolds & Wardle 1989; Smart 1991; Dokoozlian & Kliewer 1995). Shoot counts expressed as shoots per metre have been used to compare canopies across season and vineyards (Smart 1991), however shoot density was a predictor of higher winegrape quality grade (Figure 2). This would indicate that canopies that are not excessively shaded (i.e. have lower shoot densities) are beneficial to produce Cabernet Sauvignon berries to make higher quality wine. These results are consistent with previous studies showing shoot density impacts final wine quality by influencing berry chemistry (Coombe & Iland 1987).

Measures of leaf area index taken at veraison (EL 35) were seen to influence winegrape quality grade. Vineyards with lower estimates of leaf area i.e. smaller canopies were indicative of a higher winegrape quality grade. These results were consistent with the review of trials from the 1970s to the present (Smart et al. 2017). These studies concluded that vineyard canopies produced fruit with higher qualities if they were open to sunlight, as measured by shoot density, and had controlled vigour to limit the vines vegetative growth.

Leaf area index measurements taken at EL 35 was a key indicator variable for winegrape grade. This may be due to the important changes that occur at EL 35 inside the berry. The growth stage EL 35 corresponds with the onset of ripeness, where berry acidity decreases, and sugar accumulation and anthocyanin production begin (Hrazdina et al. 1984; Cortell & Kennedy 2006; Conde et al. 2007).

Canopy porosity measured as the percentage of gaps within an image was used to estimate light penetration through the canopy. Canopy porosity at flowering influence on the GS model indicated that there was a relationship between canopy porosity at flowering and winegrape quality (Figure 2). Previous research showed that low levels of shading were beneficial for winegrape quality grade at harvest (Reynolds & Wardle 1989; Dokoozlian & Kliewer 1995) however, there is likely an upper limit to light exposure, where too much light exposure reduces winegrape quality through high berry temperatures interrupting ripening processes (Bergqvist et al. 2001), or sunburn caused by direct sunlight. There are studies that have demonstrated the negative impact of high temperatures and sunburn. A temperature range inside the canopy of 17 to 26º C is considered ideal for the enzymes involved in anthocyanin production (Haselgrove et al. 2000). For this study the upper limit of light exposure was not explored, and the negative effects of excessive light exposure were not investigated. Future studies need to consider the influence of direct light exposure and high temperature on winegrape quality.

In addition to the measures of canopy growth being used in the GS model, factors that affect vineyard canopy growth influenced by vineyard establishment and management (estimated soil RAW, irrigation before veraison and the presence or absence of shoot thinning) also influenced the winegrape quality grade. A low estimated soil RAW can limit vegetative growth because soil with naturally low water holding capacity can induce vine water stress and reduce transpiration and vegetative growth (McCarthy 1997; Padgett-Johnson et al. 2003). To prevent shading a common management practice is to limit canopy growth. In this study, a low soil RAW positively correlated with higher winegrape quality grade in the GS model. High soil RAW values have been linked to high plant vegetative growth rates in grapevines (Kasimatis 1957; Veihmeyer & Hendrickson 1957). High rates of vegetative growth have been linked to low winegrape quality (Smart et al. 2017). It is known that vine water deficits generally lead to smaller berries, increased light exposure to fruit and to several changes in wine composition (Bravdo et al. 1985; Kennedy et al. 2000; Kennedy et al. 2002). These changes have been shown to produce fruit with better traits for winemaking, tannin levels, phenolic structure and colour. Reducing plant vegetative growth by using water deficit is linked to favourable grape chemistry characteristics, higher tannin, higher phenols and increased colour for winemaking (Intrigliolo & Castel 2010).

In this study the levels of irrigation applied influenced the winegrape quality grade. The GS model analysis of standardised coefficients (Figure 2) showed higher amounts of irrigation applied lead to lower grapevine quality grades. Although the negative coefficient of irrigation is consistent with the scientific explanation, as soil moisture levels are linked to plant vegetative growth (Boland et al. 1994), the precision of the estimate of the coefficient is low and the coefficient is not statistically significantly different from 0 at a 0.10 level.

Harvest model

Harvest modelling of winegrape quality grade (Figure 3) used vineyard measurements taken up to pre-harvest (EL 37) and showed that there was a correlation between predicted winegrape grade and the actual winegrape grade (R^2 of 0.646; p=0.022).

Analysis of the standardized coefficients of harvest season vineyard measurements indicates that canopy architecture measures (leaf area index and porosity) were able to predict winegrape quality grade. Additionally, grape berry size, total anthocyanins, tannin and phenolic levels at EL 37 were used in the model. This is consistent with existing knowledge where a relationship was found between berry composition at harvest, total production, and quality in France (Jones & Davis 2000), California (Jackson & Lombard 1993; Jones & Goodridge 2007) and Australia (Winter et al. 2004). Previous studies have also linked ripeness of tannins and other phenolic compounds in the grapes to the colour, flavour and aroma of wine (Conde et. al 2007; Ristic et al. 2010).

As with results of the GS model, large canopies, as measured by LAIe at veraison had a negative influence on the winegrape quality grade in the harvest model (Figure 4).

However, measures of leaf area index at EL 37 and canopy porosity at EL 35 and EL 37 were inconclusive as analysis of the models standardised coefficients did not show a significant influence on winegrape quality grade. The inconclusive results of canopy porosity measures were surprising. It is known that the exclusion of sunlight from red cultivars of *Vitis vinifera* grapes negatively alters wine colour, tannin and sensory properties (Krstic et al. 2007). Excessive canopy shade was detrimental to berry and wine composition and intensified sensory detection of ‘straw’ and ‘herbaceous’ characters in the wines (Krstic et al. 2010). Grape berries exposed to sunlight are generally higher in sugars, anthocyanins, and phenolics, and lower in titratable acidity, malate, and pH, compared to berries ripened in canopy shade (Kliewer & Lider 1968; Kliewer & Antcliff 1970; Kliewer 1977; Reynolds et al. 1986; Morrison 1988).

Colour as total anthocyanin was shown to relate positively to winegrape quality grade. In this study high anthocyanin colour levels at EL 37 was a predictor variable of higher winegrape quality grade. This was expected as previous studies have linked colour and wine quality in red grape varieties (Jackson et al. 1978; Freeman 1983; Mazza et al. 1999). Studies undertaken in the same region, mesoclimate, and with the same varieties show there is correlation observed between wine colour densities and the order of ranking previously assigned by a panel of experienced wine judges (Somers & Evans 1974). Unsurprisingly total anthocyanins were a predictor variable in the harvest model.

Total tannin and phenolic levels were both indicator variables in the harvest model. This was expected as statistical analysis of Australian wine by Mercurio et al. (2010) revealed a positive trend toward higher wine grade allocation and wines that had higher concentrations of both total phenolics and tannin, respectively. Mercurio et al. (2010) demonstrated that in general, Cabernet Sauvignon and Shiraz wines allocated to higher market value grades had higher total phenolics and higher tannin concentrations. Other studies have also found a positive relationship between total tannin level and projected bottle price used as a measure of wine quality (Kassara & Kennedy 2008). Previous studies on the effect of light exposure on specific phenolic compounds of berries from cv. Shiraz vines grown in a hot climate showed that berries that had developed on bunches receiving high levels of ambient light generally had the highest relative levels of phenolics (Haselgrove et al. 2000). Harvest modelling in this study was consistent with these studies – high tannin and high phenolics were predictors of a high winegrape quality grade.

A large berry size appears to have had a negative effect on winegrape quality grade. In the harvest models there was a link between berry size and winegrape grade (Figure 4). Berry size is recognized as an important factor determining winegrape quality (Francis et al. 2005). Berry sizes in this study ranged from averages of 0.5 to greater than 2.0 grams. Berries with an average berry size above 2.0 grams were detrimental to winegrape grade. Berries attain size via a double sigmoid growth habit which is known to be influenced by soil moisture levels (McCarthy 1997), and the many management practices that have an impact on the growth balances and microclimate of the vine (Roby & Matthews 2004). Small berries had a higher skin to fruit ratio, and a similar juice yield, compared to large berries (Walker et al. 2008).

Berry size alone is not an ideal measurement, as it did not have as much of an influence on the harvest model as the three bio-chemical measures (total tannin, phenolics and total anthocyanin). Although berries are small, which is often a desired trait, if they are malformed, they can have bitter flavours which counteract any positive traits they derive from their size. Malformed berries are associated with excessive water stress during critical phases of vine development can produce berries with harsh characters for winemaking in Cabernet Sauvignon (Ferreyra et al. 2004). Any future assessments of winegrape quality using berry size as a measure need to establish at what point fruit is too small. Secondly, measurable differences in berry size close to average, for example 1.0-1.5 grams per berry, may not have any measurable effect on winemaking. Therefore, placing emphasis on berry size alone, when the differences in berry sizes between vineyards may not be significant, is not as valuable as assessing berry composition. Berry composition was shown in this study to be a consistent influence on the winegrape quality grade prediction harvest models.

Conclusion

This study showed that Cabernet Sauvignon winegrape quality grade can be modelled by measuring canopy architecture and grape berry composition in the regions used in this study (McLaren Vale, the Adelaide Hills & Langhorne Creek). Measurements of canopy porosity and leaf area index, and grape berry composition were seen to be predictors of quality with EL 35 and EL 37 being key growth stages at which to take measurements.

Harvest models of winegrape quality grade could be developed by combining canopy architecture measurements with grape berry composition in commercial vineyards. Demonstration of winegrape grade benchmarking is valuable to compliment subjective assessment. Being able to objectively define and measure grape and wine quality, beyond the basic parameters of sugar, and acid, allows more transparency and clarity in vineyard grading. Improving the accuracy and efficiency of vineyard assessments could assist in vineyard profitability through savings and better prediction of quality to meet desired outcomes.

Additionally, early assessment models of winegrape grade could be developed by using image analysis of canopy architecture. Measurements of winegrape performance that predict wine quality early in the season have a greater value to the wine industry as management decisions can be made during the growing season to maximise quality. Early assessment allows the time to manipulate the light environment of grapevine canopies to achieve desired berry compositional outcomes and hence quality. Early assessment of colour, tannin and phenolic levels from berries can help identify high quality fruit before it is harvested.

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Chapter 5: Prepared manuscript

Assessment of canopy porosity at flowering and veraison and the influence on berry total anthocyanin in *Vitis vinifera* (cv. Shiraz) in McLaren Vale and Langhorne Creek vineyards

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Keywords: *anthocyanins, canopy porosity, canopy architecture*

Statement of Authorship

Title of Paper	Assessment of canopy porosity at flowering and veraison and the influence on berry total anthocyanin in Vitis vinifera (cv. Shiraz) in Australian vineyards.
Publication Status	☐ Published ☐ Accepted for Publication ☑ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	Hook, J., De Bei, R., Metcalfe, A., Collins, C. (2019) Assessment of canopy porosity at flowering and veraison and the influence on berry total anthocyanin in Vitis vinifera (cv. Shiraz) in Australian vineyards. (Prepared manuscript research note for submission to American Journal of Enology and Viticulture – presented as Chapter 5).

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Contribution to the Paper	Performed analysis on samples, interpreted data and wrote manuscript.
Overall percentage (%)	80%
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
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Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Introduction

The relationship between the light environment in a vine canopy and total anthocyanin levels in berries at harvest has been studied but is not widely adopted to manage and predict quality. This trial evaluated how the light environment in canopies, estimated by porosity, influenced berry colour levels of cv. Shiraz grown under hot climatic conditions in South Australia.

High total anthocyanin levels in red wine grapes is seen as a desirable trait for winemaking (Somers & Evans 1974; Jackson et al. 1978; Freeman 1983; Mazza et al. 1999). Anthocyanin production and accumulation is influenced by temperature and light exposure through enzymatic reactions and gene expression (Hrazdina, et al. 1984; Conde et al. 2007; Cortell 2006). Specifically, the influence of the canopy light environment is consistent where dense canopies, with low light intensity measured in the canopy, are seen to produce fruit with lower quality for winemaking (Smart 1985). Shaded canopies have also been found to produce fruit with lower anthocyanin (Keller & Hrazdina, 1998; Smart et al. 2017).

This study investigates the correlation between canopy porosity and total anthocyanin levels. Image analysis was used to assess canopy porosity at two key growth stages as an efficient method of obtaining data on a commercial scale. Total anthocyanins were measured from berry samples taken before harvest at the growth stage EL 37 as defined by Coombe (1995).

Materials and Methods

To explore the relationship between total anthocyanin and canopy porosity, a trial over three vintages (2014, 2015, 2016) was carried out in the McLaren Vale and Langhorne Creek wine regions of Australia on 35 commercial Shiraz vineyards.

The wine regions selected for the trial have warm climates (Table 1) under the definitions in Dry et al. 2004. A hot climatic region is one with a Mean January Temperature of 23°C or more, warm with 20 to 22.9°C and cool with less than 20°C. Both regions are situated at a latitude (35.3° S) where they received more than of 12 hours per day of sunlight during summer. There are several days from late spring to early autumn (November, December, January, February and March) where the maximum temperature exceeds 35°C (Table 2).

Table 1. Mean January Temperatures for the wine regions included in the study (Gladstone 1992).

Wine Region (GI)	Mean January Temperature (°C)
McLaren Vale	21.6
Langhorne Creek	19.9

Table 2. Climate data. The average number of days in December, January and February when the daily maximum air temperature was equal to, or exceeded, 35°C for the wine regions included in the study. Bureau of Meteorology (2019) Climate online. Available at http://www.bom.gov.au/climate/data/ [Verified 26 February 2019].

Wine Region (GI)	Bureau of Meteorology weather station ID	Mean number of days ≥ 35°C annually.
McLaren Vale	NOARLUNGA Site number: 023885	16.8
Langhorne Creek	STRATHALBYN Site number: 023747	16.4

The vineyards ranged in size from one to five hectares and were selected because they represent a range of vineyard locations, vineyard management and historical winegrape quality (Table 3). All the vineyards were drip irrigated using standard irrigation practices. Trellis systems and canopy management varied across the sites. Examples include both single and double cordons and the use of foliage wires to manipulate the canopy, while others were left to sprawl. Some sites were shoot thinned or green trimmed as part of the grape growers' standard practices. Soil types were defined by Fairburn et al. (2010) and Carosone & Cobb (1975) for the McLaren Vale and Langhorne Creek regions respectively.

Table 3. Site specific details of cv. Shiraz vineyards in the McLaren Vale (McL) and Langhorne Creek (LC) wine regions included in study.

Historical Grading	**Vine age (years)**	**Wine Region**	**Clonal material**	**Soil Type**	**Readily available water (RAW mm)**	**Vineyard floor mgmt.**	**Under vine mgmt.**	**Soil Moisture monitoring**	**Water usage band (ML)**	**Area (ha)**	**Row Orientation**	**Vine planting density (vines/ha)**	**Cordon Number**	**Trellis style**	**Shoot thinned**
A	15-20	McL	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	1.0-1.5	3.79	E/W	1852	Double	Sprawl	Yes
A	15-20	McL	1127	Black clay	75-100	Permanent sward	Herbicide	Yes	0.5-1.0	2.20	N/S	1852	Single	Catch wires	No
B	15-20	McL	n/a	Red clay loam	125-150	Permanent sward	Cultivate	Yes	1.0-1.5	4.49	N/S	1667	Single	Catch wires	No
B	15-20	McL	1654	Red clay loam	125-150	Permanent sward	Herbicide	No	1.0-1.5	5.00	N/S	2084	Single	Catch wires	No
B	15-20	McL	1654	Red clay loam	125-150	Annual cereal	Herbicide	Yes	0.5-1.0	5.64	N/S	2084	Single	Catch wires	No
A	15-20	McL	1654	Red clay loam	125-150	Permanent sward	Herbicide	No	0.5-1.0	4.05	N/S	1667	Single	Catch wires	No
B	10-15	McL	R6v28	Red clay loam	50-75	Permanent sward	Herbicide	Yes	0.5-1.0	4.15	E/W	2222	Single	Catch wires	No
A	>20	McL	n/a	Red clay loam	100-125	Permanent sward	Herbicide	Yes	0.5-1.0	2.24	N/S	1667	Single	Catch wires	Yes
A	15-20	McL	BVRC30	Black clay	75-100	Permanent sward	Cultivate	Yes	0.5-1.0	0.79	N/S	2272	Single	Catch wires	No
A	15-20	McL	BVRC30	Black clay	75-100	Permanent sward	Cultivate	Yes	0.5-1.0	1.93	E/W	2272	Single	Catch wires	No
C	10-15	McL	R6v28	Red clay loam	100-125	Permanent sward	Herbicide	Yes	1.0-1.5	0.9	E/W	2222	Single	Catch wires	No
B	10-15	McL	1654	Red clay loam	75-100	Annual cereal	Herbicide	Yes	0.5-1.0	4.27	N/S	2084	Single	Catch wires	Yes
C	10-15	McL	1654	Red clay loam	100-125	Annual cereal	Herbicide	Yes	0.5-1.0	1.74	N/S	2084	Single	Catch wires	Yes
A	15-20	McL	1127	Red clay loam	75-100	Permanent sward	Cultivate	No	0.5-1.0	3.25	E/W	2084	Single	Catch wires	No
C	10-15	McL	1654	Red clay loam	75-100	Permanent sward	Herbicide	Yes	0.5-1.0	1.11	N/S	2222	Single	VSP	No
B	>20	McL	1654	Red clay loam	50-75	Cultivate	Herbicide	Yes	0.5-1.0	1.25	E/W	2222	Single	Catch wires	No
B	>20	McL	n/a	Sand	150-175	Permanent sward	Herbicide	No	<0.5	3.24	E/W	1515	Single	Sprawl	No
B	5-10	McL	SAVII 13	Red clay loam	75-100	Permanent sward	Cultivate	Yes	1.0-1.5	0.97	E/W	2272	Single	Catch wires	No
B	10-15	McL	1654	Red clay loam	125-150	Permanent sward	Herbicide	Yes	1.0-1.5	5.05	N/S	2222	Single	Catch wires	No
C	10-15	McL	1654	Black clay	125-150	Permanent sward	Herbicide	Yes	1.5-2.0	5.05	N/S	2222	Double	Catch wires	No
B	10-15	McL	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	1.0-1.5	4.78	N/S	2222	Single	Catch wires	Yes
A	>20	McL	n/a	Red clay loam	100-125	Permanent sward	Herbicide	No	1.0-1.5	1.17	N/S	2222	Single	Sprawl	Yes
B	15-20	McL	n/a	Red clay loam	100-125	Permanent sward	Herbicide	No	1.0-1.5	3.70	N/S	2222	Single	Catch wires	Yes
B	15-20	McL	1654	Red clay loam	125-150	Permanent sward	Herbicide	No	1.0-1.5	2.88	N/S	2222	Double	Catch wires	Yes
C	15-20	McL	1654	Black clay	150-175	Permanent sward	Herbicide	Yes	1.0-1.5	3.56	N/S	2222	Double	Catch wires	Yes
A	15-20	McL	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	1.0-1.5	3.50	N/S	2222	Double	Catch wires	Yes
A	15-20	McL	1654	Black clay	100-125	Permanent sward	Herbicide	Yes	1.0-1.5	3.50	N/S	2222	Double	Catch wires	Yes
A	15-20	McL	1654	Red clay loam	100-125	Permanent sward	Herbicide	Yes	1.0-1.5	4.17	N/S	2222	Single	Catch wires	Yes
A	15-20	LC	1654	Red clay loam	100-125	Permanent pasture	Herbicide	Yes	1.5-2.0	4.56	N/S	1852	Single	VSP	Yes
C	15-20	LC	1127	Sand	125-150	Permanent pasture	Herbicide	No	>2.5	5.70	N/S	1852	Single	Catch wires	No
B	15-20	LC	n/a	Red clay loam	125-150	Permanent pasture	Cultivate	No	>2.5	6.00	N/S	1667	Single	Catch wires	No
C	15-20	LC	1654	Red clay loam	100-125	Permanent pasture	Herbicide	No	>2.5	4.56	N/S	2084	Single	Catch wires	No
D	15-20	LC	1654	Red clay loam	175-200	Annual cereal	Herbicide	No	1.5-2.0	4.50	E/W	2084	Single	Catch wires	No
A	15-20	LC	1654	Red clay loam	100-125	Permanent pasture	Herbicide	Yes	1.5-2.0	5.59	N/S	1667	Single	Catch wires	No
C	>20	LC	BVRC 30	Red Clay loam	100-125	Annual cereal	Herbicide	No	1.5-2.0	4.22	N/S	1852	Single	Catch wires	No

At each vineyard site six panels of vines, consisting of four individual vines, were selected, to give a total of 24 sample vines from each vineyard. To select the rows and the panels random digits were generated by Excel. These panels were used to assess canopy architecture at the key growth stages of 80% capfall (EL 25), and 50% veraison (EL 35) defined by Coombe (1995). The growth stages were chosen as they represented a key measurable growth stage that allowed for repeated data collection during the season. In all three years measurements were taken from the same sample panels.

Canopy architecture was measured using the VitiCanopy a mobile device application (De Bei et al. 2016). Images were collected from the assessment panels in each vineyard using an iPad Air, or iPhone 5S, 6 and 7 (Apple, Cupertino, CA) and analysed using the VitiCanopy application (Figure 1). All canopy photos were taken with the device positioned at 70 cm below the cordon. To establish the porosity and LAIe measures for a vineayrd an average of all the assessment panels was used.

Figure 1. Upward looking image of grapevine canopy at EL 35 obtained using an iPhone 7.

Canopy architecture parameters were calculated by the VitiCanopy application using algorithms described in Fuentes et al. (2014) which were calculated from Macfarlane et al. (2007). To estimate the light environment inside the canopy this study used canopy porosity, the percentage of gaps within the image (spaces) which can be related to the light penetration through the canopy.

Selected assessment panels in each vineyard were sampled before harvest at EL 37. Bunch samples were collected from all vineyards. Ten bunches were collected from each panel and then combined to form three replicates of 20 bunch samples from each vineyard. From each of the three replicate samples 100 berries were randomly collected and stored at -20°C for berry compositional measures. Total anthocyanins were measured using methods described in Mercurio et al. (2007).

Results

Canopy porosity measured at EL 25 ranged from 0.06 to 0.90. A positive correlation (R^2=0.70) was found between the canopy porosity measured at EL 25 and total anthocyanins (Figure 2) with higher grape colour associated to higher canopy porosity.

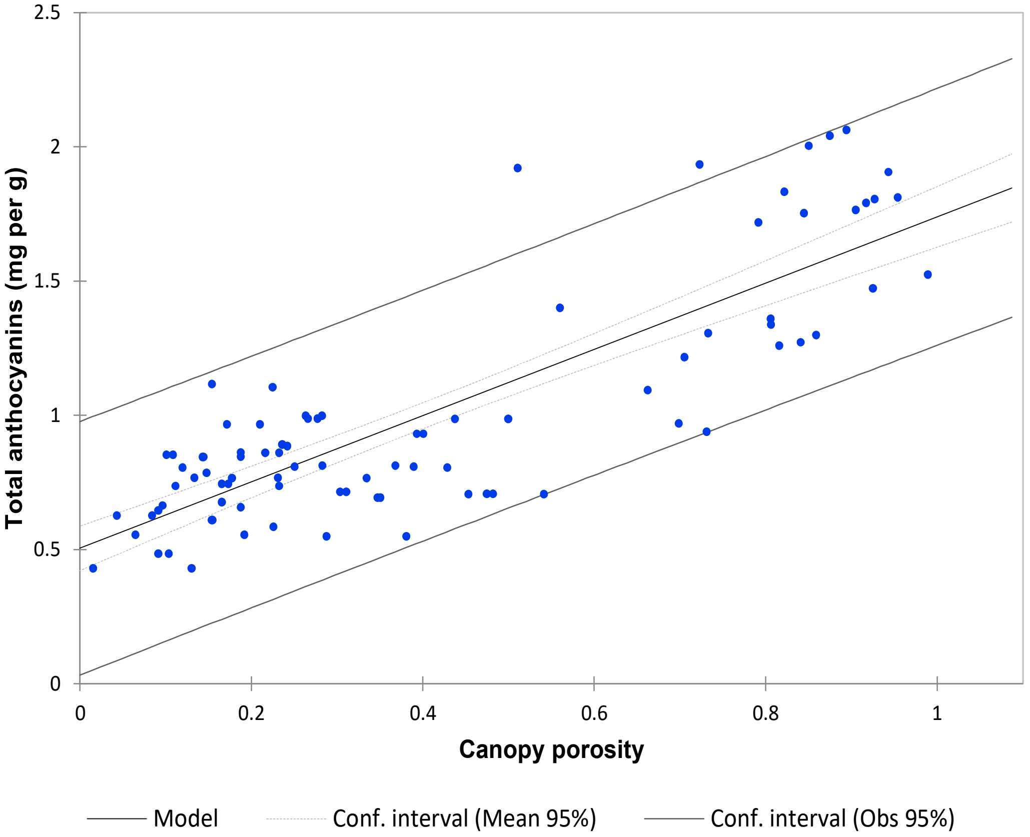

Figure 2. Linear regression between canopy porosity at EL 25 and total anthocyanin level for cv. Shiraz in McLaren Vale and Langhorne Creek, Australia in vintages 2014, 2015 and 2016 ($R^2 = 0.70$; RMSE = 0.23).

Canopy porosity measured at EL 35 ranged from 0.10 to 0.91. A correlation (R^2=0.44) was found between the canopy porosity at EL 35 and total anthocyanin levels (Figure 3). As with the EL 25 regression (Figure 2) higher grape colour was associated to higher canopy porosity, however as canopy porosity levels increase at EL 35 the data scatters and there are several outlier vineyards.

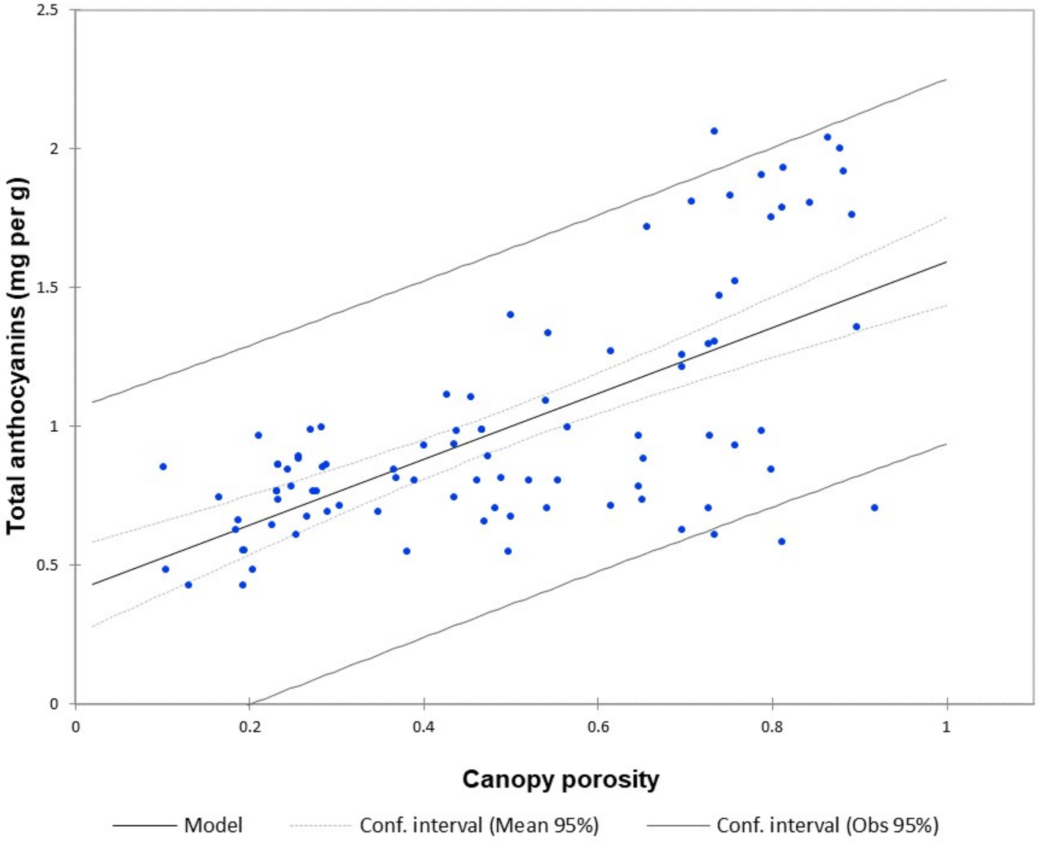

Figure 3. Linear regression between canopy porosity at EL 35 and total anthocyanin level for cv. Shiraz in McLaren Vale and Langhorne Creek, Australia in vintages 2014, 2015 and 2016 ($R^2 = 0.44$; RMSE = 0.32).

Discussion

In this study a positive correlation was found between the canopy porosity measured at EL 25 and the total anthocyanin levels at harvest (Figure 2). This was consistent with previous research that found that vineyards with open canopies with a high light exposure can produce fruit with higher total anthocyanins (Keller & Hrazdina 1998, Smart et al. 2017). By contrast, other studies have shown shading of Shiraz bunches reduces anthocyanin and flavonol concentrations in the skin (Downey et al., 2004).

Dokoozlian and Kliewer (1995) found that light had the greatest impact on fruit development during the initial stages of berry growth. Grape berry development is divided in two phases, namely phase I and phase II with the lag phase which is equally distributed between the two phases as defined by Coombe 1972. Although grape berries do not accumulate anthocyanin during this period, light exposure during Phase I appears necessary for maximum anthocyanin production. Exposing fruit to light early in berry development has been found to increase the activity of one or several anthocyanin biosynthetic enzymes (Takeda et al. 1988).

However, the correlation between canopy porosity at EL 35 and total anthocyanins (Figure 3) was lower (R^2=0.44) compared to the correlation when canopy porosity was measured at EL 25 (R^2=0.70; Figure 2). There are outlier results from vineyards with both high and low colour levels as the level of canopy porosity increases (Figure 3). It was expected that the positive correlation between canopy porosity and total anthocyanin levels would continue as anthocyanins accumulate in grape berry skin cell walls and vacuoles from veraison until harvest (Braidot, et al. 2008).

The weaker relationship at EL 35 could be explained by the influence of temperature on the development of anthocyanins. A study has shown that the accumulation of anthocyanins is dependent on both low temperature and light through the regulation of flavonoid biosynthesis pathway genes (Azuma et al. 2012). Vineyards in hot climates have been noted to have poor anthocyanin levels if they have excessive direct sun exposure as anthocyanin production and accumulation is inhibited (Bergqvist et al. 2001, Dry et al. 1999, Kliewer 1970, Kliewer 1977). Direct sun exposure leads to high berry temperatures which are not conducive to optimal anthocyanin accumulation in berries (Haselgrove et al. 2000) and the synthesis of flavonoids (Downey et al. 2004). In this study canopy porosity may have reached the upper limit of too much direct sun exposure. Levels of exposure measured by canopy porosity in this trial ranged from 0.1 (10%) to 0.91 (91%) porosity. Daytime temperatures in the wine regions included in this study regularly reach over 35°C (Table 2) which produces hot conditions. Excessive sunlight exposure can cause sunburn damage, and this may affect fruit condition when sampling for anthocyanin (Chordi et al. 2010).

Conclusion

This study demonstrates that canopy porosity measured at EL 25 correlated with berry colour at harvest. The relationship between canopy porosity at EL 35 and the colour level at harvest did not correlate as strongly. This study highlights the importance of canopy porosity and bunch exposure on anthocyanin accumulation for vineyards in warm to hot climates where maximum air temperatures regularly exceed 35°C. There is likely an ideal range of direct sun exposure to berries to maximise anthocyanin accumulation but minimise high temperatures which reduce anthocyanin production and accumulation.

The influence of temperature was not assessed in this study. Future studies linking anthocyanin accumulation with canopy porosity and the vines canopy need to consider the role of temperature. There are studies that have demonstrated the negative impact of high temperatures on anthocyanin level (Haselgrove et al. 2000) and future research needs to consider these findings before commencing trials.

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Chapter 6: General discussion

6.1 Summary

This study investigated using vine performance measurements to develop predictive models of winegrape quality and using winegrape grading. Using regression modelling two models were developed (GS and HRV) in cv. Shiraz and Cabernet Sauvignon. The methodology for developing these models was included as research papers (Chapters 3 & 4). Each of these models assessed the ability of vine performance measurements to predict winegrape quality grade.

Shiraz modelling in Chapter 3 showed that prediction using the GS model was less successful than using the HRV model. The R^2 values for the HRV were statistically higher as might be expected because they used direct measurements of berry composition. Berry composition in grapes relates closely to the composition of the final wine. However, when modelling the Cabernet Sauvignon data (Chapter 4), the GS model (R^2 of 0.678; $p=0.083$) and HRV model (R^2 of 0.646; $p=0.022$) performed at a similar level. The trial on Cabernet Sauvignon may have produced similar results due to steady growth patterns inherent in the cultivar, or seasonal weather factors for that trail season. Further investigation into the prediction of Cabernet Sauvignon wine quality from vine performance may show that the cultivar is more reliable than Shiraz.

The consistency of each vineyard performance measurement ability to predict winegrape quality gives insight into what measures are likely to be the best predictors for all vineyards. The use of canopy measurement to predict winegrape quality grade has the key advantage of time. Where these canopy measures can be actively managed by grapegrowers the potential to manipulate winegrape quality grade before harvest can be trialled or implemented.

Veraison is a key growth stage for determining winegrape quality. In this study leaf area index at EL 35 was seen to be a consistent predictor of winegrape grade across both cultivars. Variation in leaf area index (LAI) at EL 35 correlated with a change in winegrape quality grade. LAI at EL 35 had a consistent negative influence on the winegrape quality grade with high LAI measurements leading to lower winegrape quality grades. The findings highlight the links between vine size at veraison and winegrape grade. This would reinforce previous studies that show the growth stage of veraison corresponds with significant changes in berry composition (Kliewer & Lider 1968; Kliewer & Antcliff 1970; Kliewer 1977; Reynolds et al. 1986; Morrison 1988) and that the light environment inside the canopy as vines ripen is a key influencer on winegrape quality grade at harvest (Smart et al. 1981; Smart 1985; Coombe & Iland 1987; Dokoozlian & Kliewer 1995).

Vineyard techniques to reduce vine size at EL 35 are well known and include a controlled water deficit (Dry et al. 1997; McCarthy 1997) and covercrop competition to limit soil moisture (Giese, et al. 2014). Using these techniques to product an ideal canopy size at EL 35 is considered beneficial to winegrape quality grade.

Research work in this thesis showed that vineyards with high soil RAW and high levels of irrigation up to EL 35 produce vines with lower winegrape quality grade. Excess water availability can impact on the activity of enzymes and hormones, especially in relation to cell division in the developing pulp and skin, which influences the eventual size and juice content of berries (Dry et al. 1997). Controlled water deficit reduces vine vigour and increases production quality (Chaves et al. 2007). Excess soil moisture will also produce vines with bigger canopies (LAI), lower canopy porosity, bigger berry size and lower levels of total anthocyanin, total tannins and phenolic levels (Downey et al. 2004). Vineyard management techniques to reduce excess soil moisture levels will lead to smaller canopies and better conditions for ripening.

Berry composition measures were found to be predictors of winegrape quality grade in both varieties studied. Small berry size, high total anthocyanins, high tannin and phenolic levels at EL 37 correlated with higher winegrape quality grade. These findings support existing knowledge where a relationship has been found between winegrape quality and berry composition at harvest in France (Jones & Davis 2000), California (Jackson & Lombard 1993, Jones & Goodridge 2007) and Australia (Winter et al. 2004). Including measures of berry composition in assessing winegrape quality seems the most effective objective measure of quality.

As berry composition is linked to winegrape quality, undertaking vineyard management techniques that increase total anthocyanin, total tannin and phenolic accumulation is beneficial. Various canopy management techniques have been trialled including leaf removal, shoot thinning and trimming, all of which aim to increase fruit and leaf exposure to sunlight to improve berry composition (Reynolds et al. 1986, Bledsoe et al. 1988, Reynolds et al. 1989, Marais et al. 1999, Vasconcelos & Castagnoli 2000, Reynolds et al. 2005, Lohitnavy et al. 2010).

There were differences in the prediction models developed for Shiraz and Cabernet Sauvignon. In the Cabernet Sauvignon study (Chapter 4) shoot density was shown as a predictor of winegrape quality grade. This was consistent with previous studies where shoot density is a valuable measure of canopy porosity and light exposure into the canopy (Reynolds & Wardle 1989; Dokoozlian & Kliewer 1995; Smart et al. 2017). These studies concluded that vineyard canopies produced fruit with higher qualities if they were open to sunlight. Shoot counts, expressed as shoots per metre, have been used to compare canopies across season and vineyards (Smart & Robinson 1991). In the Shiraz study (Chapter 3) shoot density was shown not to be a reliable measure for predicting winegrape quality which suggests that grapevine cultivar may be a factor of variability.

Chapter 5 supports the crucial role of the vines canopy in determining winegrape quality as found in Chapter 3 & 4, but also highlights that an excess of direct sun exposure is detrimental to berry composition. In Chapter 5 canopy porosity at EL 25 was shown to correlate with anthocyanin levels at harvest while at EL 35 the correlation between canopy porosity levels and anthocyanin levels was not as strong. These results may be due to an excessive amount of direct sun exposure. In this trial canopy porosity may have reached the upper limit where too much sunlight exposure leads to high berry temperatures and impairs the berries ability to accumulate anthocyanin. These findings highlight the importance of temperature in anthocyanin production and accumulation and in terms of overall winegrape quality as vineyard studies have found excessive direct sun exposure and the resulting high berry temperature delay ripening (Crippen & Morrison 1986; Price et al. 1995; Bergqvist et al. 2001).

6.2 Limitations

The influence of temperature inside the canopy was not measured in this study. Given that berry composition measures were predictors of winegrape quality in Chapters 3 and 4, and that berry composition is driven by temperature (Haselgrove et al. 2000; Downey et al. 2006; Azuma et al. 2012) temperature should be monitored for its influence on winegrape quality. The effect of high temperatures on several other grapevine varieties has been well documented. For example, Kliewer and colleagues (Kliewer & Lider 1968; Kliewer 1977; Matsui et al. 1986; Sepúlveda & Kliewer 1986) have investigated high temperature effects on various cultivars, including Cabernet Sauvignon, and have shown reduced berry development, reduced anthocyanin accumulation and delayed ripening. Delayed ripening effects have also been observed in other varieties when vines were exposed to high temperatures (Greer & Weston 2010). Establishing the links between canopy temperature and winegrape quality grade would have improved the study.

This study did not establish a minimum canopy size or a maximum porosity of the canopy. Logically a grapevine canopy can be too small in leaf area to adequately ripen a crop. Vineyard regions with long sunshine hours and hot climates are likely to need more protection from solar heating than those grown in cool climates. The lower limits of canopy size, and the upper limits of light exposure need to be better defined for given mesoclimates. This research study used two cultivars Shiraz (Chapter 3 and 5) and Cabernet Sauvignon (Chapter 4) which have a high tolerance to light exposure. Other cultivars, particularly those with light coloured skins used to make white wine, may not benefit from greater light exposure throughout their growing season. The results of analysis of the links between light environment (Chapter 5) showed that there is an upper limit to light exposure when it comes to anthocyanin accumulation. Too greater light exposure leads to high berry temperatures which interferes with berry chemistry (Haselgrove et al. 2000) and ripening processes (Greer 2013). Many vineyard studies have examined the links between radiative (direct sun exposure) effects and high berry temperature (Crippen & Morrison 1986; Morrison & Noble 1990; Bergqvist et al. 2001). There is likely an upper limit of direct light exposure above which point there will be a reduction of berry quality caused by high temperatures.

This study used the value ascribed to the grapes as a measure of winegrape quality grade. Using the value ascribed to the vineyard assumes that this process is accurate and not without bias. To eliminate the possibility of bias in vineyard grading future studies could use small batch winemaking to produce wine from each trial vineyard for direct measurement of quality and comparison to other methods used. Experimental small batch winemaking is often used to evaluate changes in viticultural and oenological practices in research trials (Aylward 2003; Sparrow & Smart 2015). However, using small batch winemaking as a measure of winegrape quality grade on a commercial scale is challenging due to the limitations imposed by production logistics, fermenter size and expense (Sparrow & Smart 2015).

6.3 Future directions

Assessment methods used in this research were designed for use on a commercial scale. The methodologies used in this study to model winegrape quality grade allows for further investigation in other varieties and regions. Two common varieties of *Vitis vinifera* L. (cvs. Shiraz and Cabernet Sauvignon) were used in this study, in regions where they are the widely grown and recognised for their performance. In McLaren Vale, Langhorne Creek and the Adelaide Hills similar trends were seen between the performance of both cultivars. There are many other examples of where these specific grape cultivars are recognised for their abilities to make wine styles that have high value in the marketplace. Examples include, Shiraz in the Heathcote region of Victoria, Shiraz in the Barossa Valley and Cabernet Sauvignon in the Coonawarra regions of South Australia. The assessment methods in this research could also be used in regions that use other cultivars for their high-quality red wine production, Tasmania and the Yarra Valley for Pinot Noir for example.

Future studies that approach assessing winegrape quality grade on a commercial scale would benefit from greater individual vine numbers to collect the leaf area index and canopy porosity measurements. Increasing the volume of data collected can reduce errors caused by vineyard variability. Knowledge of the spatial variability of grapevine canopy density is useful in managing vineyard variability (Bramley & Trengove, 2013). Rapid assessment of the characteristics of vineyard canopies by image analysis offers distinct advantages over counting-based measurements. Count based measurements, while simple to collect, are tedious as the time taken to gather data is prohibitive. As count measurements require many hours of time to collect on a commercial scale their use is limited.

Methods of gathering canopy architecture in an automated manner would enable the massive capture of data through the growing season. It is possible this could be performed by a camera mounted on vineyard equipment programmed to capture imagery from multiple observation points. The massive capture of data can then be plotted by capture point to produce maps of canopy architecture parameters for example showing canopy porosity (Figure 6.1). Spatial variations of LAI can also be displayed as a heat map (Figure 6.2). Use of these maps allows for improved vineyard management as they show canopy variation which could be linked to berry composition and thus winegrape grade and quality.

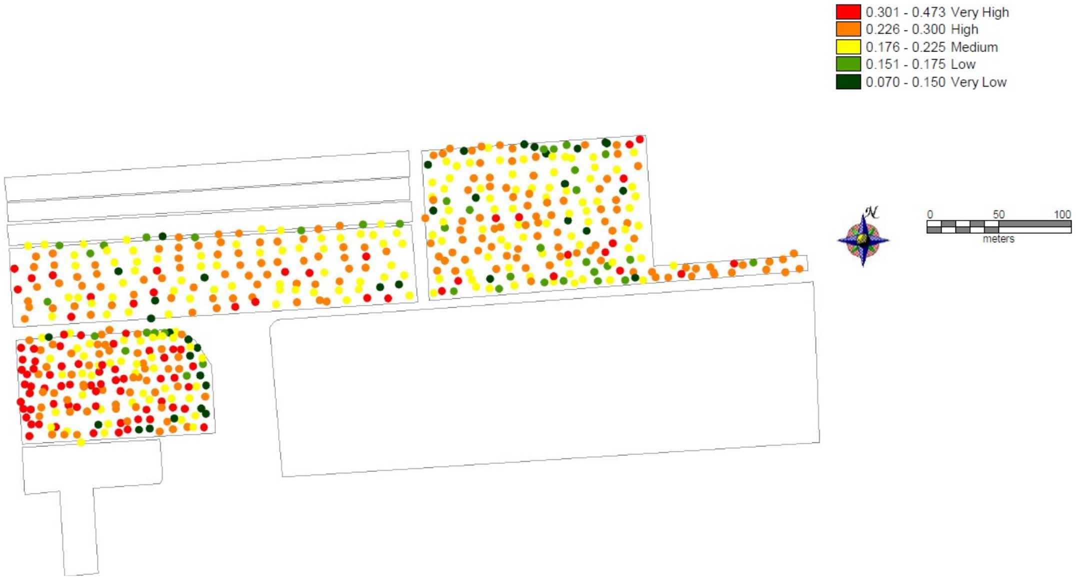

Figure 6.1: Spatial distribution map of canopy porosity data taken in a commercial cv. Shiraz vineyard in McLaren Vale, South Australia in 2019 with the VitiCanopy App (De Bei et al. 2016).

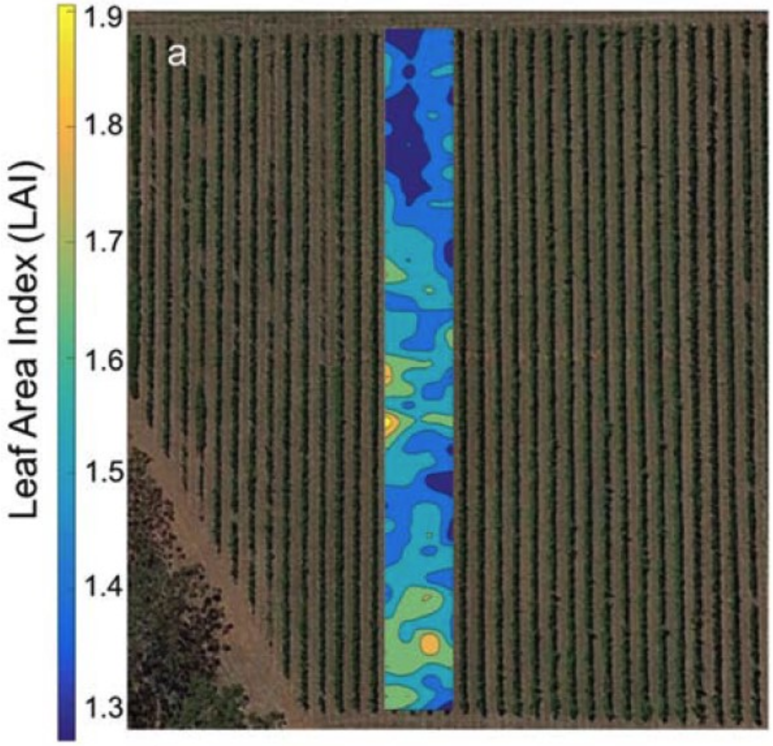

Figure 6.2: Spatial distribution map showing changes in LAI across four rows in the Semillon vineyard at the University of Adelaide Waite Campus, South Australian measured using VitiCanopy App (De Bei et al. 2015).

In conclusion this research led to a greater understanding on methods of measuring vine performance to assess winegrape quality grade. Currently winegrape quality can be assessed by price paid for the fruit at market, past performance, objective and subjective measures or a combination of these. These trials showed models of winegrape quality can be developed by using objective measurements. An early system of winegrape quality assessment (GS model) can be developed using vine canopy measures. Vine canopy measures in combination with grape berry composition can be used as a harvest assessment (HRV model). Both models assessed vine performance using practical systems that can be adopted on a wide scale. Vine canopy assessment by using image analysis takes less time than corresponding manual methods of canopy assessment. Using simplified methodology for assessing winegrape grading allows assessment on a commercial scale by grapegrowers and winemakers.

The findings have wide implications for the wine industry. Based on the results seen with the grape cultivars used in the research winegrape quality modelling could be adapted for use in other regions and on other varieties. The commercial benefit of transparent winegrape assessment is increased clarity and accountability between all parties in the wine industry.

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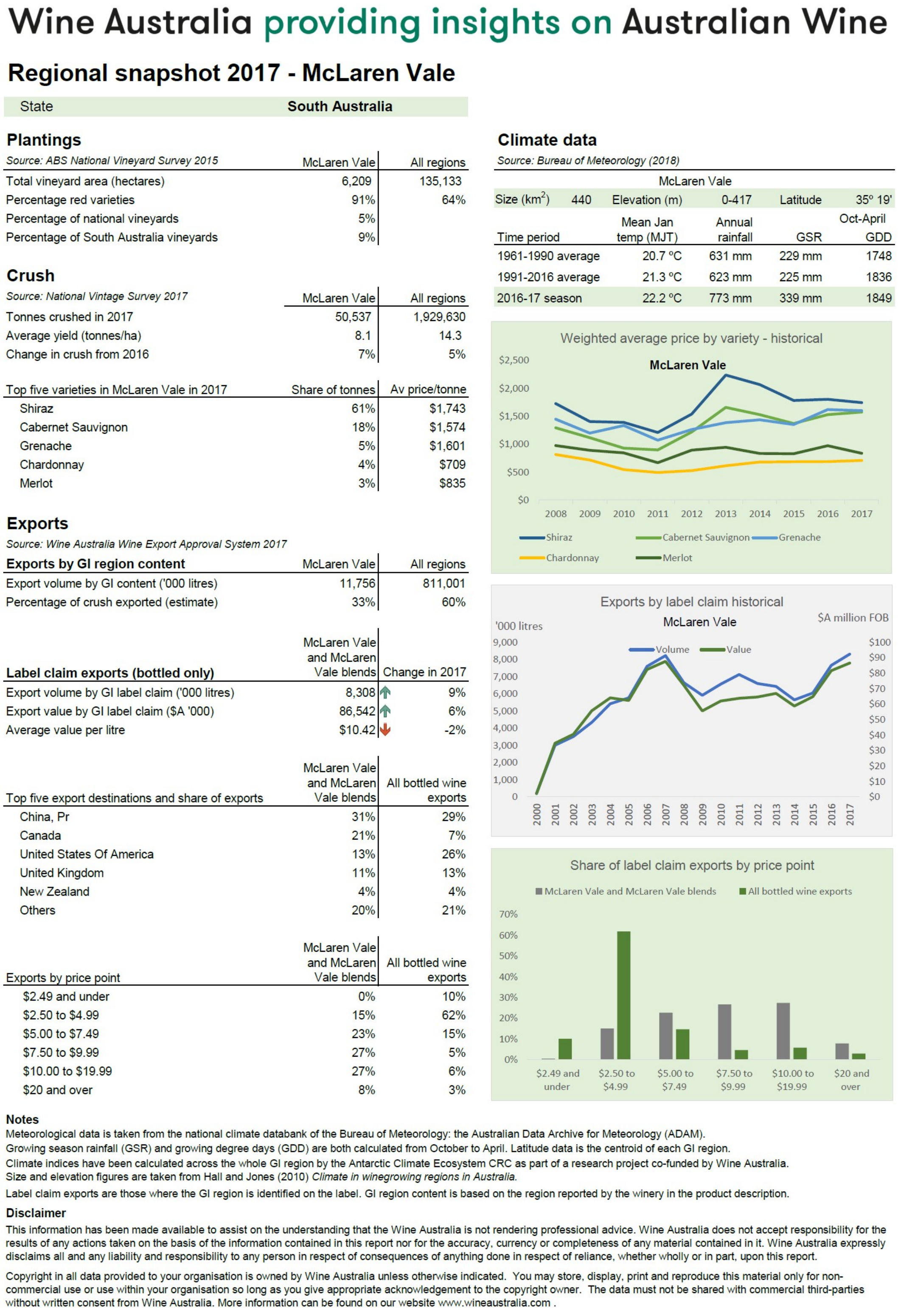
Appendices

A. Wine Australia 2017 regional insights



Wine Australia providing insights on Australian Wine

Regional snapshot 2017 - McLaren Vale

State	South Australia

Plantings

Source: ABS National Vineyard Survey 2015	McLaren Vale	All regions
Total vineyard area (hectares)	6,209	135,133
Percentage red varieties	91%	64%
Percentage of national vineyards	5%	
Percentage of South Australia vineyards	9%	

Crush

Source: National Vintage Survey 2017	McLaren Vale	All regions
Tonnes crushed in 2017	50,537	1,929,630
Average yield (tonnes/ha)	8.1	14.3
Change in crush from 2016	7%	5%

Top five varieties in McLaren Vale in 2017	Share of tonnes	Av price/tonne
Shiraz	61%	$1,743
Cabernet Sauvignon	18%	$1,574
Grenache	5%	$1,601
Chardonnay	4%	$709
Merlot	3%	$835

Exports

Source: Wine Australia Wine Export Approval System 2017

Exports by GI region content	McLaren Vale	All regions
Export volume by GI content ('000 litres)	11,756	811,001
Percentage of crush exported (estimate)	33%	60%

Label claim exports (bottled only)	McLaren Vale and McLaren Vale blends		Change in 2017
Export volume by GI label claim ('000 litres)	8,308	↑	9%
Export value by GI label claim ($A '000)	86,542	↑	6%
Average value per litre	$10.42	↓	-2%

Top five export destinations and share of exports	McLaren Vale and McLaren Vale blends	All bottled wine exports
China, Pr	31%	29%
Canada	21%	7%
United States Of America	13%	26%
United Kingdom	11%	13%
New Zealand	4%	4%
Others	20%	21%

Exports by price point	McLaren Vale and McLaren Vale blends	All bottled wine exports
$2.49 and under	0%	10%
$2.50 to $4.99	15%	62%
$5.00 to $7.49	23%	15%
$7.50 to $9.99	27%	5%
$10.00 to $19.99	27%	6%
$20 and over	8%	3%

Climate data

Source: Bureau of Meteorology (2018)

McLaren Vale

Size (km^2)	440	Elevation (m)	0-417	Latitude	35° 19'

Time period	Mean Jan temp (MJT)	Annual rainfall	GSR	Oct-April GDD
1961-1990 average	20.7 °C	631 mm	229 mm	1748
1991-2016 average	21.3 °C	623 mm	225 mm	1836
2016-17 season	22.2 °C	773 mm	339 mm	1849

Notes

Meteorological data is taken from the national climate databank of the Bureau of Meteorology: the Australian Data Archive for Meteorology (ADAM).
Growing season rainfall (GSR) and growing degree days (GDD) are both calculated from October to April. Latitude data is the centroid of each GI region.
Climate indices have been calculated across the whole GI region by the Antarctic Climate Ecosystem CRC as part of a research project co-funded by Wine Australia.
Size and elevation figures are taken from Hall and Jones (2010) *Climate in winegrowing regions in Australia.*

Label claim exports are those where the GI region is identified on the label. GI region content is based on the region reported by the winery in the product description.

Disclaimer

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Wine Australia providing insights on Australian Wine

Regional snapshot 2017 - Langhorne Creek

State	South Australia

Plantings

Source: ABS National Vineyard Survey 2015	Langhorne Creek	All regions
Total vineyard area (hectares)	5,368	135,133
Percentage red varieties	85%	64%
Percentage of national vineyards	4%	
Percentage of South Australia vineyards	8%	

Crush

Source: National Vintage Survey 2017	Langhorne Creek	All regions
Tonnes crushed in 2017	67,332	1,929,630
Average yield (tonnes/ha)	12.5	14.3
Change in crush from 2016	-3%	5%

Top five varieties in Langhorne Creek in 2017	Share of tonnes	Av price/tonne
Shiraz	38%	$882
Cabernet Sauvignon	32%	$754
Merlot	9%	$698
Chardonnay	7%	$522
Riesling	4%	$600

Exports

Source: Wine Australia Wine Export Approval System 2017

Exports by GI region content	Langhorne Creek	All regions
Export volume by GI content ('000 litres)	7,814	811,001
Percentage of crush exported (estimate)	17%	60%

Label claim exports (bottled only)	Creek and Langhorne Creek blends	Change in 2017
Export volume by GI label claim ('000 litres)	2,760 ↓	-6%
Export value by GI label claim ($A '000)	21,501 ↓	-3%
Average value per litre	$7.79 ⇨	3%

Top five export destinations and share of exports	Creek and Langhorne Creek blends	All bottled wine exports
China, Pr	46%	29%
Canada	15%	7%
United Kingdom	10%	13%
United States Of America	8%	26%
New Zealand	4%	4%
Others	17%	21%

Exports by price point	Creek and Langhorne Creek blends	All bottled wine exports
$2.49 and under	1%	10%
$2.50 to $4.99	35%	62%
$5.00 to $7.49	32%	15%
$7.50 to $9.99	15%	5%
$10.00 to $19.99	13%	6%
$20 and over	4%	3%

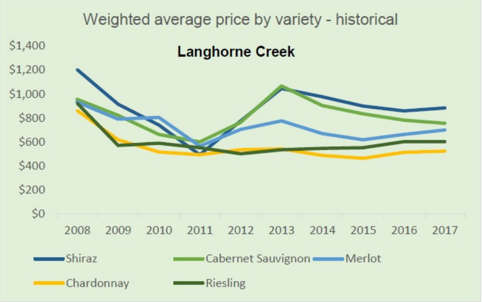
Climate data

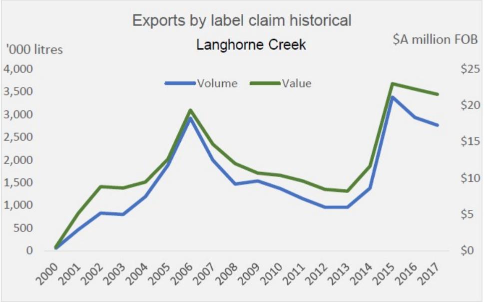
Source: Bureau of Meteorology (2018)

Langhorne Creek

Size (km^2)	240	Elevation (m)	0-64	Latitude	35° 33'

Time period	Mean Jan temp (MJT)	Annual rainfall	GSR	Oct-April GDD
1961-1990 average	20.8 °C	384 mm	174 mm	1808
1991-2016 average	21.5 °C	384 mm	169 mm	1899
2016-17 season	22.4 °C	505 mm	232 mm	1913





Notes

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Wine Australia providing insights on Australian Wine

Regional snapshot 2017 - Adelaide Hills

State	South Australia

Plantings

Source: ABS National Vineyard Survey 2015	Adelaide Hills	All regions
Total vineyard area (hectares)	3,052	135,133
Percentage red varieties	40%	64%
Percentage of national vineyards	2%	
Percentage of South Australia vineyards	5%	

Crush

Source: National Vintage Survey 2017	Adelaide Hills	All regions
Tonnes crushed in 2017	31,121	1,929,630
Average yield (tonnes/ha)	10.2	14.3
Change in crush from 2016	-2%	5%

Top five varieties in Adelaide Hills in 2017	Share of tonnes	Av price/tonne
Sauvignon Blanc	33%	$1,218
Chardonnay	22%	$1,388
Pinot Noir	18%	$1,561
Pinot Gris/Grigio	10%	$1,433
Shiraz	6%	$1,869

Exports

Source: Wine Australia Wine Export Approval System 2017

Exports by GI region content	Adelaide Hills	All regions
Export volume by GI content ('000 litres)	3,467	811,001
Percentage of crush exported (estimate)	16%	60%

Label claim exports (bottled only)	Adelaide Hills and Adelaide Hills blends	Change in 2017
Export volume by GI label claim ('000 litres)	2,196 ↑	11%
Export value in 2017 ($A '000)	19,483 ↑	11%
Average value per litre	$8.87 ↓	-1%

Top five export destinations and share of exports	Adelaide Hills and Adelaide Hills blends	All bottled wine exports
United Kingdom	31%	13%
China, Pr	16%	29%
United Arab Emirates	9%	1%
Canada	9%	7%
United States Of America	6%	26%
Others	29%	25%

Exports by price point	Adelaide Hills and Adelaide Hills blends	All bottled wine exports
$2.49 and under	1%	10%
$2.50 to $4.99	18%	62%
$5.00 to $7.49	35%	15%
$7.50 to $9.99	17%	5%
$10.00 to $19.99	24%	6%
$20 and over	5%	3%

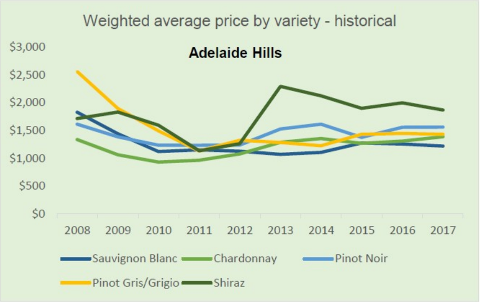
Climate data

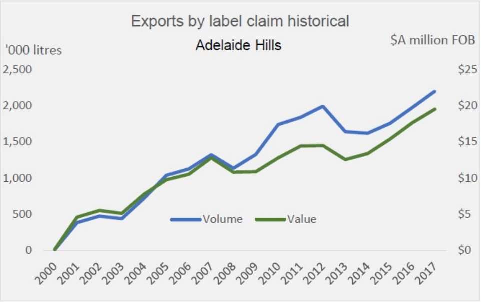
Source: Bureau of Meteorology (2018)

Adelaide Hills

Size (km^2)	1 470	Elevation (m)	149-714	Latitude	34º 98'

Time period	Mean Jan temp (MJT)	Annual rainfall	GSR	Oct-April GDD
1961-1990 average	19.6 ºC	801 mm	285 mm	1475
1991-2016 average	20.3 ºC	795 mm	276 mm	1568
2016-17 season	21.1 ºC	1007 mm	439 mm	1572





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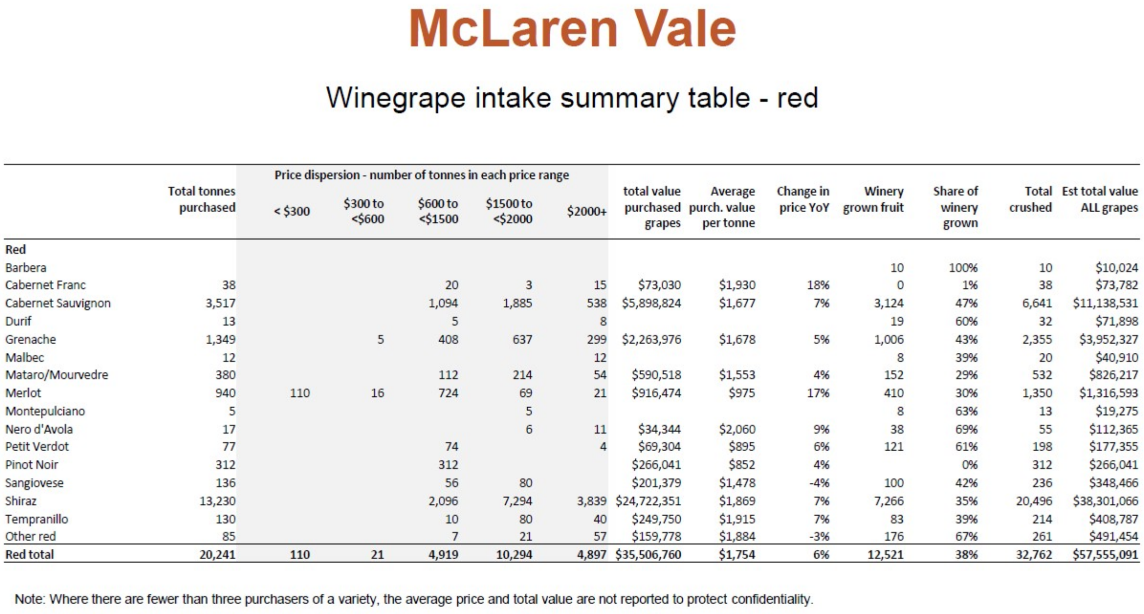
B. Vine Health Australia 2018 Winegrape Crush Survey



McLaren Vale

Winegrape intake summary table - red

	Total tonnes purchased	Price dispersion - number of tonnes in each price range < $300	$300 to <$600	$600 to <$1500	$1500 to <$2000	$2000+	total value purchased grapes	Average purch. value per tonne	Change in price YoY	Winery grown fruit	Share of winery grown	Total crushed	Est total value ALL grapes
Red													
Barbera										10	100%	10	$10,024
Cabernet Franc	38			20	3	15	$73,030	$1,930	18%	0	1%	38	$73,782
Cabernet Sauvignon	3,517			1,094	1,885	538	$5,898,824	$1,677	7%	3,124	47%	6,641	$11,138,531
Durif	13			5		8				19	60%	32	$71,898
Grenache	1,349		5	408	637	299	$2,263,976	$1,678	5%	1,006	43%	2,355	$3,952,327
Malbec	12					12				8	39%	20	$40,910
Mataro/Mourvedre	380			112	214	54	$590,518	$1,553	4%	152	29%	532	$826,217
Merlot	940	110	16	724	69	21	$916,474	$975	17%	410	30%	1,350	$1,316,593
Montepulciano	5				5					8	63%	13	$19,275
Nero d'Avola	17				6	11	$34,344	$2,060	9%	38	69%	55	$112,365
Petit Verdot	77			74		4	$69,304	$895	6%	121	61%	198	$177,355
Pinot Noir	312			312			$266,041	$852	4%		0%	312	$266,041
Sangiovese	136			56	80		$201,379	$1,478	-4%	100	42%	236	$348,466
Shiraz	13,230			2,096	7,294	3,839	$24,722,351	$1,869	7%	7,266	35%	20,496	$38,301,066
Tempranillo	130			10	80	40	$249,750	$1,915	7%	83	39%	214	$408,787
Other red	85			7	21	57	$159,778	$1,884	-3%	176	67%	261	$491,454
Red total	**20,241**	**110**	**21**	**4,919**	**10,294**	**4,897**	**$35,506,760**	**$1,754**	**6%**	**12,521**	**38%**	**32,762**	**$57,555,091**

Note: Where there are fewer than three purchasers of a variety, the average price and total value are not reported to protect confidentiality.

C. Demonstration of Alphanumerical grading system commonly used in the wine Australian wine industry. 2013 Treasury Wine Estates Contracted Winegrape Prices ($AUD) and terminology – McLaren Vale Wine Region.

Shiraz		**Cabernet Sauvignon**		**Other Red Cultivar**	
A Grade from	= $2700	A Grade from	= $2700	B1	= $2500
B1	= $2700	B1	= $2700	B2	= $1950
B2	= $2100	B2	= $2100	B3	= $1400
B3	= $1800	B3	= $1800	C1	= $1200
C1	= $1500	C1	= $1500	C2	= $900
C2	= $1000	C2	= $1000	D Grade to	= $400
D Grade to	= $465	D Grade to	= $465		

D. 2013 Winegrape Crush Survey – cv. Shiraz, Cabernet Sauvignon, Grenache, Merlot – McLaren Vale Wine Region.

Variety	Tonnes purchased	Lowest price	Highest price	Total value purchased grapes	Calc avg. purch. Value per tonne	Winery grown fruit	Total crushed	Est total value ALL grapes
Shiraz	10,966	$800	$8,500	$18,388,345	$1,677	6,485	17,451	$29,261,947
Cabernet Sauvignon	3,305	$700	$5,586	$4,493,508	$1,360	2,290	5,595	$7,607,271
Grenache	1,439	$400	$4,000	$1,956,368	$1,359	1,013	2,453	$3,333,687
Merlot	985	$600	$2,200	$964,038	$979	737	1,722	$1,685,728

E. Winegrape quality grade assessment terminology shown as equivalent bulk wine price, source *McLaren Vintners* winery - 2015.

A-Grade	i.e. > $6.00 per litre
B-Grade	i.e. $3.00-6.00 per litre
C- Grade	i.e. $3.00-1.20 per litre
D- Grade	i.e. $1.20-0.50 per litre
E- Grade	i.e. $0.50-0.35 per litre
F- Grade	Limited use