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Optimising vine balance in Australian vineyards: developing a toolbox for industry to ensure best practice, sustainability and profitability



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WINE AUSTRALIA

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Principal Investigator: **Assoc. Prof. Cassandra Collins**

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Project Supervisor: **A/Prof Cassandra Collins**
Chief Investigators: **Dr Roberta De Bei**
Dr Sigfredo Fuentes
Prof Matthew Gilliham
Prof Stephen Tyerman

University of Adelaide

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1 Abstract

Canopy management trials conducted in commercial vineyards and at the Waite campus, University of Adelaide, demonstrated that a new tool, VitiCanopy, was effective at capturing canopy architecture differences that resulted in fruit and wine compositional changes and berry and wine sensory differences. Vine balance is more easily measured with VitiCanopy than other traditional measures that are labour intensive. VitiCanopy measurements of leaf area index, canopy porosity and growth rate were also highly correlated with vine performance and quality and can be measured early in the growing season, allowing within season management decisions to be made. These outcomes provide new information and tools that will lead to more informed vineyard management in Australian vineyards.

2 Executive summary

Australian vineyards need to produce high quality fruit to remain competitive in the global market. Vineyard practitioners use a variety of management practices to control canopy size and to achieve vine balance. To help assist management decisions, researchers have developed indices to assess vine performance but they are often subjective and/or difficult for growers to apply, hence adoption by industry is low. Also, the link between canopy management, vine balance indices and wine quality has not been clearly understood.

The main objectives of the project were:

i) to determine canopy parameters that indicate optimal vine performance and wine quality and evaluate how effectively these can be manipulated using management techniques.

ii) to develop an accurate, inexpensive, labour saving toolbox for assessing vine balance in the field and deploy this toolbox to the industry.

Experimental field trials on Shiraz (in collaboration with Treasury Wine Estate) and Semillon were carried out across a number of regions (Coonawarra, McLaren Vale, Barossa, Padthaway and Adelaide-Waite Campus). At these sites, canopy manipulation treatments were performed over three seasons and focused on altering vine vigour and yield. Vine performance was assessed using measures of yield and yield components, canopy architecture, berry and wine chemistry and berry and wine sensory.

The project has met the primary objectives and has provided:

Valuable information on the outcomes of common industry canopy management practices. It was found that the outcome of the same management practice is season and region dependent. This finding is not surprising as a site's potential is largely due to the environment in which it is grown. Moreover, industry standard practices such as shoot thinning, leaf plucking and bunch thinning, proved ineffective in modifying vine performance in most cases. Practices that were effective are summarised below.

A better understanding of the effect of cover cropping as a tool to suppress excessive vigour. In all cases, canopy size and yield were effectively reduced with the use of cover crops, however, the effect on berry and wine chemistry was very limited. Wine obtained from cover crop treatments was characterised by riper aromas and a richer mouthfeel.

Information on the use of sacrificial canes as a technique to control vine vigour. The results showed that leaving four sacrificial canes ('kickers') successfully suppressed vigour but also dramatically decreased yield with strong carryover effects after two seasons of continuous application. The effects were greater when kickers were removed at veraison compared to flowering. The results also suggest that kickers tend to create high variability in canopy architecture and yield between vines that could complicate vineyard management.

New understanding on the effect of delayed winter pruning. Pruning was carried out after budburst, at EL 9-11, and appeared to be ineffective in delaying ripening and also showed very large yield reductions. Similarly to sacrificial canes, late pruning reduced shoot vigour and also created high vine variability.

Important correlations between canopy parameters, vine balance indices and vine performance. The canopy architecture measures of LAI and porosity correlated better than yield with berry and wine chemistry and sensory measures. The vine balance indicators Y/P and Y/LAI produced very similar correlations with berry and wine chemistry especially when the flowering LAI measure was used. It was also observed that the early season canopy architecture measures are better indicators of grape and wine quality than the veraison measures. Moreover, the canopy growth rate showed interesting links to grape and wine quality. A greater growth rate early in the season correlated positively with grape and wine chemistry measures. Conversely, a greater late season growth rate, from veraison to harvest, was detrimental to quality.

A toolbox in the form of two smartphone Apps, VitiCanopy and VitiSense, was created. VitiCanopy measures canopy architecture as Leaf Area Index (LAI) and canopy porosity. VitiCanopy was tested against traditional destructive methods and dedicated instrumentation with results found to be comparable to those of more established methods. The App is intended as an alternative to other destructive or non-destructive methods to estimate LAI with the advantages of being free, highly portable and providing immediate results. Since the results are geo-referenced, data can be used for GIS applications and mapping. VitiSense, was developed to make sensory assessments more accessible and able to be carried out in-field. Grape growers and winemakers taste grapes before harvest and they rely on the information from this assessment to make decisions on harvest date and grading and allocation of grapes for a specific wine style. VitiSense provides users with an easy tool to perform a structured and geo-referenced berry tasting assessment in the vineyard, and has the potential to be used for other assessments such as wine. The combination of VitiCanopy and VitiSense can provide easy indications of the links between canopy architecture and grape sensory attributes in a vineyard.

VitiCanopy has proved to be a useful tool to assist vineyard management decision making. It can be used to assess the outcome of a management intervention and to calculate canopy growth rate. For example, when VitiCanopy was unable to show a change in canopy architecture after a treatment, the treatment proved ineffective on vine performance. Vine balance can be effectively measured using new indices that calculate LAI and canopy porosity using VitiCanopy with the advantage of being easy and quick to take compared to a measure of pruning weight or destructive measures of leaf area.

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3 Background

For each variety, region and season there is an optimum vine balance (when vegetative growth and fruiting load are in equilibrium) that delivers the best possible fruit quality for a desired wine style. Vineyard managers use a variety of management practices (pruning, fruit removal, canopy manipulations) in order to control canopy size and to achieve vine balance. Moreover, to help assist management decisions, researchers have developed indices to assess vine performance but they are often too subjective, time consuming, retrospective and difficult for growers to apply. Also, the link between canopy management, vine balance indices and wine quality has not been clearly understood.

Consequences of vine imbalance

When grapegrowers and viticulturists are asked about what they are trying to achieve in the vineyard, vine balance is one of the most frequently mentioned topics. Negative effects on yield, ripening and fruit quality can occur when vines are unbalanced. For example, if the yield is too large (over-yielding) vegetative growth is often reduced, ripening slowed, and fruit quality less than desired (Bravdo et al. 1984, 1985a, Howell et al. 1987, Howell et al. 1991, Kliewer and Weaver 1971, Reynolds et al. 1986, Smart et al. 1985b, Winkler 1954, Winkler et al. 1974). Similarly, when a vine is under-yielding, this can result in excessive shoot vigour, due to the removal of competition between the allocation of carbon (C) and nitrogen (N) reserves (Winkler et al. 1974).

Managing vine balance

Before vine balance can be achieved, vine size must be established. Vine size is determined by the site and the interaction between soil, climate, plant and viticulture (Smart and Robinson 1991). Vine development, grape ripening and wine sensory attributes are highly influenced by the physical environment in which the vines grow and the management of the vines – this is known as the 'terroir effect' (van Leeuwen 2010). The commercial cost of attaining a given wine quality will be least where the vineyard environment is most suitable. The physical environment (location and design) of a vineyard has a permanent to semi-permanent influence on how the vines will grow and largely dictates the vigour of the vines (Carol 2007). Temperature, light, humidity, water supply (determined by rainfall and evapotranspiration), the soil depth, fertility and water holding capacity are important factors to achieve vine balance and desired wine quality. For example, vineyards grown in cool climates can have problems with shading resulting in lower anthocyanins and phenolics compared to exposed fruit (Crippen and Morrison 1986, Cortell and Kennedy 2006, Iacono et al. 1994, Price et al. 1995, Ristic et al. 2007). Vineyards in hot climates need to manage fruit exposure because, if excessive, it can be detrimental to fruit quality by inhibiting anthocyanin synthesis or anthocyanin degradation and lower TA (Bergqvist et al. 2001, Dry et al. 1999, Haselgrove et al. 2000, Kliewer 1970, Kliewer 1977, Kliewer and Torres 1972, Mori et al. 2007, Spayd et al. 2002).

One of the difficulties in managing vine balance in the vineyard is that grapevines are perennial plants and management decisions made in one season can have an effect on future seasons (Howell 2001). Also, season to season variation in some regions can cause large yield differences (Dry et al. 2005). These differences in yield can significantly affect leaf area per vine, leaf size, shoot length, node number and internode length, shoot maturation and root dry weight (at harvest) due to competition for reserves and photoassimilates (Bravdo et al. 1984, Edson et al. 1993, Edson et al. 1995a,b, Hunter and LeRoux 1992, Howell 1988, Candolfi-Vasconcelos and Koblet 1990, Candolfi-Vasconcelos and Koblet 1991, Motomura 1993, Quinlan and Weaver 1970). Also, other yield components such as berry number per bunch, bunch size, berry weight and bunch weight have been inversely correlated with bunches per vine (Edson et al. 1993, Edson et al. 1995b, Kaps and Cahoon 1989, Reynolds 1989, Reynolds and Wardle 1989, Reynolds et al. 1986, Reynolds et al. 1994, Weaver and Pool 1968) but positively correlated with yield (Edson et al. 1995a, Reynolds et al. 1994).

Canopy management practices allow grapegrowers and viticulturists to manage vine balance each year but can add significant costs to production. Practical management examples are described in Smart (2001, 2002), Botting (2003), Patterson (2004), Thomas (2004), Dry et al. (2005) and include practices such as pruning, bunch thinning, leaf removal, shoot thinning, shoot trimming, undervine floor management and irrigation. There have been many studies carried out on numerous cultivars looking at canopy management techniques (such as Wolf et al. 1986, Reynolds et al. 1986, Bledsoe et al. 1988, Hunter et al. 1995, Reynolds et al. 1989, Marais et al. 1999, Vasconcelos and Castagnoli 2000, Wolf et al. 2003, Main and Morris 2004, Reynolds et al. 2005, Lohitnavy et al. 2010) which concluded that treatments that increased fruit and leaf exposure to sunlight generally improved grape and wine composition (higher sugar concentrations, anthocyanins, total phenolics and lower malic acid levels, potassium and juice pH) compared to fruit in the canopy interior. Increased sunlight penetration into a canopy also improves yield by increasing inflorescence primordia initiation and subsequent fruitfulness in the next season (Buttrose 1974). Canopy management practices used in vineyards give viticulturists and winemakers the opportunity to manipulate fruit quality and target sensory characteristics for specific wine styles.

Measuring vine balance

Several measurements or calculations have been assessed as indicators of vine balance. Commonly used indicators are the yield to pruning weight (Y/P) ratio and the ratio of leaf area (m^2) to yield (LA/Y). Kliewer and Dokoozlian (2005), in an experiment conducted in California, found that the optimal LA/Y ranged from 0.5 to 1.2 while Y/P varied from 4 to 10 depending on the cultivar, site and management. Other studies support these findings (Ravaz, 1911, Bertamini et al. 1995).

Y/P has been used as an indicator of vine balance by numerous researchers (such as Bravdo et al. 1984, 1985a,b, Kliewer et al. 2000, Smart 1985, Smart and Robinson 1991, Vanden Heuvel et al. 2004,

Kliewer and Dokoozlian 2005, Dokoozlian et al. 2011). Dokoozlian et al. (2011) demonstrated a strong relationship between Y/P and aroma development for Cabernet Sauvignon vines grown in several wine regions in California. Optimal aroma profiles at lower soluble solids levels were obtained in both grapes and wine when Y/P was within the range 8-12. However, there have been some exceptions. Kliewer and Dokoozlian (2005) found that the optimal Y/P for cultivars with small bunches, such as Pinot Noir, have a lower range (i.e. from 3 to 5) and Vanden Heuvel et al. (2004) found that a Y/P ratio between 12 and 22 did not negatively impact quality in young Cabernet Sauvignon vines grown on six different training systems in Ontario, Canada. Furthermore, management has a profound influence on Y/P. For instance, divided canopies may provide an appropriate microclimate for Y/P <12 for both *V. vinifera* and hybrid varieties that are in balance (Reynolds and Wardle 1994, Reynolds et al. 1985, Reynolds et al. 1995). High-yielding varieties with thin shoots such as Cinsaut had Y/P values ranging from 4 to 15, while for varieties with long or thick shoots such as Grenache and Shiraz the range was 3 to 8 (Champagnol 1984, Santesteban et al. 2010).

The main source of sugar produced in grapevines is from leaf photosynthesis (Edson et al. 1995). Therefore, the amount of efficient leaf area needed to ripen fruit to an acceptable level of sugar is an important measure of vine balance (Patridge 1925b, 1931, Ravaz 1911, Shaulis and Robinson 1953, Kliewer et al. 2000). Leaf area must be adequate before veraison to ripen a crop, if not veraison is also delayed (Petrie et al. 2000). The optimal level of fruit yield can be determined by the leaf area required per unit weight of fruit (m^2/kg) to produce berries of maximum skin colour and total sugar accumulation in fruit (Kliewer and Dokoozlian 2005). Smithyman et al. (1997) found that 0.7 to 1.4 m^2 total leaf area per kg of fruit is required to achieve fruit maturity. A detailed review by Kliewer and Dokoozlian (2005) revealed that well balanced vines, capable of fully ripening a crop and producing high quality wines had a leaf area per kg fruit of between 0.8 to 1.2 m^2/kg for vines trained to single canopy trellis systems, and 0.5 to 0.8 m^2/kg for vines trained to divided canopy trellis systems. These corresponded to single canopy and divided canopy trellis systems Y/P values of 4 to 10 and 5 to 10, respectively.

These findings highlight the importance of understanding the role that variety, environment and management practice play in the optimum range for this measurement.

New opportunities to measure vine balance

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. Leaf Area Index (LAI) is one of the measurements most widely used by researchers to describe canopy size. It is a dimensionless index, defined as the amount of one-sided leaf tissue in a given section of ground area (Watson, 1947). It differs from total plant leaf area (LA), which is calculated as the sum of the areas of all single leaves per plant and is expressed in square metres (m^2). LAI can be measured by direct or indirect methods. The direct allometric method requires the operator to destructively harvest all the leaves from a plant

and to measure the area of each leaf using a scanner-type instrument, such as Licor 3100C (Plant canopy analyser; Li-COR, Lincoln, NE). This is a precise technique; however it is destructive, time consuming and labour intensive. Indirect measures use instrumentation which infers LAI from the measurements of light transmitted through the canopy, relying on the fact that dense canopies will absorb more light than sparse ones. Commercial instruments used for indirect LAI estimates include the Licor 2000/2200 (Plant canopy analyser; Li-COR, Lincoln, NE) or Ceptometers (Bréda, 2003) among others. These instruments can be expensive, require a trained operator to take the measurements and are reported to underestimate LAI by up to 40% (Macfarlane et al. 2000). Alternatively, indirect estimation of LAI can be performed by cover photography and gap fraction analysis (Macfarlane et al. 2007, Fuentes et al. 2008). Fuentes et al. (2014) developed an automated method for LAI estimation on grapevine which uses cover photography and MATLAB® (Mathworks Inc., Matick, MA, USA) programming techniques. This method estimates LAI and other canopy architecture parameters according to the algorithms proposed by Macfarlane et al. (2007) and it has been compared to both destructive (allometry) and non-destructive (Licor 2000) techniques, correlating with both for grapevines (Fuentes et al. 2014).

Mobile phones/smartphones and tablet PCs are now ubiquitous, more affordable and their connectivity and computing capabilities are increasing. These devices are equipped with powerful cameras, GPS capabilities, high memory and processing power. In a single snapshot from the smartphone camera the date, time and geographic coordinates can all be recorded. Thanks to these characteristics, scientific applications, in the form of smartphone Apps, are already available on the market and are expanding fast (Confalonieri et al. 2013, Delgado et al. 2013, Weng et al. 2012).

To address the issues, challenges and opportunities outlined above this project aims to identify which canopy parameters most accurately indicate optimal vine performance and to determine if an accurate and inexpensive tool can be developed to assess vine balance in the field.

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4 Project Aims and Performance Targets

This project had two aims:

1. **To determine canopy parameters that indicate optimal vine performance and wine quality and evaluate how effectively these can be manipulated using management techniques.**

   By experimentally manipulating vine performance using canopy management and irrigation scheduling to determine whether measures of vine balance and canopy density correlate with grape and wine quality using modelling and multivariate analysis techniques. The focus of this research was applied on Shiraz and Semillon as preliminary models.

   Compare measures of vine balance gathered using traditional approaches with those assessed using advanced technologies.

2. **To develop an accurate, inexpensive, labour saving toolbox for assessing vine balance in the field and deploy this toolbox to the industry.**

   By developing a smartphone application (including the leaf area index (LAI) measure developed by Fuentes et al. in press) that scores vine performance using pre-identified objective measures of vine balance and canopy density. The application will then suggest suitable management strategies to alter vine balance depending on production targets.

   This toolbox will also assess the accuracy, expense and ease-of-use of the new technologies against current vine performance assessment methods.

   Finally, it will be able to deliver project outputs to industry through networks and programs that encourage adoption of new technologies and practices.

Note: Project UA 1207 was extended until 31 December 2017 to allow for the completion of berry and wine sensory for one more season on the canopy management trial at the Waite campus and to collate all findings from all canopy management trials. By adding another year of sensory results, we were also able to make additional improvements to the VitiSense App (name changed from Berry Sense) ready for a 2018 launch.

5 Methods

Chapters 6 and 7 will describe the developed smart-device applications: VitiCanopy and VitiSense.

Field trials on Shiraz and Semillon were set up across a number of regions (Barossa, McLaren Vale, Padthaway, Coonawarra and Adelaide (Waite Campus)). At these sites, canopy manipulation treatments were carried out over three seasons. The treatments applied focused on altering vine vigour and yield and they included: sacrificial canes, shoot thinning, bunch thinning, leaf plucking and cover crops. Measurements were conducted on canopy growth and architecture, yield and yield components and grape and wine chemistry and sensory. The measurements include canopy architecture using the VitiCanopy App, node number, shoot number, bunch weight, yield, pH, titratable acidity, total soluble solids, tannins, colour, pruning weight and berry and wine sensory assessments. Detailed methods for each site will be provided in Chapters 8 and 9.

Grapevine water potential data were collected using a pressure bomb (PMS Instrument Company, Albany, OR, USA) and the MicroPHAZIR spectrophotometer (ThermoFisher Scientific, VIC, Australia) at key phenological stages (budburst, flowering, fruit set, veraison and pre-harvest) from Cabernet Sauvignon and Shiraz vines in Coonawarra, SA. Calibrations were developed using the MicroPHAZIR software and installed into the portable MicroPHAZIR unit. Details of this experiment are presented in Chapter 10.

6 Development and launch of VitiCanopy

VitiCanopy (Figure 6.1) is a smartphone and tablet PC application (App) that allows user to measure grapevine canopy architecture by taking a photo of the vine canopy. VitiCanopy was firstly launched for iOS devices in October 2015, and for Android devices in November 2016. The combined iOS and Android download of the App to date (December 2017) is about 3000 units (from Apple Store and Google Play statistics).

VitiCanopy was tested by the University of Adelaide, TWE and DJs Growers on different vineyards and varieties. Collaborators from the University of Talca (Chile), University of the Balearic Islands (Spain), the South Australian Research and Development Institute and the University of Bordeaux have also been testing the App and have provided feedback for different management approaches, training systems, varieties, clones and crops.

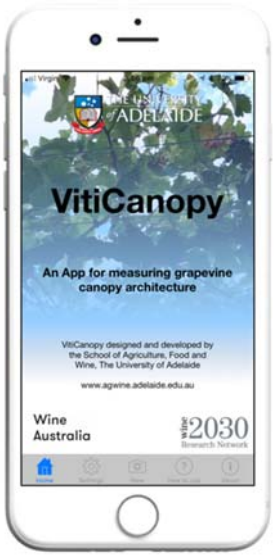


Figure 6.1: VitiCanopy Home screen as it appears on an iPhone 7.

An article describing VitiCanopy's functionality and the calibration process is presented below.

VitiCanopy: a free computer App to estimate leaf area index (LAI) and canopy porosity for grapevine

Roberta De Bei[1], Sigfredo Fuentes[3], Matthew Gilliham[1,2], Steve Tyerman[1,2], Everard Edwards[4], Nicolò Bianchini[4,5], Jason Smith[6~] and Cassandra Collins[1*]

[1] The University of Adelaide, School of Agriculture, Food and Wine, Waite Research Institute, PMB 1 Glen Osmond, 5064, South Australia. Australia; roberta.debei@adelaide.edu.au

[2] ARC Centre of Excellence in Plant Energy Biology, Waite Research Institute, PMB 1 Glen Osmond, 5064, South Australia, Australia; matthew.gilliham@adelaide.edu.au

[3] The University of Melbourne, Faculty of Veterinary and Agricultural Sciences. Parkville, 3010. Victoria. Australia; sigfredo.fuentes@unimelb.edu.au

[4]CSIRO Agriculture, Waite Campus Laboratory, Private Bag 2, Glen Osmond, SA 5064, Australia; Everard.Edwards@csiro.au

[5]The University of Bologna, Dipartimento di Scienze Agrarie (DipSA), Area Colture Arboree, Viale Fanin 46, 40127 Bologna, Italy; nicolo.bianchini@gmail.com

[6]National Wine and Grape Industry Centre, Charles Sturt University, Wagga Wagga, NSW, Australia

~Current address: Geisenheim University, Von-Lade-Straße 1, D-65366 Geisenheim, Germany; Jason.Smith@hs-gm.de

*Correspondence: cassandra.collins@adelaide.edu.au; Tel.: +61-08-8313-6813.

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Abstract: Leaf area index (LAI) is a common and important biophysical parameter used to estimate agronomical variables such as canopy growth, light interception and water requirements of plants and trees. 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. Recently, a novel smartphone and tablet PC application, VitiCanopy, has been developed by a group of researchers from the University of Adelaide and The University of Melbourne, to estimate grapevine LAI, canopy porosity, canopy cover and clumping index. VitiCanopy uses the front in-built camera and GPS capabilities of smartphones and tablet PCs to automatically implement image analysis algorithms on upward-looking digital images of canopies and calculates relevant canopy architecture parameters. Results from the use of VitiCanopy on grapevines correlated well with traditional methods to measure/estimate LAI. VitiCanopy is an accurate, user-friendly and free alternative to current techniques used by scientists and viticultural practitioners to assess the dynamics of LAI and canopy architecture in vineyards, and has the potential to be adapted for use on other plants.

Key words: canopy vigour, computer application, light extinction coefficient, image analysis, cover photography

1. Introduction

Monitoring grapevine canopy architecture is critical for the assessment of growth, vigour and light transmission through the canopy and water requirements of plants. Furthermore, canopy architecture

parameters can be correlated with yield, grape quality and the potential productivity of future seasons [1-3].

One of the most important factors in the assessment of grapevine canopies is the leaf area index (LAI), which is commonly defined as the total one-sided area of leaf tissue per unit ground surface area [4]. However, LAI is difficult to measure or estimate since it requires either destructive techniques that are labour intensive, or expensive instrumentation for indirect estimations [5].

Direct planimetric measurements can give very accurate LAI results, since they require stripping the whole canopy and scanning every leaf with a scanning planimeter (e.g. Li-3000/3100, Licor, Nebraska, USA) to obtain the total area of leaves per unit area of soil [6]. However, this method is extremely time consuming and destructive so it is of little value in a commercial setting other than for the calibration of non-destructive and indirect techniques [7,8]. Similarly, the gravimetric method is based on the correlation between leaf area and dry weight [6,7,9], which can be applied with a high percentage of accuracy. However, this technique is site and species/cultivar specific and yet another time-consuming and extremely labour intensive method to obtain accurate results [10]. Other methods that are widely applied in vineyards, use the relationship between leaf area and leaf length or shoot length [11,12]; these are common because they are simple, but nonetheless time consuming and season, site, climate and cultivar specific.

Indirect methods are based on instrumentation that measure light transmission through the canopy in the photosynthetic active radiation (PAR) wavelengths to estimate LAI (e.g. SunSCAN, Delta-T Devices Ltd, Cambridge, UK; AccuPAR, Decagon Devices, Pullman, USA). Others measure the gap fraction for different zenithal angles, such as the LAI-2000 and 2200 (Li-Cor, Lincoln, Nebraska, USA). There are advantages and disadvantages for all of these methods and they have been extensively outlined in the literature [5-7,9,13]. Indirect methods are generally faster/easier to automate, allowing for larger sampling volume. However, the dedicated instrumentation can be cost prohibitive and requires specific know-how for usage, data collection, downloading and interpretation of results. One of the most versatile and easy to use indirect methods to estimate LAI, as identified in the literature, uses digital or cover photography, which requires the use of digital cameras; this method is based on image analysis algorithms that consider the pixel count corresponding to leaf material and the gap fraction [6,14,15]. Image analysis can be performed on a *post-hoc* basis using Adobe Photoshop [13,15] or using semi-automated and automated computer analysis software [5]. An automated method to estimate grapevine LAI using digital photography and Matlab programming based on previously published works, has been proposed [15-18]. Fuentes et al. [16] and Poblete-Echeverría et al. [18] have demonstrated that cover photography and Matlab programming could be used to estimate canopy architecture parameters for grapevines and apple trees with results highly correlated with both

destructive methods and those obtained using specialised instrumentations, such as the LAI-2000. This method, applied to the wine industry and agriculture in general, could fulfil the need to have long term monitoring of spatial and temporal dynamics of canopy growth and leaf area development throughout the season. However, it still requires a customised code in Matlab and computer skills to analyse the images, restricting usage to researchers or for management purposes within major agricultural industries. To make this technology more accessible to growers and the non-scientific community, The University of Adelaide, jointly with The University of Melbourne, have developed a smartphone and tablet PC App, called VitiCanopy, to estimate canopy architectural parameters. VitiCanopy is based on cover photography obtained at 0° Zenith angle and the Matlab method for image analysis proposed for grapevines [16,19]. The VitiCanopy App has been launched in its iPhone/iPad version (iOS) and the Android version has been developed and will soon be released. Another App to measure LAI, called PocketLAI, has been proposed for use on Android smartphones [20]. The latter methodology uses the device accelerometer and gap fraction calculations to derive LAI from images taken while rotating the device [21]. PocketLAI has been tested on various crops including rice, corn, natural grassland and tree canopies and compared to other commercial tools (e.g. LAI-2000 and ceptometer) with similar results [20,22,23]. However, it has not been implemented or tested for grapevines and, until the date of this paper, it has not been released for independent testing or for commercial purposes.

This paper describes the full development, beta testing and validation of VitiCanopy, a novel App for smartphones and tablet PCs to estimate LAI and canopy porosity for grapevine.

2. Materials and Methods

2.1. VitiCanopy development

VitiCanopy, a program that can be downloaded to a smartphone or tablet device using iOS (Apple Inc., Cupertino, CA. USA), was developed using Xcode 7 and Objective-C. Some image processing (e.g. the real-time monochrome camera preview) uses a third party open source library called GPUImage, which takes advantage of the parallel processing capability of the phone's GPU (Graphical Processing Unit) by running image processing algorithms as GPU shader programs. These images are automatically analysed using the methodology and algorithms described in previous publications [5,16]. It is recommended that the images are taken using the front camera of the device to allow the operator to see the image to be taken on the screen and instantly judge its suitability for analysis. The use of a 'selfie stick' for operator comfort is also recommended. Images can be obtained using the back camera and the App also allows the analysis of images previously obtained and stored in the camera files (camera roll for iPhones/iPads). Figure 1 is an example of a suitable image for analysis with VitiCanopy. This code has been since translated into Android Studio and SDK tools and libraries (Google Inc., Cupertino, CA, USA).



Figure 1. Example of an upward looking grapevine canopy image suitable for analysis using VitiCanopy. The image was obtained using the front camera of an iPad4, at a distance of 80 cm between the vine's cordon and the device.

2.2. Algorithms used in the VitiCanopy

VitiCanopy uses the following image analysis algorithms to calculate canopy architectural parameters, which are based on gap analysis from upward-looking images of canopies and the transmission of light though the canopy to estimate LAI based on Beer's Law [14,15]:

$$f_f = 1 - \frac{tg}{tp} \quad (1)$$

$$f_c = 1 - \frac{\lg}{tp} \quad (2)$$

$$\Phi = 1 - \frac{f_f}{f_c} \quad (3)$$

Where lg = large gap pixels count; tg = total pixels in all gaps and tp = total pixels from the image; fractions of foliage projective cover (f_f); crown cover (f_c); crown porosity (Φ). The f_f parameter has been defined as the 'proportion of ground area covered by the vertical projection of foliage and branches' and Φ as the 'proportion of the ground area covered by the vertical projection of foliage and branches within the perimeter of the crowns of individual plants' [15,24].

LAI is then calculated from the Beer's Law equation as:

$$LAI = -fc\frac{\ln \Phi}{k} \quad (4)$$

where k is the light extinction coefficient ($0 > k > 1$).

The clumping index at the zenith angle, $\Omega(0)$, is calculated as follows:

$$\Omega(0) = \frac{(1-\Phi)\ln(1-f_f)}{\ln(\Phi)/f_f} \quad (5)$$

The clumping index is a correction factor to obtain effective LAI (LAI_e), which is the product of:

$$LAI_e = LAI \times \Omega(0) \quad (6)$$

Specifically, the clumping index describes the non-random distribution of canopy elements. If $\Omega(0) = 1$, it means that the canopy displays random dispersion; for $\Omega(0) >$ or < 1, the canopy is defined as clumped. Since grapevines are trained to obtain uniform and continuous rows, the value of this index should be close to 1. Therefore, for grapevine, LAI should be close to LAI_e. For the lg calculation, the App automatically generates a binary image and sub-divides this image into 25 sub-images. From each of these sub-images the App automatically counts the pixels corresponding to canopy (ones) and sky (zeros). The 5 x 5 subdivision has been shown to be the most effective to determine large gaps using the cover photography method requiring minimal computational power [5].

2.3. Description of VitiCanopy

VitiCanopy, once installed and launched on the device, presents a '**Home'** page with a menu consisting of five icons (Figure 2). An instructional YouTube video guiding users through the process is available at https://www.youtube.com/watch?v=Eqzmuruubm8. The 'Home' page contains the University of Adelaide and funding bodies' logos, with a brief description of the App. The '**Settings'** menu allows the user to set up the gap fraction threshold (see below) and to enable/disable the location services linked to the GPS. The '**New'** menu allows the user to perform new measurements. The '**How to Use'** menu contains information on how to acquire and analyse images and a description of the algorithms used to calculate canopy parameters. This menu also has examples of suitable and unsuitable images; describing most common errors, such as capturing the sun in the image and the operator head in the frame, among others. The '**About'** menu contains: i) a brief description of the capabilities of the App, ii) disclaimer notice, iii) acknowledgments, iv) supporters, v) development team, vi) programmers, vii) source code, viii) contact information and ix) a list of references.



Figure 2. VitiCanopy Home page displaying the five main menu tabs as a simplified operations flow chart.

2.4. Settings menu

The settings menu consists of two options that need to be defined by the user. The first setting option is the '**GAP FRACTION THRESHOLD'**. The gap fraction ranges from 0 to 100%. Generally, the gap fraction is set to 75%, meaning that if 75% of pixels from each of the sub-images (25 in total) correspond to sky, this sub-image is considered in the 'large gap' (lg) count for the calculations in equation 2.

The '**LOCATION SERVICE'** menu is used to enable/disable the GPS capabilities of the device within the App. By enabling this service, geo-location data will be recorded in the analysis and mapping data and allow spatial assessment within and between vineyards. Disabling the service does not disable the location services from the device's settings.

2.5. New measurement menu

When performing a new measurement, the user needs to tap the '**New'** icon and then the '**+'** icon on the top right corner of the screen, a '**FILE'** name can be entered to identify every image taken. As default, when no name is entered, the date and time will be assigned to every image and analysis. The current '**LOCATION'** (latitude and longitude data from the GPS) is reported in this screen. If the 'Not Available' message appears in this section, it means that the location service was either disabled or that there is no service at that particular location from the phone carrier provider.

By tapping the '**PHOTO SELECTION'** tab, the App will present options to either take a new image, or to choose an image from stored files (i.e. the device's camera roll). The file option allows the user to analyse digital images previously obtained. When the camera option is selected a black and white image (binary) is automatically displayed, this allows the user to visually evaluate the suitability of the image for analysis and determine whether there are obvious errors from the use of the automated threshold, which can be subsequently altered. If an image is selected from files, the App will also show it as a binary image in order to judge its suitability.

Once the '**PHOTO SELECTION'** tab is chosen, the photo is displayed as a monochrome or binary image showing the light extinction coefficient (k), which is set at 0.7 by default, since this value has been described to be the most accurate for grapevine canopies [16] (more information provided in the discussion of this paper). However, if the user requires the use of a different value, the k can be adjusted.

2.6. Outputs

Once individual images have been acquired using the camera or loaded from files, the user presses '**Done'** and a pop up message is generated which shows LAI and canopy porosity. All the images collected are stored as RGB Joint Photographic Expert Group files (.JPG) in the camera roll for further analysis (or to re-visit the analysis if required) and to keep a record of measurements. All the processed information is stored in the App as a text file (.txt). By tapping on a single analysis output the '**RESULTS'** page opens up showing all the calculated parameters from the specific image: i) calculated LAI using equation 4, ii) effective LAI_e calculated using equation 6, iii) Canopy cover (equation 1), iv) Crown porosity (equation 2), v) Clumping index (equation 5), vi) Big gaps, vii) Total gaps, viii) Total pixels, ix) Date and time for image acquisition. A '**LOCATION MAP'** is also available

which shows the exact location of where the image was taken. When scrolling down in the same window a '**SETTINGS'** tab also shows the settings used for the analysis of the specific image.

All the analysis can then be sent as a .csv file attached to an email by tapping '**Export'** on the top left corner of the '**Data table'** page.

2.7. Beta testing of VitiCanopy

The beta testing of VitiCanopy was conducted during the seasons 2013-14 and 2014-15 in different vineyards across South Australia, specifically described below. The testing included the comparison between: i) VitiCanopy and Matlab for analysing images [16]; VitiCanopy and the Plant Canopy Analyser, Licor-2000, for estimating LAI; ii) VitiCanopy and a planimetric or allometric method for measuring canopy size. Since it has been previously reported that, for apple trees, LAI calculations using the cover photography method are very sensitive to the k value used in the analysis [18] we compared different k and proxy-k values to evaluate the LAI estimation performance and sensitivity for grapevine canopies.

2.7.1. VitiCanopy vs Matlab

Images (n=113) obtained from different vintages, in different vineyards across South Australia and in days with different sky conditions were randomly selected and analysed using both VitiCanopy and the automatic customised code developed in Matlab (The Mathworks Inc., Natick, MA, USA), which has been extensively described previously [16]. Images were taken at 70 to 80 cm from the cordon. The same analysis inputs were used for all images and applied to both methods: i) number of subdivision = 5 (25 sub-images); ii) a gap fraction threshold equal to 0.75; and, iii) a common light extinction coefficient (k)=0.7 [16].

2.7.2. VitiCanopy vs Licor-2000

LAI was measured in three Shiraz (*Vitis Vinifera* L.) vineyards located at Langhorne Creek (South Australia), Hilltops (New South Wales) and Sunraysia (Victoria). Two of the vineyards, Langhorne Creek and Hilltops, were trained to a single wire, bi-lateral cordon, with the third, Sunraysia, trained to a two-wire, double bilateral cordon. All three sites were part of a management trial, which included various canopy management techniques and generated a range of LAI at each site. Measurements using the Licor-2000 (Plant canopy analyser, Li-Cor Inc., Lincoln, NE, USA) and the VitiCanopy app were made in parallel.

The Li2000 was used with the view restricted to a single panel of the trellis and encompassing the full row width, by using a 90° view cap and excluding the lowest 'ring' of the sensor during the data

processing using the FX2200 software provided by the manufacturer. The reading was taken with the sensor approximately 80 cm below the cordon and the 90° view facing along the row.

The VitiCanopy measurement used the frontal camera of an iPad mini (Apple Inc., Cupertino. CA. USA), positioned 80 cm below the vine cordon, close to the ground. A total of 86 Licor-2000 measurements *versus* image analysis from VitiCanopy were compared using linear regression and statistical analysis.

2.7.3. VitiCanopy vs planimetric and gravimetric method

Vines (n=12) were randomly selected in a Shiraz vineyard located in the McLaren Vale Region of South Australia. Vines were trained on a vertical shoot positioned (VSP) trellis with a cordon height of 100 cm from the ground. Images were obtained at 90 (n=2), 80 (n=3), 70 (n=3), 60 (n=2) and 50 (n=2) cm from the cordon from each plant using the front camera of an iPad 4 (Apple Inc., Cupertino, CA, USA). At the beginning, each vine's whole canopy was imaged (100%) and then three consecutive stripping of leaves was performed to reduce LAI until only the bare cordon was left visible. About 30% of the canopy was removed with each leaf stripping. Stripping was performed by manually plucking the leaves. Only the section of canopy that was visible in the iPad screen within each image was stripped. For this purpose, the section of visible cordon was marked using flagging tape at the cordon level for reference. Given that the field of view of the iPad front camera is about 43° (Fig. 1), the length of cordon included in the image at the different distance of the camera from the cordon is reported in Table 1.

The length of cordon in the image was used to calculate the exact LAI for the specific section of canopy. The latter value was then scaled up to represent leaf area (LA) in 1 m^2 of canopy area per 1 m^2 of soil, which is what VitiCanopy and other cover photography methods estimate and report [14,15,19]. The latter value was considered as a ground truth measurement or real LAI (LAI_r).

Table 1: Relationship between the distance of the device (iPad 4) from the vine's cordon and the length of cordon included in the image considering the iPad4's camera field of view of 43°.

Distance iPad-cordon (cm)	**Cordon length in the image (cm)**
90	70
80	64
70	54
60	46
50	38

To measure the leaf area removed with each stripping an adaptation of both the gravimetric and planimetric methods was used [6]. For the gravimetric method, the LA removed with each stripping was related to weight. From all the stripped material, 500 leaves were randomly selected and digital images were obtained with a reference area of 4 x 4 cm (black painted paper) included in each image. Total LA per scanned image was obtained using a customised Matlab code. The same leaves were weighed with a precision scale to calculate the relationship between LA and leaf weight (LW) which is described by the following equation: LA = 216.68 + 57.078 LW (LW data not shown). The LA removed with each strip was then calculated using the weight/area relationship obtained.

2.7.4. Comparison between real k versus fixed and modelled k to estimate LAI

Since LAI was measured directly using a combination of planimetric and gravimetric methods, a real k per image could be obtained by inverting equation 4 as follows:

$$k_r = -\frac{\ln \Phi}{f_c \cdot LAI_r} \quad (7)$$

where LAI_r is the real LAI from the planimetric measurements and k_r is the real k value per image obtained from the validation procedure.

The k_r values were then compared to five methods to obtain a proxy and real values of k:

i) Fixed value (k = 0.7) as reported in literature [16];

ii) Real k (k_r) calculated by using LAI_r and inverting Eq. 7.

iii) Proxy of k obtained by using the Lowess method to smooth the data combined with the curve-fitting tool from Matlab. The model was constructed using f_c (Eq. 2) and Φ (Eq. 3) as follows: k_{Smooth} = malowess (f_c, Φ), which smooths scattered data in f_c and Φ. The default window size is 5% of the length of f_f.

iv) Modelled k obtained comparing k_r with large gaps (lg), based on the fact that larger gaps will result in higher light transmission to the image acquisition point.

v) The ratio between luminance, obtained automatically from the metadata of each image (I), using a customised code written in Matlab and the maximum luminance obtained from sky images (Io = 12).

2.8. Statistical analysis

Statistical analysis to compare the performance of estimated against real values of LAI and k included: linear regressions (y = a + bx), coefficient of determination (R^2), standard error of estimates (SEE), root mean squared error (RMSE), and statistical significance of regressions with minimum p value ≤ 0.05 as significance criteria. All the analyses were performed using Matlab ver. 2016a (Mathworks Inc, Matick, MA. USA).

3. Results

3.1. VitiCanopy vs MatLab

VitiCanopy, for the majority of the images analysed, produced near identical results to those obtained with the previously developed Matlab code with the correlation producing a $R^2 = 0.97$ and a slope b = 0.98 with minimal SEE (0.3529) and RMSE (0.056) and very high statistical significance of the regression ($p<0.00001$) (Figure 3).

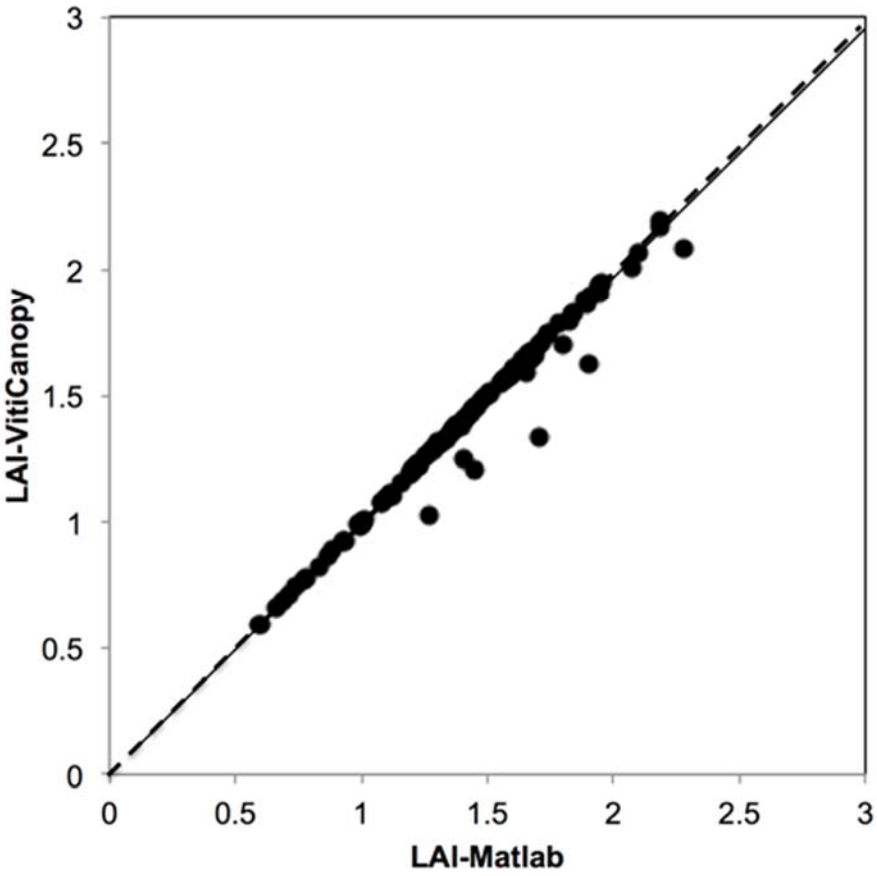


Figure 3. Relationship between the leaf area index (LAI) measured by analysing the images using the Matlab method (LAI-Matlab) and VitiCanopy (LAI-VitiCanopy). The continuous line represents the linear fitting; the dashed line represents the 1:1 relationship.

3.2. VitiCanopy vs Licor-2000

LAI ranged from 0.6 to 2.5 when measured with the Licor-2000 and from 0.6 to 3.1 when estimated using VitiCanopy in the three vineyards: Langhorne Creek, Hilltops and Sunraysia. A strong and significant linear correlation between averaged values from the two methods was found (R^2=0.95; b = 1.08; SEE = 0.51; RMSE = 0.16; $p < 0.00001$) (Figure 4).

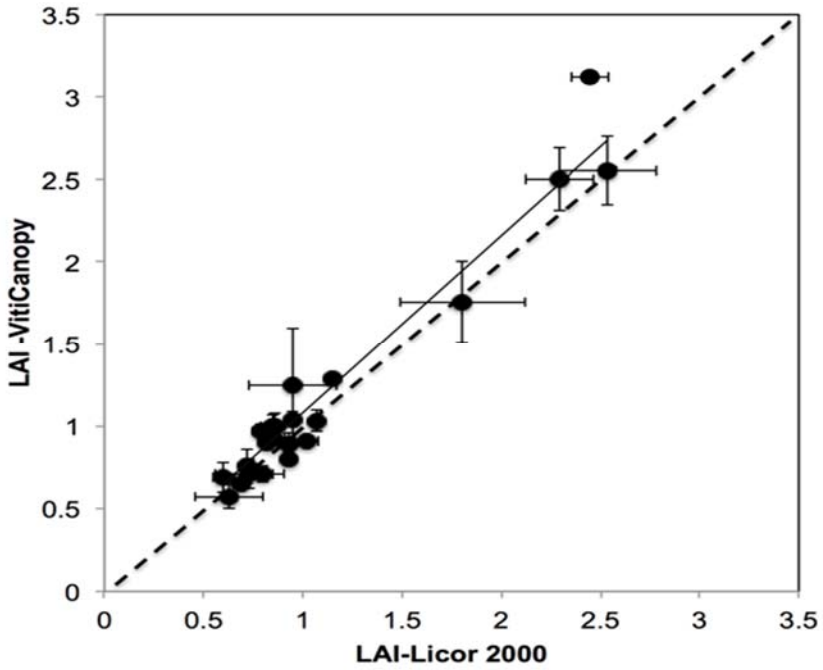


Figure 4: Relationship between the leaf area index (LAI) measured using the Licor-2000 (LAI-Licor 2000) and the VitiCanopy App (LAI-VitiCanopy) for three vineyards located in Langhorne Creek (SA), Hilltops (NSW) and Sunraysia (Vic) during the season 2013-14. Error bars correspond to the standard error of the means. The continuous line represents the calculated regression passing through the origin (0,0), the dashed line represents the 1:1 relationship.

3.3. VitiCanopy vs planimetric and gravimetric method

The goodness-of-fit for the correlation between LAI_r measured with the combination of planimetric and gravimetric methods and VitiCanopy, was tested by grouping the results based on the distance between the camera and the cordon from where the images were obtained (Table 2). The best results were achieved when the camera was placed at 80 cm from the cordon. However the results are accurate (R^2 from 0.70 to 0.89 and slope b from 0.86 to 1.15; $p < 0.00001$ for all) with distances from 50 to 90 cm from the cordon (Table 2).

Table 2: Statistics of the correlation between the results obtained with the planimetric and gravimetric method and VitiCanopy as a function of the distance between the iPad4 and the vine's cordon. R^2= coefficient of determination, b= Slope, a= Intercept, SEE= standard error of estimates, RMSE= root mean squared error.

Distance iPad-cordon (cm)	R^2	b	a	SEE	RMSE
50	0.76	1.08	0.35	0.15	0.19
60	0.79	0.86	0.47	0.05	0.11
70	0.89	1.01	0.31	0.65	0.30
80	0.89	1.06	0.28	0.30	0.21
90	0.70	1.15	0.19	0.38	0.28

Figure 5 shows the relationships between results obtained with VitiCanopy and the planimetric/gravimetric method (LAI_r) for the whole data set. The R^2 obtained was 0.84 with a slope b = 1.06, SEE = 1.89 and RMSE = 0.24 at $p < 0.00001$. For the 12 vines considered, VitiCanopy overestimated the real LAI by 0.56 on average, which corresponds to the contribution of the cordon within each image. When the average LAI obtained from images of bare cordons (LAI_e = 0.56) was subtracted to all data points, a significant improvement of the relationship was achieved in relation to the 1:1 line (R^2 = 0.86; b = 1.05; SEE = 1.89; RMSE = 0.24; $p < 0.00001$).

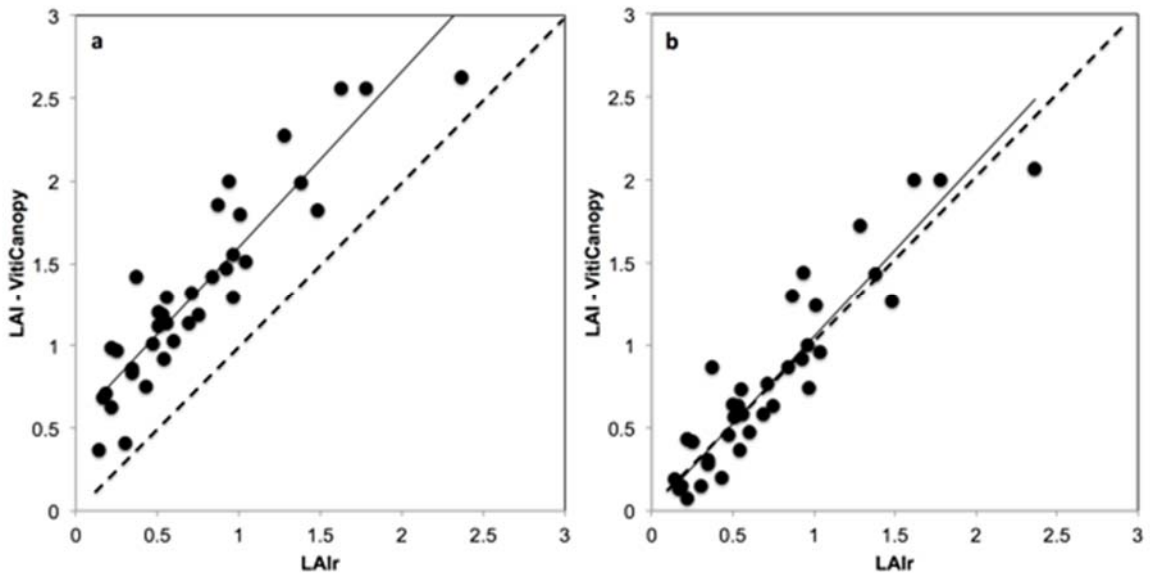


Figure 5. (a) Relationship between the leaf area index (LAI) measured by destructively removing all the leaves (LAI_r) and using the cover photography App VitiCanopy (LAI-VitiCanopy) using a common light extinction coefficient (k = 0.7) (method i) for the cv. Shiraz on a VSP trellis system in the McLaren Vale region. (b) Relationship between Real LAI and VitiCanopy LAI extracting the Y – intercept related to cordon and non-leaf material inclusion. For 5a and 5b, the continuous line represents the calculated regression; the dashed line represents the 1:1 relationship.

3.4. Comparison between real k versus fixed and modelled k to estimate LAI

As seen before, Figure 5 shows the relationship between LAI_r and LAI-VitiCanopy using a common k = 0.7, which corresponded to the application of method (i) to obtain a proxy of k. Figure 6a shows the relationship between LAI_r and LAI-VitiCanopy by applying method (ii) with k_r obtained by inverting Eq. 7, which rendered highly significant statistical analysis (Table 3) as expected (R^2 = 0.94; b = 0.98; SEE = 0.71; RMSE = 0.15; $p < 0.00001$). Figure 6b shows the LAI_r and LAI-VitiCanopy relationship by using method (iii) with comparable statistical results to method (ii) (R^2 = 0.87; b = 1.0; SEE = 1.11; RMSE = 0.18; $p < 0.00001$). Figure 6c shows the LAI_r and LAI-VitiCanopy relationship by applying method (iv) using big gaps as a proxy of k with moderate statistical results compared to the rest (R^2 = 0.83; b = 0.99; SEE = 2.13; RMSE = 0.25; $p < 0.00001$). Finally, Figure 6d shows the LAI_r and LAI-VitiCanopy relationship by applying method (v) based on image luminosity values to obtain a proxy of k with also moderate statistical results (Table 3) compared to the rest (R^2 = 0.86; b = 0.99; SEE = 2.04; RMSE = 0.24; $p < 0.00001$).

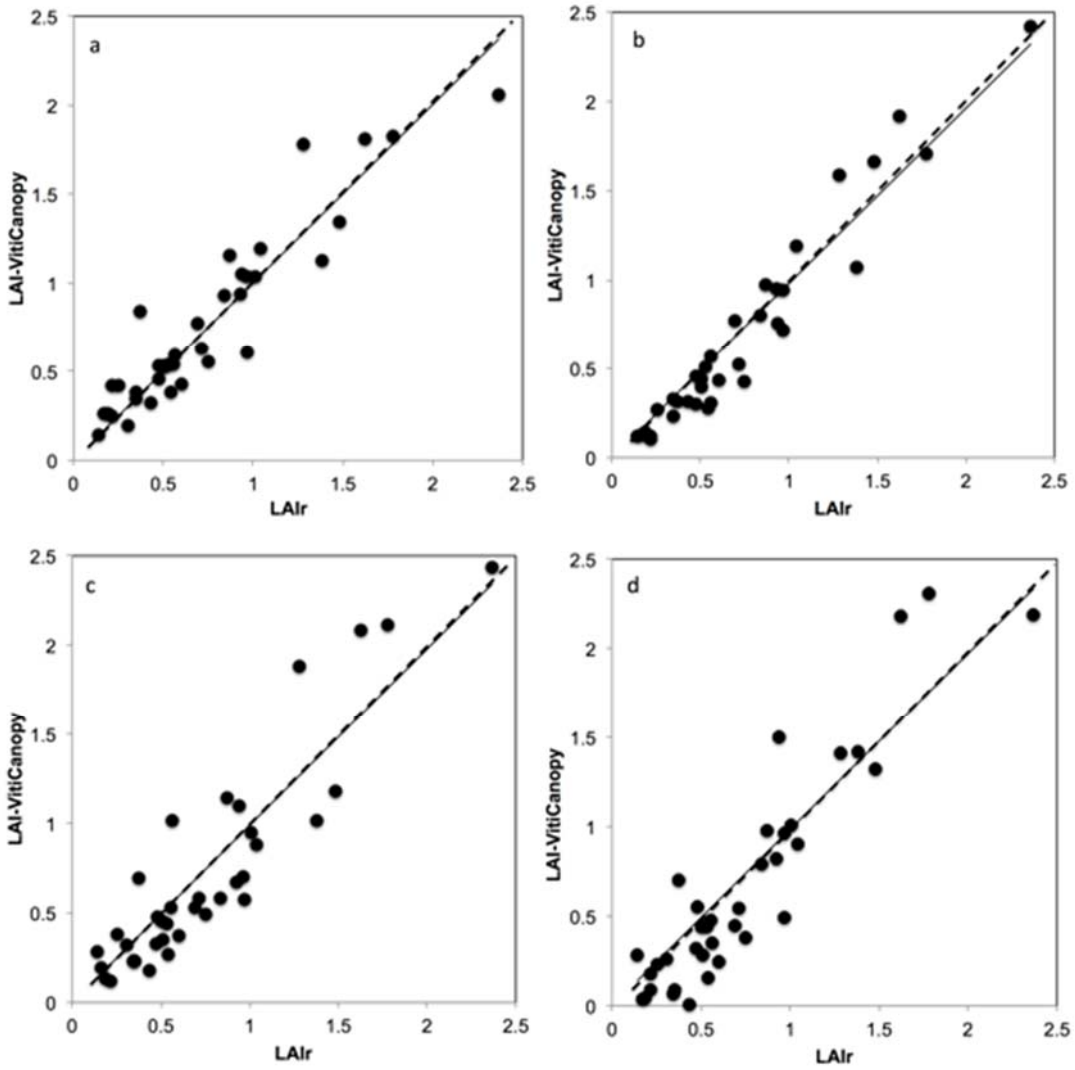


Figure 6: Linear regressions obtained from the comparison between real LAI (LAI_r) and LAI using VitiCanopy (LAI-VitiCanopy) with different methods to obtain a proxy of light extinction coefficient (k): a) obtaining a real k (k_r) by inverting equation 7 (method ii); b) Lowess linear interpolation model based on canopy cover (f_c) and porosity (Φ) (method iii); c) k obtained from a linear regression between k_r and large gaps (lg) (method iv) and d) k obtained from the ratio between image luminance (I) and maximum luminance (Io =12) (method v).

Table 3 shows the performance of methods to obtain a proxy of k. The best performing methods were i), iii) and iv) due to higher R^2, b, SEE, RMSE and p values.

Table 3: Statistical results obtained for the k-proxy models (methods iii to v) and from LAI calculation using five different methods: using a common k = 0.7 (method i); obtaining a real k (k_r) by inverting equation 7 (method ii); Lowess linear interpolation model based on canopy cover (f_f) and porosity (Φ) (method iii); k obtained from a linear regression between k_r and large gaps (lg) (method iv) and k obtained from the ratio between image

luminance (I) and maximum luminance (Io =12) (method v). Not applicable and not statistically significant are denoted by na and ns respectively.

Proxy of k	R^2	b	SEE	RMSE	p value
Method (i)	na; 0.86	na; 1.05	na; 1.89	na; 0.24	na; 1E-05
Method (ii)	na; 0.94	na; 0.98	na; 0.71	na; 0.15	na; 1E-05
Method (iii)	0.38 ; 0.87	1.72; 1.00	0.61; 1.11	0.13; 0.18	1E-04; 1E-05
Method (iv)	0.05 ; 0.83	1E-06; 0.99	2.57; 2.04	0.27; 0.24	ns; 1E-05
Method (v)	0.25 ; 0.86	0.09; 0.99	0.21; 2.04	0.08 ; 0.24	1E-03; 1E-05

4. Discussion

4.1. VitiCanopy vs MatLab

As expected, given that both VitiCanopy and Matlab use the same algorithms to calculate LAI, the relationship between the two methods showed a good and statistically significant agreement ($R^2 = 0.97$; b = 0.98; SEE = 0.35; RMSE = 0.056; p = 0.00001) (Fig. 3). The discrepancy, which is a slight underestimation (3 %) for the Matlab code compared to VitiCanopy for six out of 113 images, could be explained by differences in precision in the automatic luminosity thresholding, based on the blue channel, used by the two systems (computer versus smartphone capabilities) [5]. When an image is taken, depending on the sky conditions, even if the sun is not directly in the image, sometimes they could present brighter sections. The algorithms used for filtering in the Matlab code compared to VitiCanopy are different and for the above-mentioned images this creates underestimations of LAI due to loss of segmentation of images, in particular at the edges of the canopy or on over-illuminated leaves.

4.2. VitiCanopy versus Licor-2000

The strong relationship found between LAI measurements conducted with the Licor-2000 and VitiCanopy using a common k = 0.7 (method i) for both techniques (Fig. 4) aligns with previous findings by Fuentes and collaborators [16]. These authors found a good correlation between Licor-2000 and the

cover photography and Matlab methods for Chardonnay on a two-wire vertical training system in the Riverland Region of South Australia.

These results demonstrate that VitiCanopy can be used within the same guidelines suggested for other instruments available in the market (e.g. the Licor-2000) with the advantages of VitiCanopy being a free tool, easy to use by trained operators and the results being obtained in real time and geo-referenced. Moreover, not only LAI outputs can be obtained, but also the fractions of foliage cover (f_f) canopy projective cover (f_c), canopy porosity (Φ) and clumping index ($\Omega(0)$) are extracted from the canopy images. VitiCanopy also presents less restrictions for its use compared to the Licor-2000, in particular, VitiCanopy can be used at any time of the day as long as the sun does not appear in the image. The Licor-2000 is traditionally recommended to be used either early in the morning (after predawn), late in the day (before dusk) or in overcast day conditions for greater accuracy [25]. The latter related to the scattering of blue light through the different angles of the sensor, which has been reported to induce significant underestimations [15,17]. New instrument developments however, allow the correction of the blue light scattering by using a diffuser cap allowing measurements to be taken in full sun.

4.3. VitiCanopy and the effect of distance of images from grapevine cordons

Our findings suggest that the optimal distance from the cordon to take upward-looking images from grapevine canopies (Fig. 1) is 70 to 80 cm (Table 2). Even though good and statistically significant relationships between LAI_r and LAI-VitiCanopy were found for all distances from 50 to 90 cm from the cordon, users should take into account that at a distance of 50 cm between the device and the canopy, only 38cm of cordon will be included in the image; potentially not capturing enough of the canopy variability when making the assessment. Only when conditions prevent the adoption of the 70-80 cm distance (very low training systems), a lower distance should be considered. We recommend that images not to be taken at distances less than 50 cm for reasons outlined above.

4.4. VitiCanopy performance and cordon contribution corrections

VitiCanopy, similar to other non-destructive methods, does not separate between leaves and other plant elements (cordon, shoots and bunches). Such output is more often reported as Plant Area Index (PAI) rather than LAI [26]. This explains the overestimation of VitiCanopy (Figure 5a) compared to the planimetric method applied when using a common light extinction coefficient of k = 0.7 (method i). When images from bare cordons, after stripping all the leaf material for the validation procedure, were analysed, LAI was on average 0.56 (Figure 5a). When this was considered as a correction factor, comparable results between LAI-VitiCanopy and LAI_r (Fig. 5b) were obtained. In practical terms, if the user requires the estimation of the cordon contribution (Fig. 1), this can be achieved by using VitiCanopy at dormancy, when no leaf material is present on the vines. However, it has been previously shown that, for the variety Merlot in Chile, using the cover photography and Matlab method, the

cordon and non-leaf material contributions are important in the early phenological stages; from veraison onwards, when the canopy reaches maximum growth, this contribution becomes negligible [16]. The images used for comparison between VitiCanopy and the planimetric method in this paper were obtained at flowering and it can be assumed that at this early growth stage the contribution of the cordon was still important as supported by the results obtained (Fig. 5a) and correction needed (Fig. 5b). The latter needs to be taken into account when comparing results from VitiCanopy and other methods that exclude non-leaf material from the analysis of images [27].

4.5. The effect of variable k on LAI using the VitiCanopy App

From previous research conducted by applying the cover photography and Matlab analysis method on apple trees, it was concluded that LAI is very sensitive to the accurate selection of k [18]. The latter study demonstrated that estimating LAI using a fixed k produced unreliable results. Other models for k selection were applied and it was concluded that obtaining LAI by calculating a proxy of k using the fc from the same images was a better performing alternative. However, the best performing method required the calculation of a proxy of k (I_c) using the ratio between the photosynthetic active radiation (PAR) measured above canopy (I_o) and below the canopy at the location of imaging (I): $I_c = 1-(I/I_o)$ [18].

In this paper, different methods to obtain k for grapevines trained on a VSP were tested. The results obtained comparing LAIr with LAI-VitiCanopy using methods i) to v) showed that selecting a common k (method i) rendered very good and statistically significant results in the calculation of LAI using VitiCanopy. Unlike fruit tree canopies, grapevine canopies, especially when trained on a VSP, are continuous and generally uniform. This could explain why a common k is so effective in the case of grapevines [16], but not for the case of apple trees [18], which are trained to develop more complex branch distribution and canopy structures to maximise light penetration to the interior of the canopy.

5. Conclusions

VitiCanopy offers a versatile, accurate and inexpensive tool to monitor spatial and temporal variability of canopy architecture parameters and leaf area index within vineyards. VitiCanopy has the capability to stream processed information to growers in real time and the information is delivered in a simple and user-friendly way to assist management decisions. Despite the importance of canopy architecture measurements in vineyard management, due to the labour intensive procedures required for their estimation, they are rarely measured. VitiCanopy offers the advantages of being free and easy to use; moreover, not only LAI but also canopy porosity is measured. Viticultural practitioners and scientists can use this tool with comparable results to other technologies available in the market at a fraction of their cost and without the requirement of highly technical personnel to obtain the data, do the analysis and interpret results. Another major advantage of the cover photography method and

VitiCanopy, is that images can be stored. Stored images can be revisited for future analysis if, for example, improvements of the method are made. Stored images can also help create a historical record for a specific site and hence aid in future management decisions. Furthermore, all images and results obtained using VitiCanopy are geo-referenced providing a visual guide to variation across a vineyard.

The VitiCanopy App development team from The University of Adelaide and The University of Melbourne are working on different improvements of this novel App to add more tools to assess the effects of changes in vigour, pruning weight and other canopy architecture parameters on the quality of harvested product for different crops and fruit trees. These improvements will be reflected in future version releases of the App.

Supplementary Materials: VitiCanopy for iOS operating systems is available for free download at https://itunes.apple.com/au/app/viticanopy/id1042914901?mt=8

An instructional YouTube video on how to use VitiCanopy is available at https://www.youtube.com/watch?v=Eqzmuruubm8.

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Author Contributions: R.D., S.F., M.G., S.T. and C.C. conceived and developed the app, designed the experiments and wrote the paper. R.D. and S.F. analysed the data. E.E., J.S. and N.B. designed and conducted the experiment to compare VitiCanopy and Licor-2000 and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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7 Development of VitiSense

Grape growers and winemakers taste grapes before harvest and they rely on the information from this assessment to make decisions on harvest date and grading and allocation of grapes for a specific wine style. Researchers also carry out berry sensory assessment (BSA) by forming a panel of 10-12 assessors, who are asked to score a series of attributes, including pulp, skin and seed attributes. The scores are generally recorded on a line scale using either specific software installed in a computer (which requires one computer per assessor) or assessments on paper. Once the assessment is completed, if conducted on a paper, each of the attributes, for each sample and each assessor is measured with a ruler in order to extract the numerical information and proceed to the statistical analysis. This process is slow and time consuming and it can delay the acquisition of results.

VitiSense was created to make berry sensory quality assessments easier to perform in the vineyard and to potentially map the results of these assessments across a vineyard to make more informed management decisions. For researchers, VitiSense could help to overcome some of the difficulties in data extraction from the assessments and could also be useful for laboratory assessments for other products such as wine, as the tool is easy to use and portable as it runs on smartphones and tablets.

VitiSense (Figure 7.1) allows users to create and distribute assessment templates and perform assessments. The ease of use of the App allows users to simply create a structured template to assess chosen attributes of both grapes and wine. There is no limit to the number of attributes or samples that can be assessed and the assessment results can be sent to a nominated email account as a .csv file.



Figure 7.1: VitiSense Home screen as it appears on an iPhone 7.

How to use the App

When launching VitiSense the user is presented with a '**Home'** page with icons at the bottom of the page (Figure 7.2):



Figure 7.2: VitiSense Home screen icons as it appears on an iPhone 7.

- **Home**: contains basic information about the App.
- **Settings**: allow operators to nominate a user (username), enable the '**Location Service**' and enable the creation of a new template through the '**Develop Template'**
- **Info**: contains a guide on how to use the App and information about the development team and funding sources.
- When the '**Develop Template**' is disabled from Settings, only the '**Assess**' icon is displayed at the bottom of the home page to enable users to initiate an assessment.
- When the '**Develop Template**' is enabled from Settings, the icon '**Develop**' will appear at the bottom of the page for users to build new templates.

Settings menu (Figure 7.3)

- **VitiSense Version**: Displays the version of VitiSense being used.
- **Username**: Name of the person filling in the assessments. When an assessment is completed, this identifier is automatically associated with each assessment as it is created.
- **Location Services**: Checks to see if location services have been allowed for VitiSense on this device. If not it can take the user to the device's Settings screen to enable it.
  Note: For location logging to be used when filling in assessments location services needs to be enabled.
- **Develop Template**: VitiSense allows templates to be created, by default this option is disabled. This option toggles the ability to create templates by showing/hiding the '**Develop**' option in the tab bar at the bottom of the screen and reveals the '**Develop Options**' on the Setting screen.
- **Develop Options**: (Only visible if 'Develop Template is enabled), allows users to modify the scale for each attribute, modify the low, middle and high anchor's name, enable/disable the location service and nominate the email address where results will be sent.



Figure 7.3: VitiSense Settings screen as it appears on an iPhone 7.

Template development enabled mode

In '**Settings**' enable the '**Develop Template**' option.

How to create a Template

When the '**Develop Template**' is enabled, the App works in Administrator mode and templates can be created and distributed to assessors.

The '**Develop Options**' menu appears in the '**Settings**' page once the Develop Template mode is enabled. From this menu, the user can assign the scale values (set on 0-15 by default), the scale anchor's text (set to low and high by default), switch on location recording and set the email where results will be sent. Each of the options can be modified by tapping on them.

Once the settings have been selected, a new template can be built from the '**Develop**' tab at the bottom of the page.

Tap on '**Develop**' and start a new template by tapping on the '+' symbol on the top right corner of the screen.

Tap on '**Title**' to name the template and save. If a name is not entered the date and time will be used by default. Once the template has been named, it will appear in the list on the '**Develop**' page.

By tapping on the template of interest, a pop up will show the options: Edit, Categories, Copy, Export and Cancel (Figure 7.4).

- **Edit** allows the user to rename the template, enable/disable the location service and change the email where the results will be sent.
- **Categories** allows the user to create the categories of attributes to be assessed.

- **Copy** creates a copy of the template by first popping up a dialog to rename the template. Template's names need to be unique in the VitiSense app.
- **Export** creates a file of the template to be shared with other VitiSense apps on other devices.

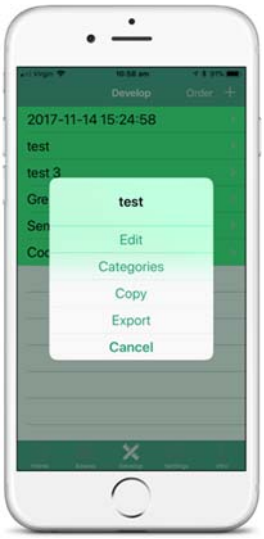


Figure 7.4: VitiSense template development screen as it appears on an iPhone 7.

In the categories screen, by tapping on the '+' a title for the category can be entered (i.e. 'PULP CHARACTERISTICS' if a template for berry sensory is being built) and saved. By tapping on the just created category's title and tapping again on the '+', the attributes, within that category to be assessed can be created and the scale range and anchor's text modified by tapping on the relative tabs. '**Save**' and continue creating more attributes as just described.

Once the list of attributes and categories have been created, the order in which to assess them can be decided/modified by tapping on '**Order**' and dragging the attribute in the required position.

Ordering

The '**Order**' button can be found at the top right of the screen; it allows templates, categories and attributes to be reordered. Tapping on '**Order**' adds a tab to the right hand side of each row, this tab can be used to pull the row to a new location (Figure 7.5). Once reordering has been completed press '**Done**' to save the changes.

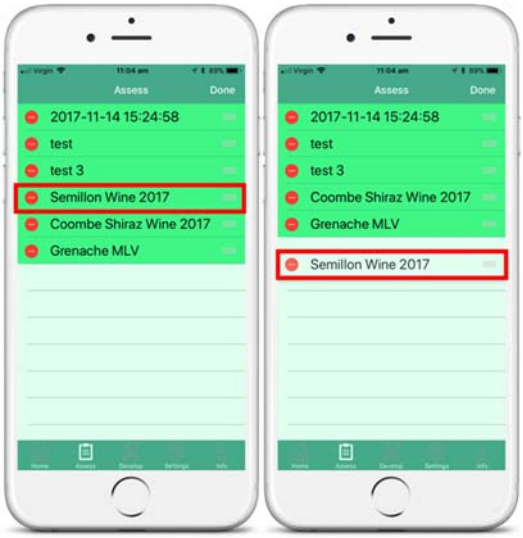


Figure 7.5: VitiSense ordering option showing the Semillon template being moved to a new position at the bottom of the list of templates.

Deleting

All templates can be deleted in the develop tab by sliding the name to the left. Delete removes the template and any associated assessments from the VitiSense app.

In the 'Develop' page, multiple templates can be created and stored. Also, templates for similar assessments can be copied by tapping on the name of the template, then on '**Copy**' and renaming them.

All stored templates in the Develop tab can be modified until they are exported. Once a template has been exported it is not possible to modify it anymore. A pop up warning message is displayed when trying to modify a finalised template.

Once a survey has been created, it can be distributed.

Export Template

On the Develop screen, tap on the template name and chose the export option from the pop up. This creates a file with '.vitisense' extension. This file can then be distributed using other apps such as email or web storage (i.e. iCloud) (Figure 7.6).



Figure 7.6: VitiSense template 'Export' option showing the possible ways to export templates between devices.

Import Template

Templates are moved between different devices by the use of a file with the extension '.vitisense'. When an assessor opens the file on their device, VitiSense will import the template into the app. Ways of file distribution include email, web storage (i.e. iCloud) or download from a website.

Assessment enabled mode

In '**Settings**' disable the '**Develop Survey**' option.

When this option is disabled the App will work in assessment only mode and templates cannot be created or modified. The '**Develop**' tab at the bottom of the screen will disappear and only the '**Assess**' option will be available.

When tapping on '**Assess**' the page will display all the stored templates.

This is the initial screen for judges who will be completing an assessment, it shows a list of templates known to VitiSense on the device (Figure 7.7).

The position of the templates can be changed on the screen, if required, using the '**Order**' option. Swiping left over a name row reveals the delete option, this will remove the survey from the VitiSense app.

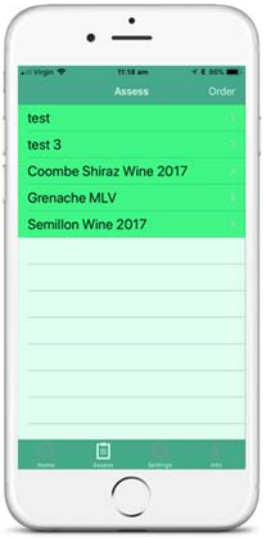


Figure 7.7: VitiSense assessment screen showing all the templates known to VitiSense.

By tapping on the template name row, a '**Detail**' screen for the template is shown.

To initiate an assessment, tap on the template name. You will be taken to the detail page where the template name, number of samples already assessed and email to which the results will be sent are displayed.

Performing Assessment

Ensure the user has added his individual '**Username'** in the '**Settings**' menu. Each user at the beginning of an assessment must fill in the Username.

To initiate an assessment, tap on the survey name. You will be taken to the '**Detail**' page. Tapping on the '+' starts a new sample and a unique code/name is entered. When the sample number/name is entered the template opens and the assessment can commence. The assessment page shows the template title, the unique name/code of the sample and location (GPS coordinates) of the device when the assessment was created (Figure 7.8). Tapping on the coordinates shows the location on a map.

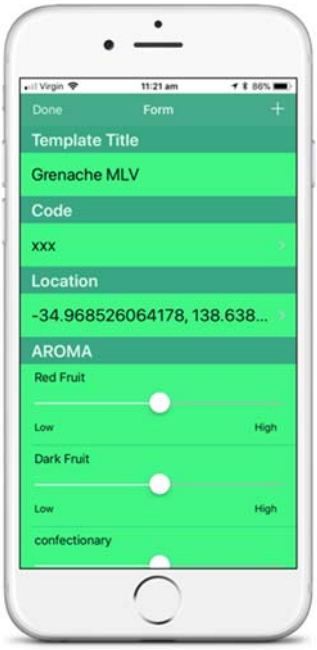


Figure 7.8: VitiSense assessment performance screen showing the template title, the unique sample code, the GPS coordinate of the device at the time the assessment is being done and the attributes to assess (only three in this screen).

After the location, the series of attributes to assess the sample is shown. Assessments are performed by sliding the cursor on the line scale to the position representing the assessors score for that attribute. Once the whole list of attributes is assessed, tap on '**Done**' located in the top left corner of the screen to finish. Each assessed sample will be stored in the '**Completed Assessments**' page. In the '**Completed Assessments**' page each sample can be edited or deleted by sliding the name row to the left. Once all samples have been judged the results can be sent to the nominated email by pressing on the '**export symbol**' on the top right corner of the screen, next to the '+'.

The submit option creates an email with an attachment containing the filled in assessments to be sent to the creator of the survey.

Email Results

After the assessments have been completed, the results can be emailed to the Administrator. The Submit button is found at the top right corner of the screen. It collates the assessment results into a file and attaches it to an email.

The VitiSense app is unable to collate results from multiple devices, however the Username and the unique code for each assessment are the two key fields used to identify who filled in the survey and the item being measured.

8 Canopy management trials in commercial vineyards

A canopy management trial to assess a range of management strategies altering vine growth and grape quality was established in partnership with Treasury Wine Estate (TWE).

Treatments changed the ratio between canopy size and fruit load by altering either yield through bunch thinning, or canopy size via leaf plucking, shoot thinning and trimming. Other techniques that reduced vine vigour without an active manipulation of the canopy were also applied, such as cover cropping and sacrificial canes. In all trials and treatments, canopy size was measured throughout the growing season using the newly developed VitiCanopy App with the aim of assessing whether the new tool could quantify the canopy architecture changes resulting from the different treatments imposed.

Materials and Methods

Experimental sites

Four commercial vineyards in four Australian wine regions were used for the trial: Coonawarra (COO), McLaren Vale (MLV), Padthaway (PDT) and Barossa (BAR). The trial ran for three consecutive seasons: 2013-14 (season 1-S1), 2014-15 (season 2-S2) and 2015-16 (season 3-S3). All four trials were carried out on Shiraz vines with the specifications reported in Table 8.1.

Table 8.1: Vineyard details at the four commercial sites: Coonawarra (COO), McLaren Vale (MLV), Padthaway (PDT) and Barossa (BAR).

	COO	MLV	PDT	BAR
Year planted	-	1998	Grafted in 2002	2000
Clone	R6WV28	Unknown	Unknown	1654
Rootstock	5C Teleki	Own roots	Semillon BVRC14	140 Ruggeri
Trellis	Bilateral spur pruned cordon	Single wire	Single wire	Single wire + catch wire
Shoot positioning	Vertical	Sprawling	Sprawling	Sprawling
Vine spacing (m)	2	2	2	2
Row spacing (m)	3	3	3	3
Row orientation	N-S	E-W	E-W	-
Bud number	40	60	85-90	36

Experimental design

A range of canopy management treatments was applied, such as: traditional canopy management, floor management and sacrificial canes. Sacrificial or ‘kicker’ canes are extra canes retained at pruning with the purpose of controlling vigour and improving vine balance (Longbottom, 2003). Kickers can then be removed, depending on the season and the desired effect, either around flowering or veraison.

The traditional management included:

i) Control (C), where no canopy intervention was performed during the growing season;

ii) Shoot thinning (ST) was applied according to the management's directions by removing short and weak shoots, double shoots and shoots that did not carry any fruit. As such, the percentage of shoot removal varied in each season. ST was conducted at EL stage 15-17;

iii) Leaf plucking (LP) was applied at EL 29-32 by removing five to seven leaves per shoot on the eastern side of the canopy (as is standard industry practice);

iv) Bunch thinning (BT) was applied at EL 33-35 by leaving one bunch per count shoot;

v) Early Trim (ET) was applied by trimming the eastern side of the canopy down to 5-6 leaves at EL 29-32;

vi) Mid row Cover Crop (CC): a Ryegrass cover crop was planted in the mid-row in MLV and Lucerne planted in PDT;

vii) Mid row and under vine Cover Crop (Complete CC): a ryegrass cover crop was planted in the mid row and under vine in MLV;

viii) Late pruning where pruning was carried out at EL stage 9-11 (LatePR);

The KC treatments were carried out by leaving four extra 10 node canes per plant at pruning. Differences between treatments were related to the orientation of the KC and the phenological stage at severing, as shown in Table 8.2. The treatments applied in each region and in each growing season are shown in Table 8.3.

Table 8.2: Summary of the sacrificial canes (KC) treatments.

Treatment	# Sacrificial canes	Sacrificial canes orientation	Timing of removal
K UP	4	Upward	EL 33-35
K DOWN	4	Downward	EL 33-35
K EARLY	4	Downward	EL 21-26
K + BT	4 + bunch thinning	Downward	EL 33-35

Table 8.3: Summary of the treatments applied in each season in the four Regions: COO= Coonawarra, MLV= McLaren Vale, PDT= Padthaway and BAR= Barossa.

Treatment	S1				S2				S3			
	COO	MLV	PDT	BAR	COO	MLV	PDT	BAR	COO	MLV	PDT	BAR
Control (C)	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦
Shoot Thinning (ST)	♦	♦			♦	♦			♦	♦		
Leaf Plucking (LP)	♦	♦			♦	♦			♦	♦		
Bunch Thinning (BT)	♦	♦			♦	♦			♦	♦		
Trimming on the Eastern side			♦				♦				♦	
K UP	♦	♦			♦	♦				♦		
K DOWN	♦	♦			♦				♦			
K EARLY	♦	♦			♦				♦			
K + BT	♦	♦			♦	♦			♦	♦		
Cover Crop mid row		♦	♦			♦	♦			♦	♦	
Cover Crop mid row + under vine		♦				♦				♦		
Late Pruning		♦				♦				♦		

The trial design was slightly different for the four regions:

Coonawarra, the experiment was set up in four consecutive rows and a fully randomised block design was chosen with each treatment repeated once along one row in blocks of three panels of three vines each (Figure 8.1). All measurements were taken on the middle vine of each panel to give a total of three vines measured per treatment replicate.



Figure 8.1: Trial design in the Coonawarra commercial vineyard. The eight treatments were randomly replicated four times on four adjacent rows. Each treatment replicate consisted of three adjacent panels of three vines. Three panels of three vines were used at the beginning and the end of the trial rows as buffers. Each number and colour correspond to a different treatment as follows: 1=Control (C), 2= four kicker canes per vine oriented upward and removed at EL 33 (K UP), 3= four kicker canes per vine oriented downward and removed at EL 33-35 (K DOWN), 4= four kicker canes per vine oriented downward and removed at EL 21 (K EARLY), 7= Shoot Thinning (ST), 9=Leaf Plucking (LP), 10= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot (K +BT), 11= Bunch Thinning (BT).

McLaren Vale, the experiment was set up in four consecutive rows, two of which were dedicated to the cover crop treatments. A fully randomised block design was chosen with most treatments repeated three times along rows 1 and 4 in blocks of two panels of three vines each. The exceptions were the cover crop treatments which were set up in rows 2 and 3 as shown in Figure 8.2. All measurements were taken on the middle vine of each panel for a total of two vines repeatedly measured per treatment replicate.

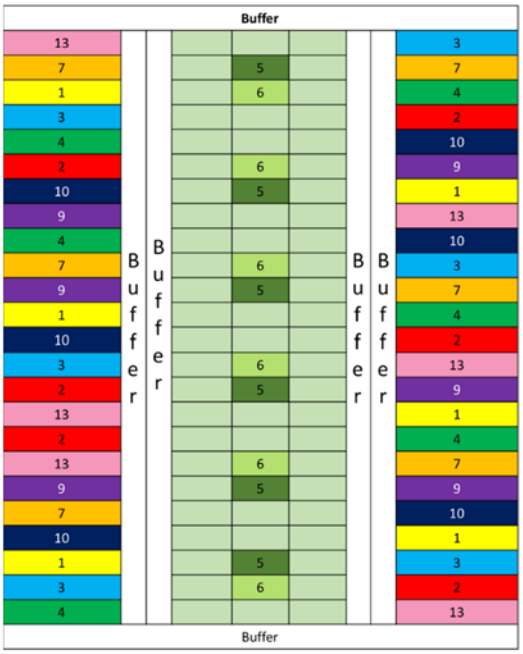


Figure 8.2: Trial design in the McLaren Vale commercial vineyard. The 10 treatments were randomly replicated six times on four adjacent rows. The three middle rows were dedicated to the cover crop treatments (in green). Each treatment replicate was made of three panels of three vines. Two panels of three vines were used at the beginning and the end of the trial rows as buffers. Each number corresponds to a different treatment as follows: 1=Control (C), 2= four kicker canes per vine oriented upward and removed at EL 33 (K UP), 3= four kicker canes per vine oriented downward and removed at EL 33-35 (K DOWN), 4= four kicker canes per vine oriented downward and removed at EL 21 (K EARLY), 5= cover crop in the mid row (CC), 6= Cover Crop in the mid row and under vine (Complete CC) 7= Shoot Thinning (ST), 9=Leaf Plucking (LP), 10= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot (K +BT), 13= Late Pruning (LatePR).

Padthaway, the experiment was set up in nine rows with a buffer row in between each of them. Three rows were dedicated to the cover crop treatment and six to all other treatments (Figure 8.3). A randomised block design was chosen with each treatment repeated once along one row in two panels of three vines each. The cover crop treatment was set up in three rows with buffer rows on each side and replicated twice on the same row. All measurements were conducted on two designated 2 m sections in each treatment replicate.

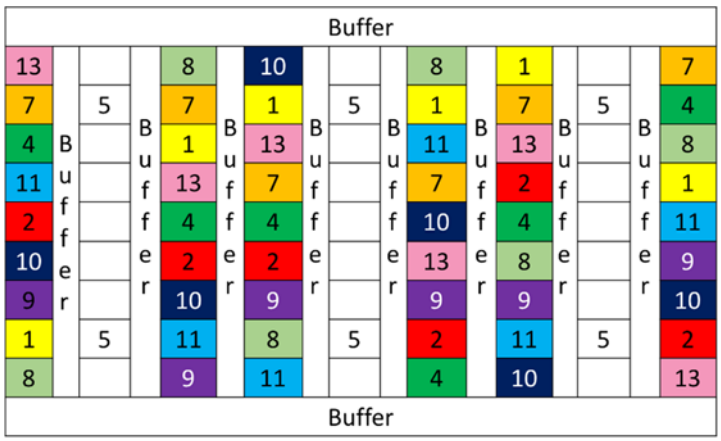


Figure 8.3: Trial design in the Padthaway commercial vineyard. The 10 treatments were randomly replicated six times on nine rows separated by buffer rows. Each treatment replicate consisted of two adjacent panels of two vines. Three panels of two vines were used at the beginning and the end of the trial rows as buffers. Each number and colour corresponds to a different treatment as follows: 1=Control (C), 2= four kicker canes per vine oriented upward and removed at EL 33 (K UP), 4= four kicker canes per vine oriented downward and removed at EL 21 (K EARLY), 5= cover crop in the mid row (CC), 7= Shoot Thinning (ST), 8 = Early Trim on the eastern side of the canopy (ET), 9=Leaf Plucking (LP), 10= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot (K +BT), 11 = Bunch Thinning (BT), 13= Late Pruning (LatePR).

Barossa, the experiment was set up in six consecutive rows and a fully randomised block design was chosen with each treatment repeated once along one row in blocks of two panels of three vines each (Figure 8.4). All measurements were conducted on the middle vine of each panel to give a total of two vines measured per treatment replicate.

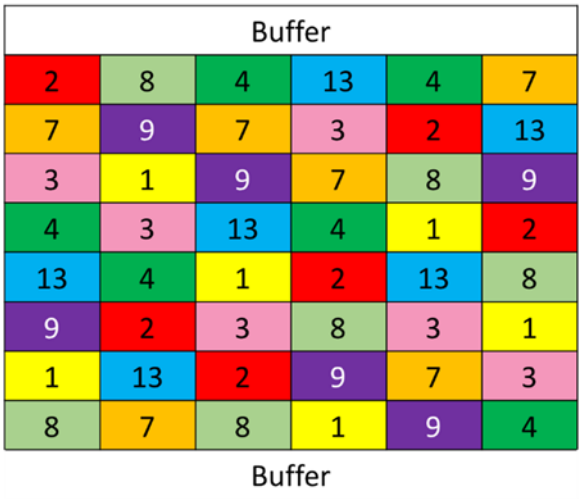


Figure 8.4: Trial design in the Barossa commercial vineyard. The eight treatments were randomly replicated six times on six rows. Each treatment replicate consisted of two adjacent panels of three vines. Three panels of three vines were used at the beginning and the end of the trial rows as buffers. Each number and colour corresponds to a different treatment as follows: 1=Control (C), 2= four kicker canes per vine oriented upward and removed at EL 33 (K UP), 4= four kicker canes per vine oriented downward and removed at EL 21 (K EARLY), 7= Shoot Thinning (ST), 8 = Early Trim on the eastern side of the canopy (ET), 9=Leaf Plucking (LP), 11 = Bunch Thinning (BT), 13= Late Pruning (LatePR).

Weather conditions

The weather conditions for the sites were sourced from the nearest Australian Bureau of Meteorology weather stations (http://www.bom.gov.au/):

- Coonawarra (SA) (station number 26091)
- Willunga (SA) (station number 23753)
- Padthaway South (station umber 026100)
- Nuriootpa PIRSA (station number 023373)

For comparison, the mean average temperature and rainfall for the growing season, October to April, were calculated for the 30-year average (1983-2013 = long term average (LTA)) and for the three growing seasons of interest, 2013-14 (S1), 2014-15 (S2) and 2015-16 (S3). The Growing Degree Days (GDD) were calculated as described in Gladstones (2011) with base 10 °C and 19 °C cut offs.

A summary of the average monthly temperatures and monthly rainfall for each of the growing seasons and the long-term average (LTA) is shown in Figure 8.5.

Coonawarra

The GDD over the three seasons was 1378, 1377 and 1676 for S1, S2 and S3 respectively. Only S3 was warmer compared to the LTA GDD of 1397. The LTA total rainfall was 230 mm; S1 rainfall was similar to the LTA with a total of 244 mm while S2 was drier (180 mm) and S3 much drier again than the LTA with a total rainfall of 112 mm. S3 had very low rainfall throughout the whole season and average temperatures significantly higher than the LTA in October, December and January. Worth mentioning are the two very rainy months of October 2013 and January 2015, when greater than 60 mm precipitation occurred in just one rain event.

McLaren Vale

All three growing seasons were warmer than the LTA (GDD 1699) with GDD of 1766, 1795 and 1896 for S1, S2 and S3 respectively. The total rainfall was lower than the LTA of 189 mm in all three growing seasons. The lowest rainfall was recorded in S3, 121 mm, which fell mostly from January to March.

Padthaway

All three growing season of the trial showed GDD above the LTA which was 1426 with S3 being particularly warmer (GDD= 1706). Monthly average temperatures in S3 were above LTA. The total rainfall was below the LTA in all seasons.

Barossa

In the Barossa Valley the LTA GDD was 1627. S1 was cooler than the LTA with GDD of 1551 while S2 was an average season with a sum of 1632. S3 was much warmer than the average with a GDD sum of 1865. The monthly average temperature was below the LTA only in February while it was well above

average for the rest of the growing season. S3 was also the driest of the three with a total rainfall of 144 mm compared to 210, 230 and 174 of the LTA, S2 and S3 respectively. February 2014 was particularly wet with a monthly total rain of 90 mm.

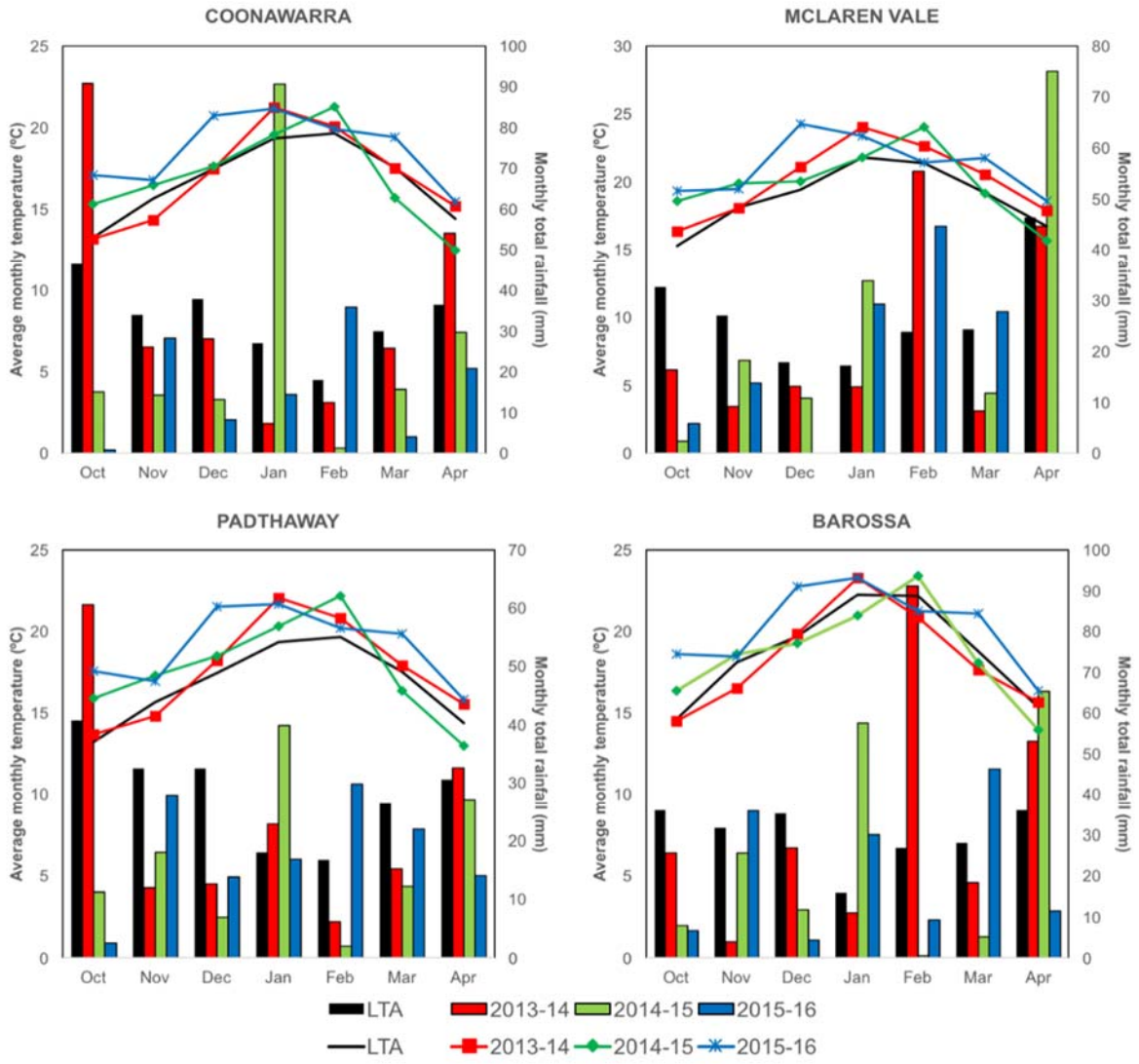


Figure 8.5: Average monthly temperature and rainfall calculated for the growing season October to April for seasons 2013-14, 2014-15 and 2015-16 and the 30-year long term average (LTA=1983-2013) at four sites: Coonawarra, McLaren Vale, Padthaway and Barossa.

Canopy architecture, yield components and grape composition

Canopy architecture was measured using the VitiCanopy App (De Bei et al. 2016). In all three seasons images were taken using an iPad 4 (Apple Inc., Cupertino, CA, USA). One image was taken on each side of the middle vine in each panel at 80 cm from the vine cordon (De Bei et al. 2016). In the four trials, images were taken throughout the growing season as shown in Table 8.4. As we were unable to intensively monitor all trials with the available resources (personnel), in consultation with TWE, it was decided that more intensive monitoring would be carried out in the Coonawarra (COO) and McLaren Vale (MLV), where TWE personnel could also be involved. Canopy images were taken as a minimum at flowering, veraison and harvest for all three seasons in COO and MLV and in season three in PDT and BAR.

Table 8.4: Phenological stages when the canopy architecture was measured using the VitiCanopy App in the three growing season.

	COO			MLV			PDT			BAR		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
EL 15				*		*						
EL 23	*	*	*	*	*	*			*			*
EL 29				*								
EL 33				*								
EL 35	*	*	*	*	*				*			*
EL 38	*	*	*	*		*			*			*

Harvest was decided by vineyard managers and was based on commercial maturity with a total soluble solid (TSS) accumulation target in the berries of 26 °Brix. All treatments were harvested on the same day in all three seasons (Table 8.5) apart from the Late PR which was generally harvested 15 days after.

Table 8.5: Harvest dates for the four vineyards (Coonawarra, McLaren Vale, Padthaway and Barossa) in the three growing seasons: 2013-14 (S1), 2014-15 (S2) and 2015-16 (S3).

	Harvest date S1	Harvest date S2	Harvest date S3
Coonawarra	Apr 15th	Mar 17th	Mar 15th
McLaren Vale	Feb 19th	Feb 13th	Feb 18th
Padthaway	Apr 2nd	Feb 24th	Mar 7th
Barossa	Feb 18th	Feb 18th	Mar 15th

All treatments were hand harvested and the number of bunches and yield per vine were recorded. Cordon length was also measured so that yield and its components could be measured on a per m basis.

From yield and bunch number, the average bunch weight was determined. When wines were made from specific treatments, the harvested fruit from three plants per treatment replicate was combined into 20 kg vented crates to form one replicate to be used for winemaking and chemical and sensory analysis. A random subsample of 50 berries per treatment and per replicate was collected, crushed by hand in plastic bags and the juice expressed, collected in 10 mL tubes and centrifuged at 5000 rpm for five minutes (Hettich Universal, Germany) before TSS, pH and titratable acidity (TA) (Autotitrator; Crison instruments Barcelona, Spain) determination (Iland et al. 2004). TSS was tested with a digital refractometer (BRX-242 Erma Inc. Tokyo, Japan). Another random subsample of 50 berries was collected to measure berry weight and stored at -20°C until anthocyanin, phenolic and tannin analyses were performed. Total grape tannins were measured using the methyl cellulose precipitable (MCP) assay proposed by Mercurio et al. (2007). Total anthocyanins and phenolics were determined according to Iland et al. (2004).

At pruning, the weight of all one-year-old wood was collected from each middle vine in each of the three panels allocated to each treatment replicate.

Berry sensory assessment

At harvest, from the treatments destined for winemaking, a sample of 300 berries was randomly chosen for berry sensory assessment (BSA) (Lohitnavy et al. 2010). Berries of similar size were cut from the bunch rachis with scissors and the pedicel was left on the berries in order to limit oxidation and deterioration. Berries were stored in a -20 °C freezer until assessment. BSA was carried out at the sensory facility of the University of Adelaide at the Waite Campus following the procedure described in Lohitnavy et al. (2010) and Olarte Mantilla et al. (2013). The procedure required two stages: 1) training session(s) and 2) evaluation session(s).

The training was conducted according to Olarte Mantilla et al. (2013); briefly, 10 to 12 assessors with previous BSA experience were selected for the DA and trained over three sessions in S1 and two in S2 and S3 (most of the panellists were the same as in the previous season). During the training sessions, the assessors were asked to evaluate berry samples from all the treatments with the aim of reaching an agreement on the number and type of attributes to score during the formal sessions.

The assessors reached a consensus on a list of 24 descriptors and on using a 0-15 line scale with three anchors. The list of descriptors is reported in Table 8.5.

Table 8.5: List of descriptors/attributes assessed by the panellists during the berry sensory analysis with their scale left, middle and right anchor. The attributes are divided in three categories: Pulp, Skin and Seed Characteristics. Panellists were given instructions on how to assess each category as described in Olarte-Mantilla et al. (2013).

Attribute	Left anchor	Middle anchor	Right anchor
Pulp Characteristics			
Dark Fruit	Low	Moderate	High
Red Fruit	Low	Moderate	High
Dry Fruit	Low	Moderate	High
Detachment of pulp from skin	Easy to detach	50%/50%	Difficult to detach
Juiciness	All is gelatinous	50%/50%	All is juicy
Sweetness	Low	Moderate	High
Acidity	Low	Moderate	High
Skin Characteristics			
Disintegration of the skins	Easy, homogenous mixture		Very difficult, big pieces
Acidity	Low	Moderate	High
Grape flavour	Low	Moderate	High
Bitterness	Low	Moderate	High
Astringency	Low	Moderate	High
Tannic intensity	Low	Moderate	High
Tannin size	Soft and silky grains	Medium size grains	High grade sand paper
Seeds Characteristics			
Colour	Green, yellow-green	Brown-green	Dark brown
Crushability	Soft like pepitas	Crunchy like roasted hazelnuts	Brittle like passionfruit seeds
Flavour	Herbaceous		Toasted
Bitterness	Low		High
Astringency	Low		High
Likability	Dislike		Like

During the formal assessment, the panellists were presented with 12 to 15 three-berry samples in a randomised sample presentation order for each assessor. Each sample was evaluated twice by each assessor. The sensory ratings were collected using custom-built web-based software

(cloud.sensorypanel.net/agwine) where the attributes were presented in the order shown in Table 8.5 and each attribute was associated with a line bar with a cursor that the assessor could move either using the mouse or by tapping on the screen of a tablet PC. The software collates the data for each session in an Excel file with the sample name in the rows and the assessor name and all the attributes in the columns. At completion of the assessment an Excel file with all the information was downloaded for statistical analysis.

Winemaking

For winemaking, and when possible, the field replicates were maintained in order to produce three wines per treatment. For the Coonawarra trial wines were made only from three out of the four replicates. In McLaren Vale, the six field replicates were combined to form three replicates as follows: 1 and 4, 2 and 5, and 3 and 6.

The fruit was stored for 24 hours in a cold room at 2 °C. The day after harvest, the fruit was crushed and de-stemmed using a small scale combined crusher de-stemmer (Grifo Macchine Enologiche, Piadena, Italy). At the crusher, 0.2 g/L of potassium metabisulfite was added. A 4 L sample of crushed grapes and must was transferred into 5 L food grade fermentation vessels (Amber Plastics Pty Ltd, Carrum Downs, Vic, Australia). The vessels were then moved to a controlled temperature growth room and maintained at 20-22 °C for fermentation.

Fermentations were inoculated with 0.2 g/L of commercial dried yeast AWRI 796 (Maurivin, Toowoomba, NSW, Australia) and 0.2 g/L of di-ammonium phosphate (DAP). Fermentation dynamics were monitored daily by measuring temperature and checking the density with a hydrometer. When the fermentations reached 10 °Baume an extra 0.2 g/L of DAP was added along with a malolactic bacteria culture (Lalvin VP14, Lallemand, France) at 0.2 mg/L to complete primary and secondary fermentation concurrently. When the measured density was below 2 °Baume and after at least five days on skins, wines were pressed and transferred into 2.2 L Schott bottles until completion of malolactic fermentation. Wines were bottled into 375 mL glass bottles and crown sealed. The wines were then stored at a constant 15 °C until sensory and chemical analysis.

Wine chemical analysis

The finished wines were analysed for pH and TA as described by Iland et al. (2004) (autotitrator; Crison instruments Barcelona, Spain). The concentration of alcohol (% v/v) was determined using an Alcolyzer Wine ME (Anton Paar, Graz, Austria). Colour was determined using the modified Somers assay using a high throughput method in 96 well plates (Mercurio et al. 2007). This method was used to determine phenolic substances and anthocyanins (mg/L). Tannin concentration was determined using the methyl cellulose precipitable (MCP) tannin assay as reported by Mercurio et al. (2007), the results provide tannin concentration expressed in epicatechin equivalents (mg/L).

Wine sensory descriptive analysis

The finished wines were assessed using descriptive analysis (DA) by a panel of assessors as described in Mantilla et al. (2015) and similarly to what has been described above for berry sensory assessments. Assessors were trained for two, two-hour sessions in all three seasons. Training included ranking exercises for taste attributes such as acidity, astringency and bitterness and identification of unknown aroma standards. During the training, the assessors were also asked to try the wines from the trial and reach a consensus on the attributes to score during the formal assessment.

The list of attributes is presented in Table 8.6.

Table 8.6: List of attributes assessed by the panellists during wine descriptive analysis with relative scale left, middle and right anchors. The attributes are divided in categories: Aroma, Taste, Flavour, Mouthfeel and Aftertaste.

Attribute	Left anchor	Middle anchor	Right anchor
Aroma			
Dark Fruit	Low	Moderate	High
Red Fruit	Low	Moderate	High
Confectionery	Low	Moderate	High
Savoury	Low	Moderate	High
Dusty	Low	Moderate	High
Green	Low	Moderate	High
Spice	Low	Moderate	High
Floral	Low	Moderate	High
Taste			
Salty	Low	Moderate	High
Bitter	Low	Moderate	High
Acid	Low	Moderate	High
Sweetness	Low	Moderate	High
Flavour			
Dark Fruit	Low	Moderate	High
Red Fruit	Low	Moderate	High
Ripeness	Low	Moderate	High
Savoury	Low	Moderate	High
Green	Low	Moderate	High
Spice/Pepper	Low	Moderate	High
Floral	Low	Moderate	High
Mocha/Chocolate/Coffee	Low	Moderate	High
Mouthfeel			
Body	Thin	Medium	Viscous and mouth filling
Astringency	Low	Medium	High
Tannins	Fine	Medium	Coarse
Alcohol	Low	Medium	High
Aftertaste			
Overall Length	Short	Medium	Long
Fruit length	Short	Medium	Long
Bitter length	Short	Medium	Long
Acidity length	Short	Medium	Long
Savoury length	Short	Medium	Long
Alcohol	Low	Moderate	High
Bitter	Low	Moderate	High

For the final wine assessment assessors were presented with 12 to 15, 30 mL wine samples in clear, ISO standard glasses covered with a petri dish. All wines were assessed in duplicate in a randomised sample presentation order for each assessor. Data were collected using the same custom-built software used to assess the berries.

Statistical analysis

Analysis of variance (ANOVA), repeated measures ANOVA and Principal Component Analysis (PCA) were performed using XLSTAT Version 2015.4.01.20116 (Addinsoft SARL, Paris, France). Means were compared using Tukey's honest significant difference (HSD) test ($P \leq 0.05$). Sensory data were analysed using SenPAQ (Qi statistics, UK), a two-way mixed model ANOVA was performed with random assessors. Correlations were analysed using Pearson correlation coefficient and the statistical language R (R Core Team, 2017). The correlations maps between vine balance indices and grape and wine chemistry and sensory attributes were calculated using the R package *corrplot* (Wei and Simko, 2016) and only significant correlations ($P \leq 0.05$) are represented in the maps.

Results

For clarity, the results will be presented separately for each canopy management trial (Coonawarra, McLaren Vale, Barossa and Padthaway) and then discussed together at the end of this chapter. Also, the effects of the use of kicker canes (KC) and late pruning (Late PR) compared to the control (C) have been separated from the other canopy management treatments.

Coonawarra

Traditional canopy management results

The effect of the treatments in S1 was small and not statistically significant on the yield and yield components (Table 8.7). As expected the number of canes per m of cordon was significantly different for the ST treatment in S1. Also, the number of bunches was the same for all treatments indicating that the BT treatment was ineffective. On the contrary, in S2, significant differences in bunch number were observed for BT. ST showed no differences with C, with even the number of canes being the same as C. The yield in S2 was not statistically different. In a similar way, yield was not different in S3. BT bunch number was lower than all other treatments however the weight of those bunches was significantly higher than C and LP.

Table 8.7: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning) on yield and yield components of Shiraz grown in Coonawarra during three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Berry weight	Pruning weight (kg)	Cane/m (#)
2013-14	C	1.97	19.44	98.70	0.85	1.10	18.41 ab
	ST	1.86	17.15	109.44	0.83	1.15	15.40 b
	LP	2.22	22.22	98.86	0.84	1.04	20.44 a
	BT	2.20	20.20	104.90	0.85	1.17	19.51 a
	P-value (T)	ns	ns	ns	ns	ns	0.001
2014-15	C	2.41	30.70 a	77.72	1.15	0.78	22.03
	ST	2.61	31.24 a	79.03	1.14	0.95	24.01
	LP	1.18	23.77 ab	49.17	0.85	0.82	23.71
	BT	1.44	15.25 b	93.17	0.98	0.82	18.15
	P-value (T)	ns	0.007	ns	ns	ns	ns
2015-16	C	2.63	35.70 a	69.99 bc	1.04	0.80	19.75
	ST	2.58	29.17 a	86.76 ab	1.02	0.77	16.32
	LP	1.71	30.10 a	61.43 c	0.93	0.91	21.88
	BT	1.49	15.01 b	97.83 a	1.14	0.97	19.14
	P-value (T)	ns	0.003	0.005	ns	ns	ns
	Season (S)	ns	0.003	< 0.0001	0.002	< 0.0001	0.003
	S x T	ns	0.016	ns	ns	ns	0.039

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test ($P \leq 0.05$). ns = not statistically significant.

The canopy management imposed on the same vines over three seasons produced some differences in canopy architecture, described here as LAI and canopy porosity (Figure 8.6). In S1, LAI was different only at harvest when LP showed the lowest values while porosity was not different throughout the growing season. However, those differences were not maintained when measured in the following phenological stages. In S2, ST reduced LAI significantly from the time of application to harvest while canopy porosity was increased only at flowering. Unexpectedly, in S3 a loss of LAI was observed for all treatments from flowering to veraison, probably due to the hot and dry conditions of the growing season. LP applied at veraison decreased LAI even further and differences were maintained up to harvest when ST and LP showed the smallest LAI. Canopy porosity did not show a significant treatment

effect but an increase from flowering to veraison was observed, which is related to the observed decrease in LAI.

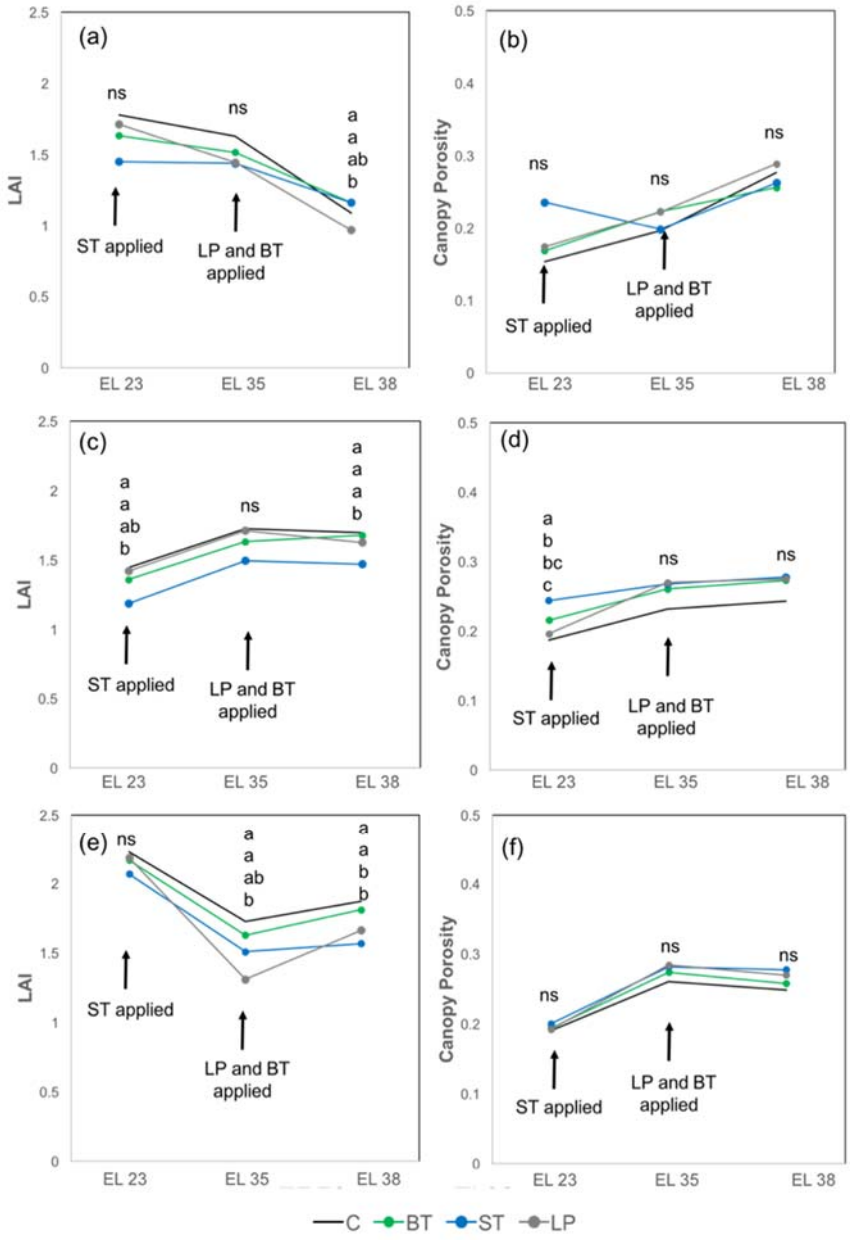


Figure 8.6: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning) on canopy architecture of Shiraz grown in Coonawarra applied for three consecutive seasons (2013-14, 2014-15 and 2015-16). LAI season 1 (a), season 2 (c), season 3 (e). Canopy porosity season 1 (b), season 2 (d) and season 3 (f).
Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

All treatments were harvested on the same day in each season and only in S1 TSS was significantly different, being higher for C and ST (Table 8.8). For all the other berry chemistry measures no differences were observed between treatments. A season effect is evident for all the measured parameters.

Table 8.8: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning) on berry chemistry measurements of Shiraz grown in Coonawarra applied for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	TSS (Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Tannin (mg/g)	Iron Reactive Phenolics (mg/g)
2013-14	C	25.72 a	3.33	6.03	1.88	2.38	7.15
	ST	25.79 a	3.29	6.27	1.90	2.56	7.37
	LP	25.16 b	3.31	6.09	1.89	2.37	7.00
	BT	25.29 b	3.31	6.08	1.99	2.20	7.67
	P-value (T)	0.005	ns	ns	ns	ns	ns
2014-15	C	26.60	3.63	5.28	2.37	4.23	9.13
	ST	26.80	3.58	5.42	2.30	3.95	8.80
	LP	27.37	3.76	4.64	2.76	4.38	10.06
	BT	27.13	3.71	4.88	2.32	4.25	9.64
	P-value (T)	ns.	ns	ns	ns	ns	ns
2015-16	C	27.27	3.61	6.47	1.72	2.78	9.07
	ST	26.77	3.44	6.65	1.69	2.80	8.40
	LP	27.63	3.63	6.11	1.65	2.81	8.16
	BT	27.30	3.57	6.17	1.63	2.46	7.78
	P-value (T)	ns	ns	ns	ns	ns	ns
	Season (S)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	S x T	ns	ns	ns	0.023	0.033	0.004

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In S1, wines were made from C, ST and KC. Here results from C and ST are shown. The chemical components analysed only showed a difference in alcohol concentration (Table 8.9). In the following two seasons wines were also made from LP and BT and the chemical analysis revealed differences in titratable acidity with the highest measured in ST and the lowest in LP and BT. Also, BT showed the highest tannin content while the lowest was measured in C.

Table 8.9: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning) on wine chemistry of Shiraz grown in Coonawarra applied for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	Alcohol (%v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2013-14	C	13.720 b	3.65	6.71	285.25	31.52	-
	ST	14.723 a	3.65	6.71	352.93	35.89	-
	P-value (T)	0.039	ns	ns	ns	ns	
2014-15	C	14.93	3.64	8.01 b	681.28	46.98	229.26 b
	ST	14.85	3.61	8.47 a	673.13	46.05	297.20 ab
	LP	15.25	3.83	7.62 c	744.87	52.32	236.85 ab
	BT	15.23	3.72	7.53 c	696.83	47.92	354.40 a
	P-value (T)	ns	ns	0.000	ns	ns	<0.0001
2015-16	C	15.98	3.86 a	7.37	710.33	57.99	492.44
	ST	15.16	3.67 b	7.40	715.91	54.79	454.57
	LP	15.83	3.94 a	7.07	702.43	61.32	497.80
	BT	15.39	3.97 a	6.91	725.11	51.43	427.53
	P-value (T)	ns	0.004	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)

** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

Berry sensory assessment (BSA) did not show great differences between samples however, the same four attributes were observed to be significantly different in all three seasons. The PCA plot in Figure 8.7 shows that the first two principal components explain most of the variation in the dataset. In particular, PC1 explains 98.14% of the variability and is related to differences in seed astringency and bitterness, skin disintegration and acidity and pulp acidity between ST and LP.

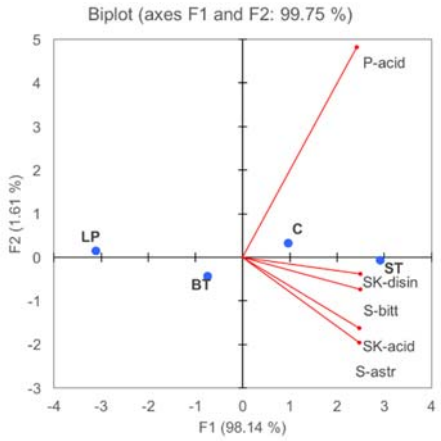


Figure 8.7: Principal component analysis of berry sensory attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the berries from four canopy management treatments in the Coonawarra Region. Data is an average of three seasons. C= Control, BT= Bunch Thinning, LP= Leaf Plucking and ST = Shoot Thinning. BSA attributes: S-astr= seed astringency, SK-disint=ease of skin disintegration, P-acid= pulp acidity and S-bitt= seed bitterness.

In S1 wine was made only from KC treatments and ST. Figure 8.8 shows the comparison between C and ST. The ST wines were higher in red fruit and savoury aroma and also tasted saltier compared to C. Dark fruit, acidity and astringency characters were higher in C. The KC will be discussed later in this chapter.

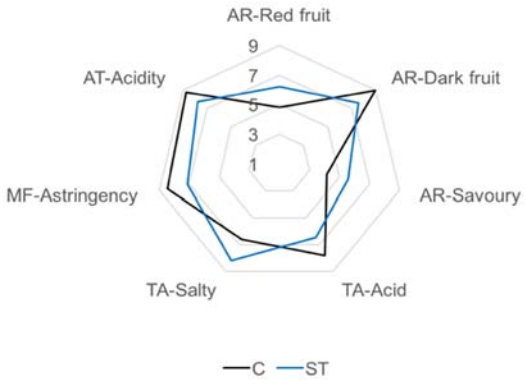


Figure 8.8: Radar plot of attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the wines from two canopy management treatments in the Coonawarra Region in season 1 (2013-14). C= Control and ST = Shoot Thinning. Attributes: S-astr= seed astringency, SK-disint=ease of skin disintegration, P-acid= pulp acidity and S-bitt= seed bitterness. AR= aroma, TA= taste, MF= mouthfeel and AT= aftertaste.

Greater differences between the wines were observed in S2 and S3, particularly when more treatments were included for winemaking (Figure 8.9). In S2, BT and ST, were characterised by more intense floral and green aromas and more intense mocha flavours. LP was perceived as more alcoholic, with more body and a longer finish. C wines were described as salty. In 2016, alcohol, as an aroma descriptor, was again associated with LP and also C; both wines were also perceived as having a more intense jammy flavour. BT had more body but also a more savoury aroma while the most liked wine was ST which was rated as being more acidic.

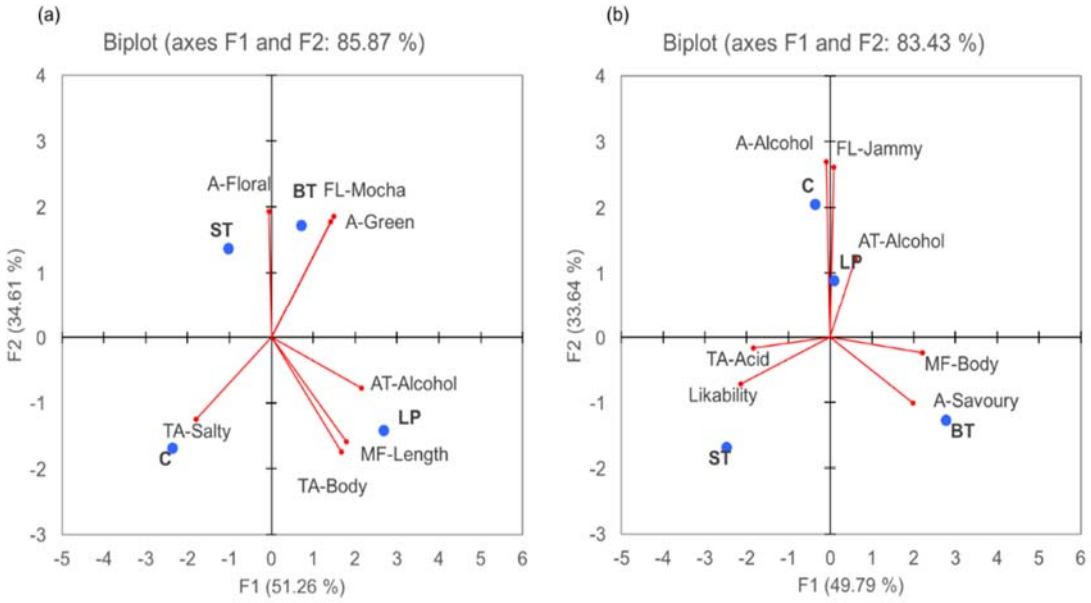


Figure 8.9: Principal component analysis of wine attributes found significantly different at P ≤ 0.2 by a panel of 12 assessors from four canopy management treatments in the Coonawarra region. Figure on the right shows data from S2 (2014-15) and figure on the left shows data from S3 (2015-16). C= Control, BT= Bunch Thinning, LP= Leaf Plucking and ST = Shoot Thinning. A= aroma, FL= flavour, TA= taste, MF= mouthfeel and AT= after taste.

Kicker canes

Repeated measure ANOVA showed no significant interaction between season and treatment (SxT) (Table 8.10). Not surprisingly, a significant effect of the season on the yield components was shown. Bunch number per m was greater in S2 and S3 compared to S1 and the opposite was found for bunch weight resulting in no significant difference in yield between seasons. In S1 the pruning weight of KC treatments was significantly lower, with the exception of KUP compared to C. In S2 no significant differences between treatments were observed. By S3, the strongest differences of all the three seasons were observed with yield and yield components; significantly lower for kicker cane treatments. KDOWN and K+BT in particular had an effect on yield and yield components. KC treatments also reduced bunch weight with more effect when the KC are oriented downward and when associated with a BT treatment. The K EARLY treatment's only effect was to lower pruning weight compared to C. K DOWN definitely had an impact on the vines, yield was reduced by more than 50%, so were bunch and pruning weights and the number of canes. Given the combination of KC with BT, it is not surprising that yield for the K+BT was reduced by 55%, number of bunches by 53%, pruning weight by 24% however, the yield reduction was driven by bunch number as no differences were observed in bunch weight and cane number compared to C.

Table 8.10: Effect of kicker canes (KC) on yield and yield components of Shiraz grown in Coonawarra applied during three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Pruning weight (kg)	Cane/m (#)
2013-14	C	1.98	19	98.7	1.10 a	18
	K EARLY	1.74	17	90.5	0.82 bc	16
	K UP	2.07	21	98.3	0.99 ab	15
	K DOWN	1.57	17	85.5	0.77 c	16
	K + BT	1.76	17	104.4	0.84 bc	15
	P-value (T)	ns	ns	ns	0.001	ns
2014-15	C	2.42	31	77.7	0.79	45
	K EARLY	1.72	31	51.4	0.68	39
	K UP	1.96	30	65.0	0.74	35
	K DOWN	0.83	22	38.3	0.61	41
	K + BT	0.93	14	57.1	0.66	33
	P-value (T)	ns	ns	ns	ns	ns
2015-16	C	2.61 a	36 a	70.1 a	0.80 a	20 ab
	K EARLY	2.09 ab	35 a	56.2 ab	0.61 bc	20 a
	K DOWN	1.33 b	29 a	44.8 b	0.47 c	17 b
	K + BT	1.22 b	17 b	70.8 a	0.61 b	18 ab
	P-value (T)	0.048	0.007	0.034	0.000	ns
	Season (S)	ns	0.000	< 0.0001	< 0.0001	< 0.0001
	S x T	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

It was not possible to measure canopy architecture in the KC treatments at flowering since there was not enough space (at least 70-80 cm, (De Bei et al. 2016)) between the camera and the canopy due to the sprawling shoots of the KC. Data were then collected only at veraison (EL 35), after the severing of the KC and before harvest. Similarly to yield and yield component observations, the effect of the KC on the canopy architecture was mild in S1 but became more evident in the following two seasons.

In S1 the LAI in K DOWN and K+BT was reduced, as expected, after the KC removal, however no effect was observed in canopy porosity (Table 8.11). Also, K EARLY and K UP were no different to C. At harvest the LAI was greatly reduced compared to the veraison measurement. The effect of KC on

canopy architecture in S2 was not statistically significant for LAI at veraison while KC reduced LAI at harvest and significantly increased canopy porosity compared to C. Differences were significant at harvest when C had the highest LAI and lowest porosity amongst treatments. In S3 LAI was lower and canopy porosity higher when both K DOWN and K + BT were applied.

Table 8.11: Effect of kicker canes (KC) on canopy architecture (LAI and canopy porosity) measured at EL stage 35 (veraison) and EL stage 38 (harvest) using the VitiCanopy App on Shiraz grown in Coonawarra during three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	LAI EL 35	Canopy Porosity EL 35	LAI EL 38	Canopy Porosity EL 38
2013-14	C	1.68 ab	0.20	1.09	0.28
	K EARLY	1.55 abc	0.18	1.00	0.30
	K UP	1.84 a	0.17	1.10	0.29
	K DOWN	1.38 bc	0.20	0.99	0.29
	K + BT	1.21 c	0.26	1.04	0.27
	P-value (T)	0.05	ns	n.s.	ns
2014-15	C	1.73	0.23 b	1.70 a	0.24 d
	K EARLY	1.43	0.28 a	1.46 bc	0.28 ab
	K UP	1.51	0.27 a	1.60 ab	0.26 cd
	K DOWN	1.48	0.27 a	1.36 c	0.29 a
	K + BT	1.43	0.27 a	1.55 abc	0.23 bc
	P-value (T)	ns	0.010	0.034	0.000
2015-16	C	1.73 a	0.26 c	1.87 a	0.25 c
	K EARLY	1.52 a	0.29 b	1.61 b	0.28 b
	K DOWN	1.14 b	0.33 a	1.47 c	0.31 a
	K + BT	1.06 b	0.34 a	1.51 bc	0.30 a
	P-value (T)	0.001	< 0.0001	< 0.0001	< 0.0001
	Season (S)	0.000	< 0.0001	< 0.0001	0.000

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

No differences were observed in berry maturity and chemistry at harvest but for TA which, in S1 was higher for K UP while in S2 was higher for K DOWN (Table 8.12). KC were excluded from winemaking in S3 due to the fact that this practice, with four KC per plant, was deemed commercially unviable due to the significant yield reductions observed in the final season. Due to this, no basic

chemistry measurements (TSS, pH, TA) were carried out in S3, however colour, phenolics and tannins measures were conducted but did not show significant differences between treatments.

Table 8.12: Effect of the use of kicker canes (KC) on berry chemistry of Shiraz grown in Coonawarra for two consecutive seasons (2013-14, 2014-15).

Season	Treatment (T)	TSS (Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Tannin (mg/g)	Iron Reactive Phenolics (mg/g)
2013-14	C	25.69	3.33	6.01 b	1.88	2.38	7.15
	K EARLY	25.46	3.28	6.25 ab	2.05	2.34	7.35
	K UP	25.02	3.28	6.51 a	1.78	2.41	7.16
	K DOWN	25.49	3.33	6.18 b	1.96	2.42	7.22
	K + BT	25.18	3.32	6.11 b	1.98	2.13	7.23
	P-value (T)	ns	ns	0.018	ns	ns	ns
2014-15	C	26.60	3.63	5.28 b	2.37	4.23	9.13
	K EARLY	26.40	3.56	5.58 b	2.19	4.34	9.51
	K UP	26.93	3.62	5.17 b	2.32	4.09	8.69
	K DOWN	26.90	3.55	6.70 a	2.47	4.22	9.33
	K + BT	27.00			2.54	4.28	9.84
	P-value (T)	ns	ns	0.017	ns	ns	ns
	C				1.72	2.78	9.07
	K EARLY	-	-	-	1.66	3.00	8.90
	K DOWN	-	-	-	1.47	2.58	7.83
	K + BT	-	-	-	1.58	2.42	7.52
	P-value (T)				ns	ns	ns
	Season (S)				<0.0001	<0.0001	<0.0001
	SxT				ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Similarly to berry chemistry, no differences were observed in any of the wine chemistry analysed (Table 8.13). No wines from KC were made in S3.

Table 8.13: Effect of the use of kicker canes (KC) on wine chemistry of Shiraz grown in Coonawarra for two consecutive seasons (2013-14, 2014-15).

Season	Treatment (T)	Alcohol (%v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2013-14	C	13.72	3.65	6.71	285	31.52	-
	K EARLY	14.15	3.46	7.27	274	30.84	-
	K DOWN	13.79	3.47	7.09	271	31.38	-
	K + BT	14.26	3.56	7.17	293	33.13	-
	P-value (T)	ns	ns	ns	ns	ns	
2014-15	C	14.90	3.65	7.94	673.04	47.16	229.26
	K EARLY	14.95	3.56	8.50	645.96	43.93	233.61
	K UP	15.19	3.63	8.37	708.48	46.98	273.57
	P-value (T)	ns	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)

** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

The berry and wine sensory analysis conducted with a trained panel did not show any differences when KC berries and wines were compared to C. The only exception to this was in S1 where the panel observed a more intense savoury aroma in K+BT wines compared to the other KC treatments but not to C (data not shown).

McLaren Vale

Traditional canopy management and cover cropping

In the first two seasons of imposing treatments on the vines, differences were observed only for pruning weight, which was lower in the Complete CC every year (Table 8.14). In S3, the number of bunches per m of cordon was significantly lower in ST while bunch weight was the lowest in the Complete CC (Table 8.14). As per previous two seasons, the pruning weight in the Complete CC was lower than in all the other treatments.

Table 8.14: Effect of canopy management on yield and yield components of Shiraz grown in McLaren Vale applied for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Berry weight (g)	Pruning weight (kg)
2013-14	C	2.64	31.62	82.69	1.08	1.13 a
	ST	2.51	28.12	86.00	1.03	1.04 a
	LP	2.56	32.48	77.27	1.03	1.03 a
	CC	2.17	29.50	73.29	0.96	0.94 a
	Complete CC	1.90	33.41	55.35	0.85	0.56 b
	P-value (T)	ns	ns	ns	ns	< 0.0001
2014-15	C	2.64	24.42	102.25	1.67	1.02 a
	ST	2.56	24.94	101.65	1.56	0.94 a
	LP	1.93	24.03	81.03	1.58	0.98 a
	CC	1.34	21.76	57.64	1.56	0.71 ab
	Complete CC	2.50	21.10	112.73	1.47	0.44 b
	P-value (T)	ns	ns	ns	ns	0.046
2015-16	C	4.19	42.42 a	96.33 a	1.22	0.93 a
	ST	2.71	24.14 c	108.44 a	1.15	0.78 a
	LP	3.51	38.73 ab	88.62 ab	1.12	0.87 a
	Complete CC	2.19	31.62 bc	66.54 b	0.92	0.41 b
	P-value (T)	ns	0.004	0.027	ns	0.006
	Season (S)	0.021	< 0.0001	0.002	< 0.0001	0.009
	SxT	ns	0.045	0.035	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Canopy architecture was significantly different in response to management in S1. The cover cropping treatments, in particular, reduced LAI and increased canopy porosity especially when used both in the mid row and under vine area. Surprisingly, LAI and porosity in the LP treatment were significantly different from C for the whole season even though LP was carried out at EL 33 (Figure 8.10).

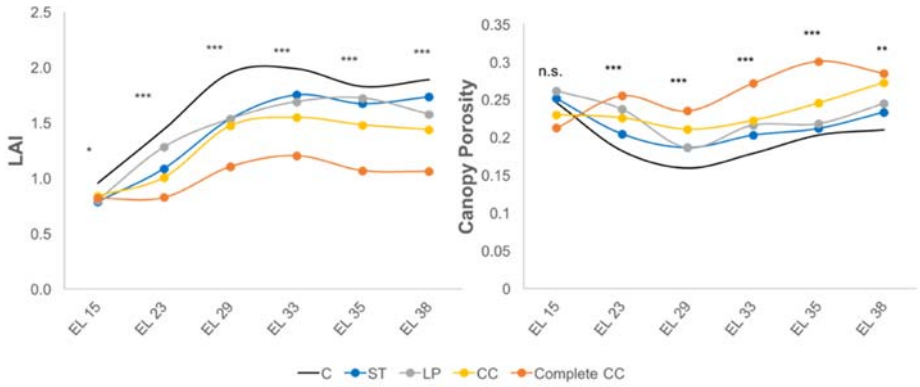


Figure 8.10: Effect of canopy management on the leaf area index (LAI) and canopy porosity of Shiraz grown in McLaren Vale in season 1 (2013-14). C= Control, ST= Shoot Thinning, LP= Leaf Plucking, CC= cover crop in the mid row, Complete CC= cover crop in the midrow and under vine. Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant *= significant at P≤0.05, **= significant at P≤0.01, *= significant at P≤0.001.**

Due to a change in management, canopy images for canopy architecture analysis in S2 were taken only at flowering (EL 23), veraison (EL 35) and harvest (EL 38) however, the images taken at EL 38 were found to be unsuitable (sun captured in the image) for analysis with VitiCanopy so they were excluded from the dataset (Figure 8.11). At EL 23, C and LP showed the higher values of LAI and C, in particular, had very low canopy porosity. At EL 35, similarly to what was observed in the previous season, C had the highest LAI while the lowest was again measured in the cover crop treatments. Canopy porosity at EL 35 was not different between treatments.

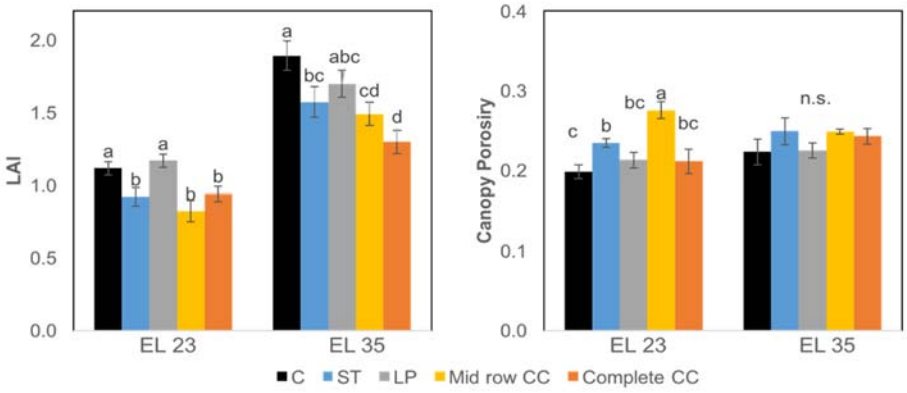


Figure 8.11: Effect of canopy management on the leaf area index (LAI) and canopy porosity of Shiraz grown in McLaren Vale in season 2 (2014-15). C= Control, ST= Shoot Thinning, LP= Leaf Plucking, CC= cover crop in the mid row, Complete CC= cover crop in the mid row and under vine. Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In S3, canopy architecture was measured also at EL 15, immediately after carrying out ST, which decreased LAI and increased porosity significantly and was maintained throughout the season (Figure 8.12). Complete CC, as shown previously, decreased LAI and increased porosity compared to C in a similar fashion to ST. LP was completed at EL 35, its effect was evident on both LAI and porosity compared to C.

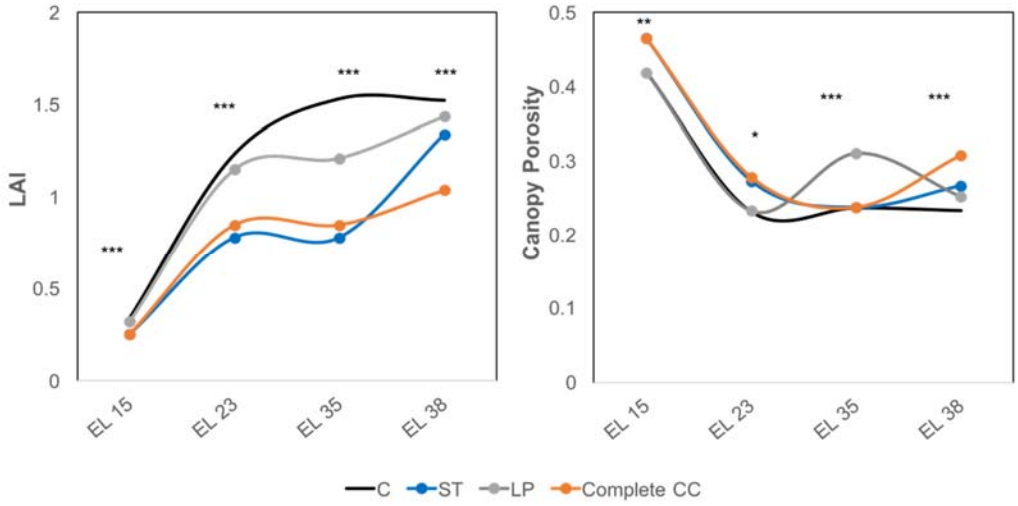


Figure 8.12: Effect of canopy management on the leaf area index (LAI) and canopy porosity of Shiraz grown in McLaren Vale in season 3 (2015-16). C= Control, ST= Shoot Thinning, LP= Leaf Plucking, Complete CC= cover crop in the mid row and under vine. Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). *= significant at P≤0.05, **= significant at P≤0.01, *= significant at P≤0.001**

A highly significant season effect was found in the berry chemistry results however no significant interaction was found with the treatments except for tannin and phenolic content (Table 8.15). When analysed per season, berry chemistry showed little difference between treatments, pH was lower in Complete CC in S1 and TSS was higher in the same treatment in S2 indicating advanced maturity compared to the other treatments and to C. In S2 Complete CC had a much higher tannin and phenolic content in the berries compared to the other treatments.

Table 8.15: Effect of canopy management on berry chemistry measures applied on Shiraz vine in McLaren Vale for three consecutive seasons (2013-14, 2014-15, 2015-16).

Season	Treatment (T)	TSS (Brix)	pH	TA (g/L)	Anthocyanins (mg/g)	Tannins (mg/g)	Iron Reactive Phenolics (mg/g)
2013-14	C	25.17 a	3.56 a	4.67	2.15	3.02	9.00
	ST	25.17 a	3.56 a	4.74	2.12	3.09	8.38
	LP	25.0 a	3.59 a	4.83	2.08	3.04	8.59
	CC	24.93 ab	3.53 a	4.61	2.07	3.04	8.60
	Complete CC	24.72 b	3.47 b	4.74	2.29	3.36	9.26
	P-value (T)	0.016	0.004	ns	ns	ns	ns
2014-15	C	26.23 b	3.56	5.27	2.22	3.77 b	8.20 b
	ST	26.83 ab	3.58	5.54	2.09	3.37 b	7.47 b
	LP	26.17 b	3.58	5.42	2.09	3.34 b	7.73 b
	Complete CC	28.03 a	3.53	5.69	2.71	4.75 a	11.77 a
	P-value (T)	0.017	ns	ns	ns	0.010	0.001
2015-16	C	24.11	3.24	9.76	1.75	1.28	5.18
	ST	23.47	3.37	9.62	1.87	1.26	4.74
	LP	22.82	3.30	9.66	1.74	1.29	4.70
	Complete CC	23.47	3.27	10.00	1.84	1.31	5.55
	P-value (T)	ns	ns	ns	ns	ns	ns
	Season (S)	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	SxT	ns	ns	ns	ns	0.011	<0.0001

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In S1, no differences were measured in wine chemistry (Table 8.16). In S2, given the high TSS of the Complete CC at harvest, the alcohol % was also higher than in the other treatments. TA was higher in LP and Complete CC while anthocyanins were lower for these same treatments. The highest phenolic content was measured in ST and the lowest in the Complete CC. In S3 the only difference detected in wine chemistry was in the alcohol concentration that, again, was higher in Complete CC (Table 8.16).

Table 8.16: Effect of canopy management on wine chemistry measures applied to Shiraz grown in McLaren Vale for three consecutive seasons (2013-14, 2014-15, 2015-16).

Season	Treatment (T)	Alcohol (%v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2013-14	C	14.48	3.51	6.22	234.79	44.37	-
	ST	14.33	3.45	6.40	254.29	44.80	-
	LP	14.56	3.52	6.15	247.46	45.01	-
	P-value (T)	ns	ns	ns	ns	ns	
2014-15	C	15.41 b	3.62	8.23 b	558.39 a	47.23 b	1886
	ST	15.65 b	3.64	8.25 b	580.55 a	52.89 a	1675
	LP	15.36 b	3.64	8.55 a	492.89 b	43.72 bc	1595
	Complete CC	16.54 a	3.63	8.68 a	476.15 b	41.09 c	1478
	P-value (T)	0.000	ns	0.003	0.002	0.003	ns
2014-15	C	14.77 b	3.68	12.16	539.67	47.81	1134
	ST	15.08 ab	3.73	10.65	604.81	50.48	1174
	LP	14.59 b	3.75	10.61	571.78	49.84	1215
	Complete CC	15.36 a	3.74	10.78	611.52	51.94	1182
	P-value (T)	0.049	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test ($P \leq 0.05$). ns= not statistically significant.

*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)

** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

BSA conducted on berries from S1 did not show any significant differences between attributes. In S2 and S3, as shown in Figure 8.13, a few attributes differed between treatments. S1 Complete CC was found to have more intense dark fruit flavour and also higher astringency in the seeds. For the other attributes; jammy flavour of the pulp, skin acidity and skin astringency were similar for LP and Complete CC while ST was more similar to C (Figure 8.13). The seed characteristics differentiated the treatments in S3, with Complete CC having more herbaceous, bitter and astringent seeds; while C was at the other end of the spectrum. Also, pulp acidity was higher in C and LP and lower for Complete CC and ST. C and LP were the most liked berries by the panellists.

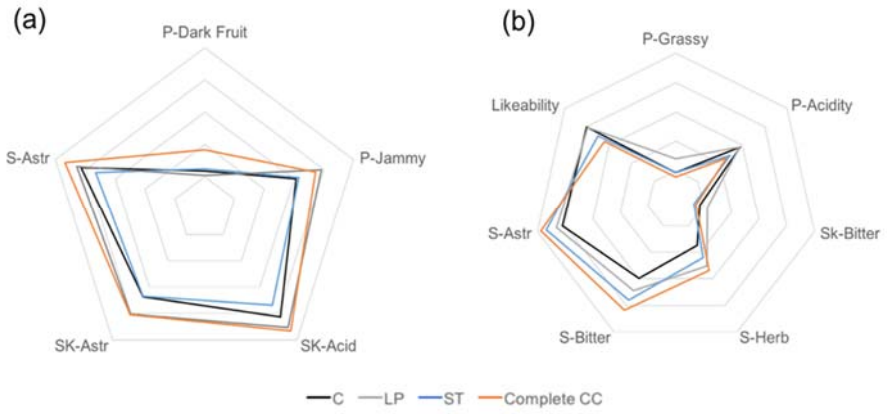


Figure 8.13: Radar plot of attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the berries from different management systems in McLaren Vale in season 2 (2014-15, (a)) and season 3 (2015-16, (b). C= Control, ST= Shoot Thinning, LP= Leaf Plucking and Complete CC= cover crop in the mid row and under vine. Attributes: P= pulp, SK= Skin, S= seed.

As observed in BSA and berry and wine chemistry from S1 the wines did not show any difference when subjected to descriptive analysis. Similarly, no differences were measured in S3 however, in S2 a few attributes were significantly different between wines from different management treatments; C wines showed less dark fruit aroma and flavour while Complete CC was more astringent and tannic and also presented a longer after taste. The most liked wine was the one obtained from the C vines (Figure 8.14).

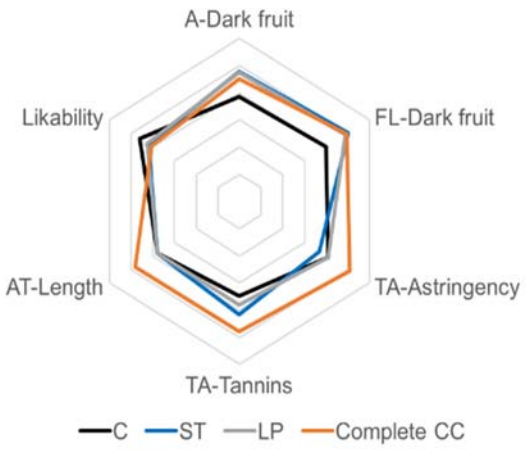


Figure 8.14: Radar plot of attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the wines from different management systems in McLaren Vale in season 2 (2014-15). C= Control, ST= Shoot Thinning, LP= Leaf Plucking and Complete CC= cover crop in the mid row and under vine. Attributes: A= Aroma, FL= Flavour, TA= Taste and AT= After Taste.

Effect of late pruning

Pruning vines after budburst (LatePR), at EL stage 9-11, had a very strong effect on the yield and yield components compared to C vines that were pruned at dormancy (Table 8.17). As an average over three seasons, yield was reduced by 57%, the number of bunches per metre of cordon by 32%, bunch weight by 28% and the pruning weight by 29%. Yield was 30% lower in LatePR already in S1.

Table 8.17: Effect of late pruning (LatePR) on yield and yield components of Shiraz grown in McLaren Vale applied during three consecutive seasons (2013-14, 2014-15 and 2015-16).

Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Berry weight (g)	Berries/bunch (#)	Pruning weight (kg)
C	3.16 a	32.82 a	93.76 a	1.316 a	72.166 a	1.05 a
LatePR	1.39 b	22.30 b	67.14 b	1.091 b	60.699 a	0.75 b
P-value (T)	0.008	0.000	0.022	0.000	ns	0.002
Season (S)	0.08	0.000	0.022	0.000	ns	0.002

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Canopy architecture measurements were carried out at EL 23 and EL 35 in all three seasons and they showed that LAI at EL 23 was significantly smaller in LatePR compared to C (Table 8.18). The EL 35 measures did not show differences between the two treatments in the first two seasons, in S3 however, LatePR did show a significantly smaller canopy at veraison.

Table 8.18: Leaf area index and Canopy porosity measured at El 23 (flowering) and El 35 (veraison) for the control (C) and the late pruning (Late Pr) treatments on Shiraz grown in McLaren Vale in three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	LAI EL 23	Canopy Porosity EL 23	LAI EL 35	Canopy Porosity EL 35
2013-14	C	1.44 a	0.18 b	1.83	0.20
	Late Pr	0.86 b	0.28 a	1.79	0.23
	P-value (T)	0.002	0.002	ns	ns
2014-15	C	1.11 a	0.20 b	1.89	0.22
	Late Pr	0.92 b	0.24 a	1.76	0.23
	P-value (T)	0.028	0.028	ns	ns
2015-16	C	1.23 a	0.23 b	1.53 a	0.23 b
	Late Pr	0.25 b	0.46 a	1.23 b	0.28 a
	P-value (T)	< 0.0001	< 0.0001	0.013	0.019
	Season (S)	< 0.0001	< 0.0001	0.001	0.016
	SxT	< 0.0001	< 0.0001	0.451	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In S1 and S2 the LatePR treatment was harvested two weeks after the C while in S3, since it was the last season of the trial, both treatments were harvested at the same time. TSS in S1 was higher in C while in S2 TSS for LatePR was 30 °Brix which indicated that the fruit was over ripe. In S1 TA was lower and total anthocyanins content was higher in C, but all the other measurements were similar. In S3, when the two treatments were harvested together, none of the measures were significantly different between treatments (Table 8.19).

Table 8.19: Effect of Late Pruning (LatePR) on berry chemistry of Shiraz grown in McLaren Vale in seasons 2013-14, 2014-15 and 2015-16.

Season	Treatment (T)	TSS (°Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Tannin (mg/g)	Iron Reactive Phenolics (mg/g)
2013-14	C	25.04 a	3.56	4.670 b	2.153 a	3.02	9.00
	LatePR	24.47 b	3.52	5.27 a	1.88 b	3.10	7.97
	P-value (T)	0.006	ns	0.024	0.001	ns	ns
2014-15	C	26.23 b	3.56 b	5.27	2.22	3.77	8.20
	LatePR	30.00 a	3.74 a	5.09	2.06	3.66	8.88
	P-value (T)	0.000	0.005	ns	ns	ns	ns
2015-16	C	24.10	3.24	7.32	1.75	1.28	5.18
	LatePR	22.70	3.20	9.36	1.68	1.30	5.59
	P-value (T)	ns	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Wine from the LatePR treatment was made only in the first two seasons. As shown in Table 8.20 no differences in wine chemistry were observed in S1 while in S2 the alcohol concentration, pH and TA were higher in LatePR.

Table 8.20: Effect of late pruning (LatePR) on wine chemistry of Shiraz grown in McLaren Vale in seasons 2013-14 and 2014-15.

Season	Treatment (T)	Alcohol (% v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2013-14	C	14.48	3.51	6.22	234.79	44.37	-
	LatePR	14.56	3.52	6.15	247.46	45.01	-
	P-value (T)	ns	ns	ns	ns	ns	
2014-15	C	15.41 b	3.62 b	8.23 b	558.39 a	47.23	1886.03
	LatePR	16.94 a	3.74 a	8.60 a	522.93 a	44.24	1315.73
	P-value (T)	0.001	0.046	0.023	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)

** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

Berry sensory analysis highlighted differences between C and LatePR only for three attributes in each of the two seasons (Figure 8.15). In S1 the C was judged as having higher red berry flavour in the pulp, less dark fruit flavour in the skin and had darker seeds. In S2, given the LatePR treatment was harvested at 30 °Brix, berries were described as having a greater jammy character in both pulp and skin and also had higher dark fruit flavour.

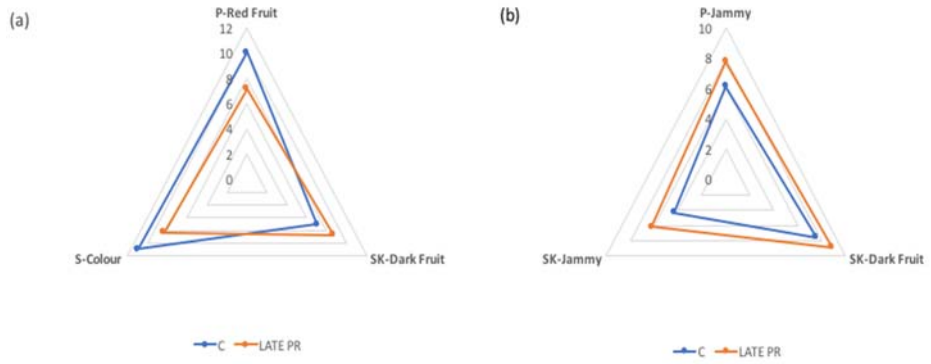


Figure 8.15: Radar plot of attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the berries of control (C) and late pruning (LatePR) in McLaren Vale in season 1 (2013-14, (a)) and season 2 (2014-15, (b). Attributes: P-Red Fruit= red fruit flavour of the pulp, SK- Dark Fruit= dark fruit flavour of the skin, S-Colour= colour of the seeds (higher numbers for darker seeds), P-Jammy= jammy flavour of the pulp, SK-Jammy= jammy flavour of the skin.

Wines obtained from the LatePR were differentiated from C for only three attributes in S1: bitter taste, aftertaste and alcohol aftertaste (Figure 8.16). There was no significant difference in the likeability of the wines. In S2, most likely due to the fact that LatePR was harvested at a higher TSS, the wines obtained from LatePR were associated with overripe characters such as dark fruit and jammy. Also, LatePR wines were judged to be more tannic and alcoholic with a longer aftertaste and the C wines were preferred (higher likeability score).

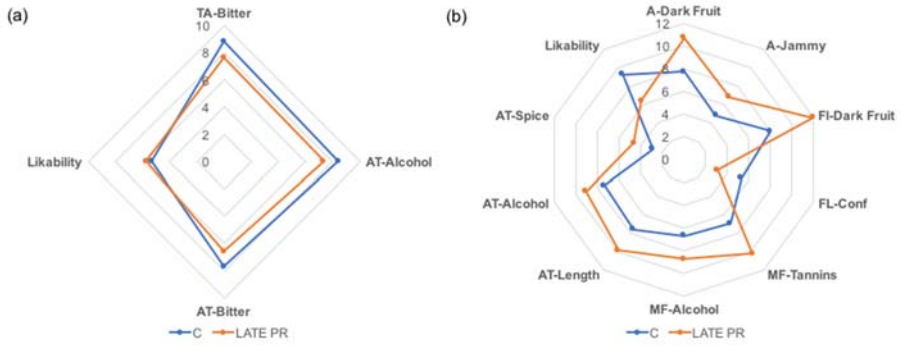


Figure 8.16: Radar plot of attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the wines of control (C) and late pruning (LatePR) in McLaren Vale in season 1(2013-14, (a)) and season 2 (2014-15, (b). Attributes: TA= taste, AT= After Taste, A= Aroma, FL= Flavour, MF= Mouthfeel.

Kicker canes

Four KC treatments were applied in S1 while in the subsequent two seasons only KUP and K+BT were still used since K DOWN and K EARLY were deemed commercially unsuitable for the McLaren Vale region (Table 8.21). The seasonal effect on the yield and yield components were significant, as such the results have been presented by season. In general, KC in S1 significantly reduced yield, the number of bunches per m of cordon and the pruning weight. The effect was greater when KC were removed late and were associated with BT. Similar to observations in the Coonawarra, in S2, probably due to an increased variability between plants induced by the use of KC, the yield was not statistically different between the various treatments. The number of bunches was lower for K+BT however no differences were observed in bunch weight and berry weight. The pruning weight was significantly reduced in all of the KC treatments. In S3, only K UP and K + BT were maintained as treatments and they significantly reduced yield and yield components compared to C. Berry weight however was not affected.

Table 8.21: Effect of kicker canes (KC) on yield and yield components of Shiraz grown in McLaren Vale applied for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Berry weight (g)	Pruning weight (kg)
2013-14	C	2.64 a	31.61 a	82.69	1.08	1.13 a
	K EARLY	2.38 ab	29.93 a	77.30	1.04	0.71 c
	K UP	1.72 bc	24.50 bc	71.04	1.01	0.69 c
	K DOWN	1.97 abc	26.49 ab	72.64	0.96	0.95 b
	K + BT	1.38 c	20.92 c	68.58	0.92	0.70 c
	P-value (T)	0.048	0.002	ns	ns	< 0.0001
2014-15	C	2.64	24.42 a	102.25	1.69	1.02 a
	K UP	1.78	19.44 ab	90.52	1.42	0.45 b
	K + BT	1.47	13.73 b	106.01	1.61	0.42 b
	P-value (T)	ns	0.003	ns	ns	0.000
2015-16	C	4.19 a	42.42 a	96.33 a	1.22	0.93 a
	K UP	1.84 b	33.36 b	54.80 b	0.96	0.42 b
	K + BT	1.39 b	20.08 c	68.54 b	1.02	0.43 b
	P-value (T)	0.000	< 0.0001	0.001	ns	0.000
	Season (S)	0.008	< 0.0001	0.000	< 0.0001	< 0.003
	SxT	0.004	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Canopy architecture was measured at six time points during the growing season 2013-14, corresponding to EL stages 15, 23 (flowering), 29, 33 (pea size), 35 (veraison) and 38 (harvest) (Figure 8.17). No significant differences were observed in LAI and Canopy Porosity until EL 31, which corresponds to when KC were removed, in all treatments but K EARLY, a drop in LAI and an increase in porosity compared to C was observed.

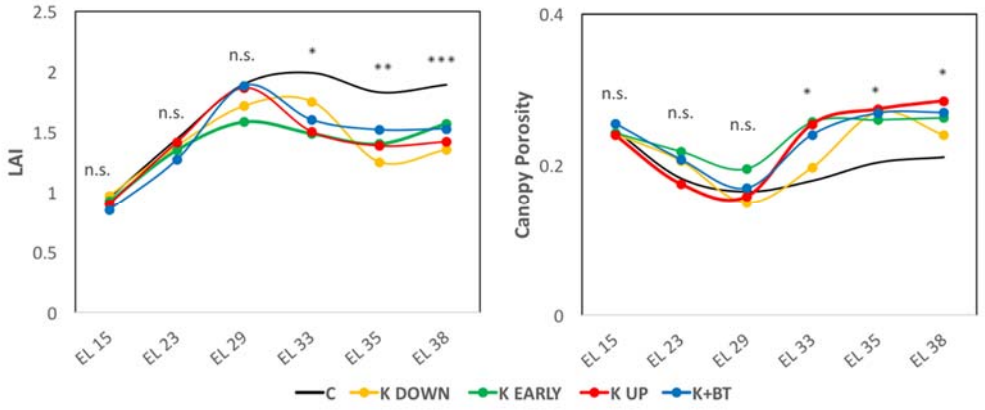


Figure 8.17: Effect of kicker canes in season 1 (2013-14) on canopy architecture (LAI and Canopy porosity) of Shiraz grown in McLaren Vale. C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K DOWN= four kicker canes per vine oriented downward and removed at EL 33-35, K EARLY= four kicker canes per vine oriented downward and removed at EL 21, K+BT= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot. Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Only two canopy architecture measurements were conducted in S2, at flowering (EL 23) and veraison (EL 35). C showed smaller canopies in EL 23 and bigger in EL 35 compared to K UP (Figure 8.18). No significant differences were found in canopy porosity (data not shown).

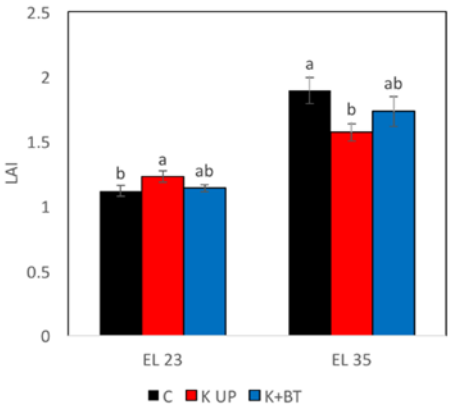


Figure 8.18: Effect of kicker canes in season 2 (2014-15) on leaf area index (LAI) of Shiraz grown in McLaren Vale. C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K+BT= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot. Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In S3 only K+BT and KUP were maintained as treatments since MLV management deemed K DOWN and K EARLY commercially unsuitable for the specific site. LAI and porosity were collected at EL 15,

23, 35 and 38. At EL 35 the KC were removed. The results show differences between KC and C in both LAI and porosity only at the time point when the kickers were removed (Figure 8.19).

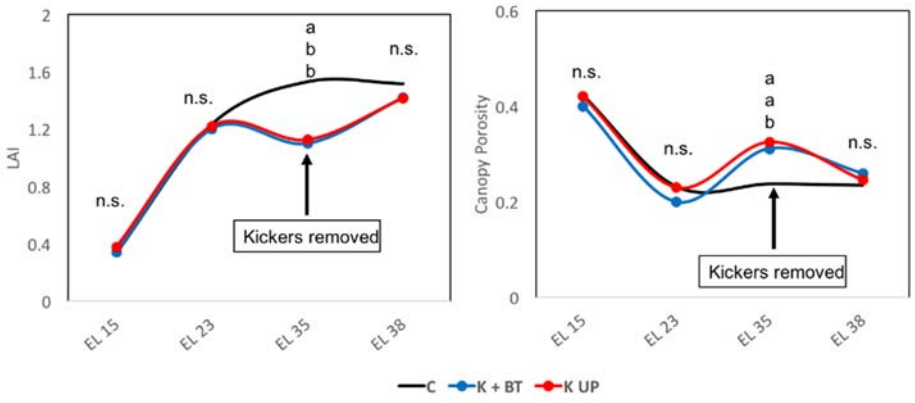


Figure 8.19: Effect of the use of kicker canes in season 3 (2015-16) on leaf area index (LAI) and canopy porosity of Shiraz grown in McLaren Vale. C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K+BT= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot.

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Since all treatments in the trial were harvested at the same time, not all of them had reached the targeted TSS of 26 °Brix. The highest TSS was measured in K+BT and the lowest in K EARLY (Table 8.22). pH results differed too, ranging from 3.56 to 3.48. No differences were observed for any of the other berry chemistry parameters. No differences in berry chemistry were observed in S2 and in S3 either, only the pH was higher in K UP compared to C and K + BT in S3.

Table 8.22: Effect of kicker canes (KC) on berry chemistry of Shiraz grown in McLaren Vale for three consecutive seasons (2013-14, 2014-15).

Season	Treatment (T)	TSS (Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Tannin (mg/g)	Iron Reactive Phenolics (mg/g)
2013-14	C	25.04 ab	3.56 a	4.67	2.15	3.02	9.00
	K EARLY	23.93 c	3.48 b	4.67	2.01	2.73	8.21
	K UP	24.63 b	3.51 ab	4.64	2.18	2.91	8.85
	K DOWN	24.82 ab	3.54 a	4.69	2.18	2.55	7.82
	K + BT	25.16 a	3.52 ab	4.58	1.99	2.97	8.34
	P-value (T)	0.000	0.021	ns	ns	ns	ns
2014-15	C	26.07	3.55	5.27	2.22	3.77	8.20
	K UP	26.22	3.54	5.88	2.05	3.72	8.23
	K + BT	26.87	3.59	5.22	2.15	3.55	7.95
	P-value (T)	ns	ns	ns	ns	ns	ns
2015-16	C	24.10	3.24 b	9.75	1.75	1.28	5.18
	K UP	23.23	3.37 a	8.96	1.68	1.27	4.94
	K + BT	23.13	3.28 b	9.00	1.73	1.30	5.24
	P-value (T)	ns	0.010	ns	ns	ns	ns
	Season (S)	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	SxT	ns	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In S1 no differences were observed in any of the wine chemistry analysed (Table 8.23). In S2 every alcohol was higher in C, pH was the lowest in K UP while TA was higher in K + BT; anthocyanins, phenolics and epicatechins were highest in C. No wines were made with KC treatments in S3.

Table 8.23: Effect of kicker canes (KC) on wine chemistry of Shiraz grown in McLaren Vale for two consecutive seasons (2013-14, 2014-15).

Season	Treatment (T)	Alcohol (%v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2013-14	C	14.48	3.51 b	6.22	234.79	44.37	-
	K EARLY	14.52	3.46 b	6.37	260.43	47.15	-
	K UP	14.53	3.50 b	6.4	259.00	45.2	-
	K + BT	14.93	3.58 a	6.16	271.49	48.27	-
	P-value (T)	ns	ns	ns	ns	ns	ns
2014-15	C	15.41 b	3.62 a	8.23 a	558.39 a	47.23 a	1886.03 a
	K UP	15.86 a	3.57 b	8.34 a	503.81 b	46.27 a	1482.73 ab
	K + BT	16.07 a	3.64 a	7.96 b	508.26 b	42.27 b	1124.53 b
	P-value (T)	0.001	0.013	0.001	0.001	0.001	0.019

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)

** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

Berry sensory analysis in S1 compared C, K UP and K+BT. Only four attributes were significantly different (Figure 8.20). Red fruit pulp flavour was higher for K + BT while the other three attributes (pulp and skin acidity and seed astringency) were higher in K UP. In S2 none of the assessed attributes were significantly different between treatments.

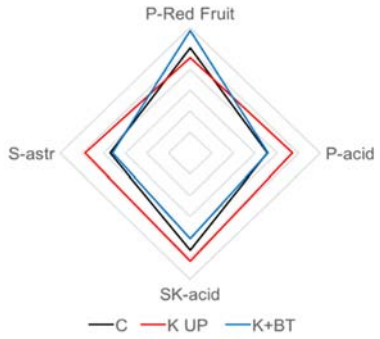


Figure 8.20: Radar plot of attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the berries from control and KC treatments in McLaren Vale in season 1 (2013-14). C= Control, K UP = kicker canes oriented upwards, K + BT= kicker canes oriented upwards and bunch thinning. Attributes: P= pulp, SK= skin, S= seed.

Wines were made from KC in S1 and S2 however no differences were detected during the descriptive analysis.

Barossa

Traditional canopy management

All the treatments had no significant effect on yield, bunch weight and pruning weight in any of the seasons (Table 8.24). In S1 and S2 the number of bunches was lower in BT. In S2, ST also had significantly lower bunches than C. In S3 the bunch number was higher in LP. The number of canes per m was the lowest in ST, as expected, in S1 and S2 however no differences were observed in S3.

Table 8.24: Effect of the use of canopy management treatments (C= control, ET= early trimming on the eastern side of the canopy, ST= Shoot Thinning, LP=Leaf Plucking and BT= Bunch Thinning) on yield and yield components of Shiraz grown in Barossa during three consecutive seasons (2013-14, 2014-15, 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Pruning weight (kg)	Cane/m (#)
2013-14	C	2.42	48.61 a	49.85	0.41	24.93 bc
	ET	2.75	47.95 a	58.41	0.42	27.49 a
	ST	2.30	42.82 a	54.49	0.45	23.84 c
	LP	2.16	47.83 a	46.35	0.43	26.45 ab
	BT	2.10	33.39 b	74.27	0.46	25.80 abc
	P-value (T)	ns	0.000	ns	ns	0.025
2014-15	C	1.76	32.29 ab	54.83	0.48	22.89 a
	ET	1.99	31.62 ab	61.36	0.41	25.39 a
	ST	1.53	27.60 bc	56.04	0.42	19.58 b
	LP	1.64	34.52 a	47.10	0.42	25.39 a
	BT	1.46	25.40 c	58.06	0.46	23.98 a
	P-value (T)	ns	0.010	ns	ns	0.006
2015-16	C	1.80	36.61 b	51.32	0.42	24.27
	ET	2.53	36.83 b	70.27	0.50	25.02
	ST	1.69	33.73 b	51.34	0.43	20.67
	LP	1.93	49.37 a	40.59	0.42	27.25
	BT	2.01	32.22 b	64.54	0.49	24.20
	P-value (T)	ns	ns	ns	ns	ns
	Season (S)	<0.0001	< 0.0001	ns	ns	0.003
	S x T	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Canopy architecture was only measured in S3 at three phenological stages: EL 23 (Flowering), EL 35 (veraison) and EL 38 (harvest), however no differences were observed between treatments (Figure 8.21).

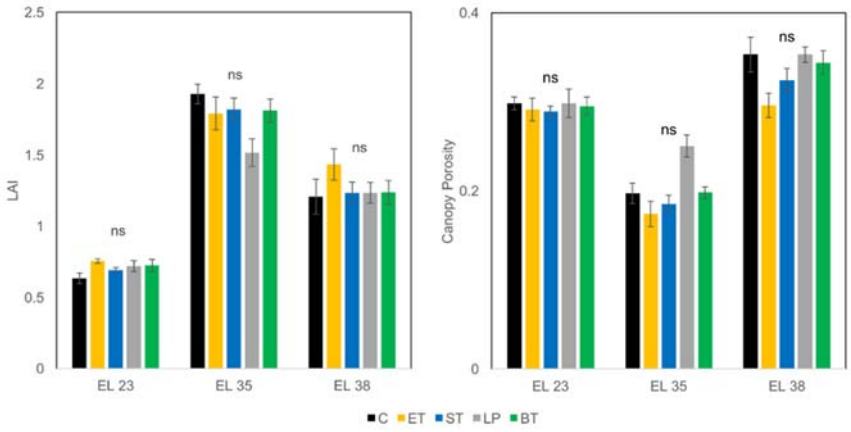


Figure 8.21: Effect of the use of canopy management treatments (C= control, ET= Early Trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking and BT= Bunch Thinning) on canopy architecture (LAI and Canopy Porosity) of Shiraz grown in Barossa in 2015-16.

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Berry chemistry measures of TSS, pH and TA at harvest did not show differences for the three seasons (Table 8.25). Differences were observed in S1 with both phenolic and tannin content in the berries, being significantly lower in C compared to the other treatments. Tannins were also low in LP. In S2 no differences were observed while in S3 anthocyanins and phenolics were the lowest in C.

Table 8.25: Effect of the use of canopy management treatments (C= Control, ET= early trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking and BT= Bunch Thinning) on berry chemistry measurements of Shiraz grown in Barossa for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	TSS (°Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Iron Reactive Phenolics (mg/g)	Tannin (mg/g)
2013-14	C	24.53	3.73	5.80	1.66	10.55 b	3.09 c
	ET	24.31	3.70	5.87	1.67	11.77 ab	3.85 a
	ST	24.28	3.72	5.82	1.77	12.27 a	3.78 ab
	LP	24.34	3.73	5.65	1.75	11.41 ab	3.39 bc
	BT	24.50	3.72	5.80	1.74	11.16 ab	3.51 abc
	P-value (T)	ns	ns	ns	ns	0.04	0.011
2014-15	C	28.06	3.82	9.38	1.76	11.73	5.70
	ET	30.73	4.17	9.10	1.71	11.51	5.69
	ST	29.94	4.06	9.39	1.80	12.57	6.06
	LP	28.44	3.89	9.11	1.54	12.65	5.94
	BT	31.73	4.27	8.95	1.62	12.15	5.89
	P-value (T)	ns	ns	ns	ns	ns	ns
2015-16	C	25.39	3.50	6.88	1.86 b	8.50 b	3.44
	ET	24.69	3.48	7.70	1.87 ab	8.74 ab	3.29
	ST	24.81	3.49	7.53	1.96 ab	9.54 a	3.59
	LP	24.499	3.48	7.75	2.05 a	9.41 ab	3.40
	BT	25.07	3.48	7.82	2.04 a	9.23 ab	3.27
	P-value (T)	ns	ns	ns	0.03	0.04	ns
	Season (S)	< 0.0001	< 0.0001	< 0.0001	0.000	< 0.0001	< 0.0001
	S x T	0.004	0.001	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In the last season of the trial, wines were also made from all treatments. When wine chemistry was measured only the total anthocyanins and phenolics concentration was different between treatments, in particular both these compounds were lower in ET and ST which is not in line with what was observed in the berries (Table 8.25).

Table 8.25: Effect of the use of canopy management treatments (C= control, ET= early trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking and BT= Bunch Thinning) on wine chemistry measurements of Shiraz grown in Barossa in 2015-16.

Season	Treatment (T)	Alcohol (% v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2015-16	C	14.94	4.11	8.94	674.71 ab	59.49 ab	1327
	ET	14.88	4.12	8.91	600.18 c	52.18 c	1106
	ST	14.73	4.18	9.06	636.12 bc	55.07 bc	1122
	LP	14.96	4.11	8.90	687.45 a	60.62 a	1473
	BT	15.03	4.23	8.93	681.86 ab	59.03 ab	1311
	P-value	ns	ns	ns	0.008	0.008	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)

** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

Berries were evaluated by a panel of assessors for their sensory characteristics and only three attributes were found to be different between treatments. The PCA plot in Figure 8.22 shows that 93.58% of the variability is explained by PC1 which mostly separates C from ST and LP (which group together) for green flavour of the pulp, more prominent in ST and LP and seed characteristics; seeds from C were darker and crushed more easily compared to those of ST and LP.

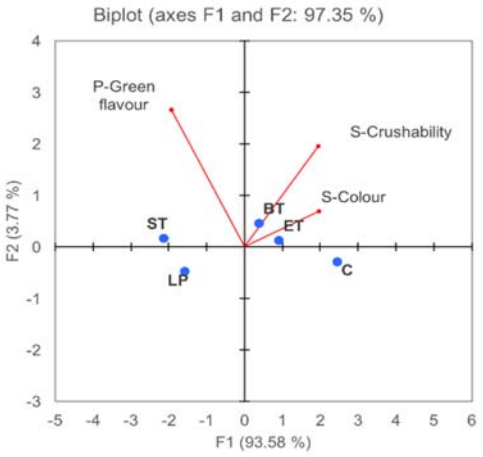


Figure 8.22: Principal component analysis of the attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the berries from different canopy management treatments in the Barossa trial in season 3 (2015-16). C= Control, ET= early trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking and BT= Bunch Thinning. Attributes: P= pulp, S= seeds.

Wine descriptive analysis did not find any differences between treatments except for the intensity of pepper flavour which was greater in LP compared to all other treatments (data not shown).

Kicker Canes

The use of different KC treatments produced some significant differences compared to C only in S1 and were mostly related to K DOWN, which was applied only in this first season. Yield was different, and lower than C, for K DOWN, so was the number of bunches per m. This latter measure was also different in K UP compared to C. Bunch weight was the same in all treatments while pruning weight was lower in K EARLY and K UP compared to C; the number of canes per m was the highest in C (Table 8.26).

Table 8.26: Effect of the use of kicker canes (KC) (C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K EARLY= four kicker canes per vine oriented downward and removed at EL 21, KDOWN= four kicker canes per vine oriented downward and removed at EL 33-35) applied for three consecutive seasons (2013-14, 2014-15 and 2015-16) on yield and yield components of Shiraz grown in Barossa.

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Pruning weight (kg)	Cane/m (#)
2013-14	C	2.42 a	48.61 a	49.85	0.41 a	24.93 a
	K EARLY	2.17 ab	43.01 ab	49.61	0.29 bc	18.80 b
	K UP	1.78 ab	40.64 b	43.56	0.24 c	19.75 b
	K DOWN	1.49 b	33.78 c	44.16	0.35 ab	18.91 b
	P-value (T)	0.04	0.001	ns	0.001	<0.0001
2014-15	C	1.61	29.58	53.54	0.48	21.88
	K EARLY	0.93	26.56	35.20	0.27	18.60
	K UP	1.18	29.07	40.76	0.23	22.03
	P-value (T)	ns	ns	ns	ns	ns
2015-16	C	1.80	36.61	51.32	0.42	24.27
	K EARLY	1.26	32.59	39.36	0.30	19.75
	K UP	1.51	36.28	42.24	0.30	19.60
	P-value (T)	ns	ns	ns	ns	ns
	Season (S)	<0.0001	<0.0001	ns	ns	ns
	S x T	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Canopy architecture measured in S3 showed a reduction in LAI at EL 35 and 38 when KC were used while no differences were measured in canopy porosity (Figure 8.23).

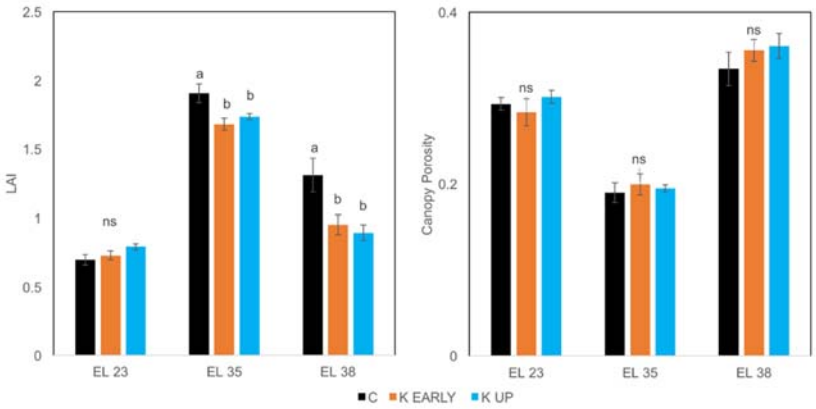


Figure 8.23: Effect of the use of kicker canes in season 3 (2015-16) on canopy architecture (LAI and Canopy porosity) of Shiraz grown in Barossa. C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K EARLY= four kicker canes per vine oriented downward and removed at EL 21.

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant**.**

Berry chemistry measured for three seasons only showed a significant difference in total tannins in S1 and S3. In S1 tannins were highest in K DOWN followed by K EARLY while in S3 K EARLY showed the lowest content (Table 8.27).

Table 8.27: Effect of the use of kicker canes (KC) (C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K EARLY= four kicker canes per vine oriented downward and removed at EL 21, K DOWN= four kicker canes per vine oriented downward and removed at EL 33-35) for three consecutive seasons (2013-14, 2014-15 and 2015-16) on berry chemistry of Shiraz grown in Barossa.

Season	Treatment (T)	TSS (Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Iron Reactive Phenolics (mg/g)	Tannin (mg/g)
2013-14	C	24.53	3.73	5.80	1.66	10.55	3.09 b
	K EARLY	24.00	3.76	5.62	1.66	10.96	3.37 ab
	K UP	24.69	3.71	5.83	1.66	10.73	3.15 b
	K DOWN	24.94	3.74	5.50	1.81	12.05	3.71 a
	P-value (T)	ns	ns	ns	ns	ns	0.009
2014-15	C	28.12	3.83	9.37	1.75	11.74	5.70
	K EARLY	25.26	4.06	8.90	1.47	12.53	5.96
	K UP	30.34	3.67	9.75	1.64	12.22	5.97
	P-value (T)	ns	ns	ns	ns	ns	ns
2015-16	C	25.39	3.50	6.88	1.86	8.50	3.44 a
	K EARLY	25.20	3.47	7.60	1.81	8.52	2.93 b
	K UP	25.32	3.50	7.28	1.93	8.55	3.22 a
	P-value (T)	ns	ns	ns	ns	ns	0.012
	Season (S)	<0.0001	<0.0001	<0.0001	0.001	<0.0001	<0.0001
	S x T	0.000	0.045	0.032	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Effect of late pruning

Late pruning was applied only in S2 and it significantly reduced the number of bunches per m and increased bunch weight compared to C (Table 8.28). Interestingly all fruit was harvested on the same day meaning that the late pruning treatment was not effective at delaying harvest date.

Table 8.28: Effect of late pruning (LatePR) carried out in season 2014-15 on yield, yield components and berry chemistry of Shiraz grown in Barossa.

	C	LatePR	P-value
Yield/m (kg)	1.75	1.47	ns
Bunch/m (#)	32.69 a	20.39 b	0.000
Bunch weight (g)	54.98 b	71.31 a	0.043
Pruning weight (kg)	0.48	0.50	ns
Cane/m (#)	22.98	21.42	ns
TSS (Brix)	28.14	28.01	ns
pH	3.83	3.79	ns
TA (g/L)	9.36	9.66	ns
Total Anthocyanins	1.75	1.64	ns
Iron Reactive Phenolics	11.75	10.72	ns
Tannins	5.70	5.10	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test ($P \leq 0.05$). ns= not statistically significant.

Padthaway

Traditional canopy management

Significant differences between treatments were evident from S1; yield was reduced in all treatments apart from LP. The lowest crop was harvested from the BT followed by Complete CC; these were also the treatments with the lowest number of bunches. The heaviest bunches were found in C while ET had the lightest. Berry weight was higher in C while ET, ST and BT were significantly smaller. Surprisingly, the pruning weight was the highest in Complete CC while the cane number per m was very different between treatments with the highest in C and the smallest in BT and ST. In S2 yield and bunch number were lower in Complete CC followed by BT compared to C, as in S1. No differences were found in bunch weight while berry weight, on average, was lower than in S1 with the smallest berries found in ST. C, ST and Complete CC had higher pruning weight compared to the other treatments (Table 8.29).

The yield in C in all three seasons was very consistent and the highest out of all treatments. In S3, as shown in the previous two seasons, yield was significantly lower in BT and Complete CC which, again, also produced the smallest berries. Small berries were also found in ST in S3. Bunch weight for C was similar to the previous seasons while for Complete CC, it was lower and the lowest in the trial, followed by LP. The heaviest berries were harvested from BT and the smallest from LP. The pruning weight was different between C and all the other treatments where it was significantly reduced. The number of canes per m was the highest in LP and lowest in Complete CC (Table 8.29).

Table 8.29: Effect of the use of canopy management treatments (ET= early trimming on the eastern side of the canopy, ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and Complete CC= cover crop in the mid row and under vine) on yield and yield components of Shiraz grown in Padthaway during three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Berry weight	Pruning weight (kg)	Cane/m (#)
2013-14	C	3.26 a	56.55 a	62.85 a	0.99 a	0.58 b	37.34 a
	ET	1.99 cd	47.51 a	41.89 c	0.86 b	0.54 b	29.61 bc
	ST	2.41 bc	52.76 a	44.98 bc	0.86 b	0.69 ab	25.78 d
	LP	3.03 ab	51.73 a	58.27 ab	0.90 ab	0.62 b	27.57 cd
	BT	1.19 e	18.73 b	56.07 abc	0.82 b	0.59 b	25.60 d
	Complete CC	1.41 de	25.11 b	56.71 abc	0.92 ab	0.78 a	32.32 b
	P-value (T)	0.000	0.000	0.000	0.030	0.041	0.026
2014-15	C	3.15 a	48.65 a	64.49 a	0.77 a	0.61 a	34.07 a
	ET	2.59 abc	40.04 ab	64.03 a	0.70 bc	0.36 b	31.96 ab
	ST	2.65 ab	42.64 a	61.50 a	0.68 c	0.54 a	30.00 b
	LP	2.47 abc	41.95 a	56.26 a	0.74 abc	0.49 ab	32.27 ab
	BT	2.14 bc	31.87 bc	63.50 a	0.76 ab	0.48 ab	29.95 b
	Complete CC	1.73 c	27.14 c	66.23 a	0.75 ab	0.51 a	31.42 ab
	P-value (T)	0.045	0.000	ns	0.028	0.029	ns
2015-16	C	3.28 a	57.33 ab	60.39 a	0.73 abc	0.71 a	31.19 bc
	ET	3.14 ab	64.33 a	49.26 ab	0.74 ab	0.32 c	35.23 ab
	ST	2.63 abc	51.69 b	52.14 ab	0.77 ab	0.54 ab	32.83 abc
	LP	2.62 abc	59.16 ab	44.08 b	0.65 c	0.49 b	37.03 a
	BT	2.55 bc	49.77 b	52.07 ab	0.79 a	0.48 b	32.91 abc
	Complete CC	1.96 c	47.41 b	41.15 b	0.70 bc	0.40 bc	30.45 c
	P-value (T)	0.009	0.055	0.083	0.017	0.001	0.045
	Season (S)	0.002	< 0.0001	0.000	< 0.0001	< 0.0001	< 0.0001
	S x T	0.011	0.001	ns	ns	< 0.0001	< 0.0001

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Canopy architecture was measured at flowering (EL 23), veraison (EL 35) and harvest (EL 38) but only in S3. Differences between treatments were found only for LAI at veraison, which was the highest in BT followed by C. ST, LP and Complete CC had very similar LAI throughout the whole season while LAI in ET was the lowest (Figure 8.24).

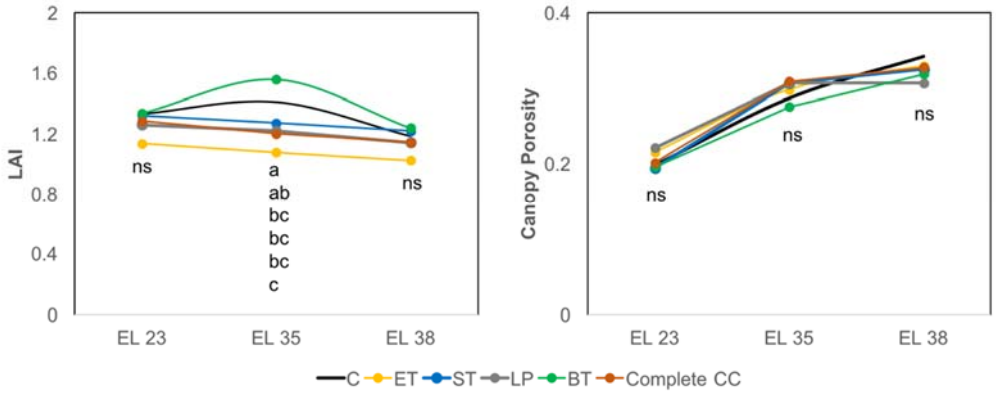


Figure 8.24: Effect of the use of canopy management treatments (C= control, ET= Early Trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and Complete CC= cover crop in the mid row and under vine) on canopy architecture (LAI and Canopy Porosity) of Shiraz grown in Padthaway in 2015-16.

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant**.**

Berry maturity measures (TSS, pH and TA) were different only in S2 when pH results were significantly higher in Complete CC compared to C, all other treatments were similar to C (Table 8.30). TA was similar in all treatments compared to C however, differences were observed amongst treatments with the highest TA measured in ET while the lowest in Complete CC. In S1 berry anthocyanins, phenolics and tannins were the lowest in the Complete CC. Also, compared to C, the anthocyanins were significantly lower in LP, the phenolics in ST while tannins were higher in LP and BT.

Table 8.30: Effect of the use of canopy management treatments (ET= early trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and Complete CC= cover crop in the mid row and under vine) on berry chemistry measurements of Shiraz grown in Padthaway for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	TSS (°Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Iron Reactive Phenolics (mg/g)	Tannins (mg/g)
2013-14	C	22.24	3.31	5.72	2.34 a	9.16 a	2.75 bc
	ET	23.23	3.38	5.37	2.13 ab	8.75 ab	2.91 ab
	ST	22.92	3.35	5.48	2.01 ab	7.65 bc	2.41 cd
	LP	23.20	3.35	5.50	1.82 b	9.05 a	3.21 a
	BT	23.49	3.41	5.02	2.33 a	9.46 a	3.22 a
	Complete CC	22.15	3.39	4.88	1.97 b	6.84 c	2.23 d
	P-value (T)	ns	ns	ns	0.017	0.003	< 0.0001
2014-15	C	25.75	3.31 bc	6.12 abc	1.98	9.58	2.19
	Early Trim	24.96	3.26 c	6.57 a	2.18	9.68	2.32
	ST	26.18	3.39 ab	5.78 bc	2.00	9.81	2.23
	LP	25.48	3.29 c	6.36 ab	2.18	9.44	2.28
	BT	25.67	3.30 bc	6.32 ab	2.18	9.68	2.15
	Complete CC	26.42	3.44 a	5.67 c	2.15	10.28	2.17
	P-value (T)	ns	0.003	0.031	ns	ns	ns
2015-16	C	23.14	3.24	5.87	1.95	8.85	3.09
	Early Trim	22.51	3.22	5.80	1.72	8.56	2.99
	ST	23.02	3.23	5.83	1.88	8.46	2.89
	LP	23.12	3.22	5.67	1.88	9.24	3.19
	BT	22.84	3.22	6.00	2.00	9.05	3.20
	Complete CC	22.46	3.22	5.58	2.13	8.88	2.91
	P-value (T)	ns	ns	ns	ns	ns	ns
	Season (S)	< 0.0001	< 0.0001	< 0.0001	0.000	< 0.0001	< 0.0001
	S x T	0.004	0.028	0.323	0.001	0.005	0.001

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In the last season of the trial, wines were also made from all treatments and the wine chemistry results for alcohol, pH and phenolics were significantly different for the ET compared to C (Table 8.31). No other differences between treatments were observed.

Table 8.31: Effect of the use of canopy management treatments (ET= early trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and Complete CC= cover crop in the mid row and under vine) on wine chemistry measurements of Shiraz grown in Padthaway in 2015-16.

Season	Treatment (T)	Alcohol (%v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2015-16	C	14.80 a	3.96 a	9.06	559.44	47.58 ab	1094.72
	Early Trim	13.79 b	3.79 b	9.14	501.86	42.91 b	935.31
	ST	14.83 a	3.95 a	8.97	577.62	49.75 a	1138.28
	LP	14.66 a	3.89 ab	9.29	597.03	52.64 a	1282.84
	BT	15.00 a	3.87 ab	9.34	577.07	50.38 a	1393.40
	Complete CC	15.07 a	3.95 a	9.20	591.14	52.32 a	1338.83
	P-value (T)	0.023	0.044	ns	ns	0.018	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.
*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)
** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

Berry sensory assessment (BSA) did not show differences between samples while some differences were found when wines were subjected to descriptive analysis (DA). In particular, the PCA plot in Figure 8.25 shows that most of the variation (87%) is explained by the first two principal components. The main source of variation in the data set is related to differences in the alcohol aftertaste and overall length between C, LP and BT, which group together (very similar sensorial characteristics), and ET and, to a less extent ST. C, LP and BT were also associated with pepper flavour (FL-Pepper). PC 2, which explains 18.5% of the variability is related to Complete CC which was perceived as having a more intense jammy flavour and was the most liked wine overall.

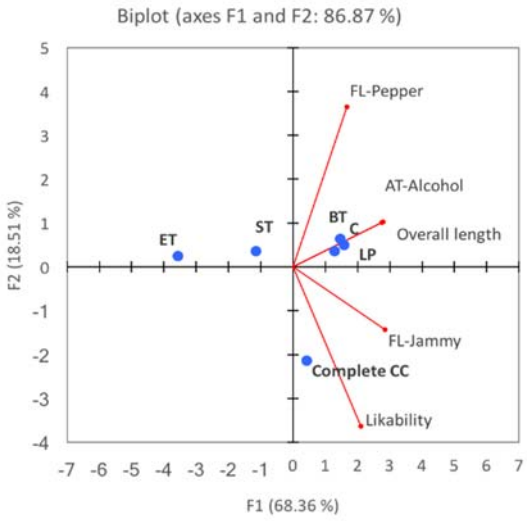


Figure 8.25: Principal component analysis of the attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the wines from two canopy management treatments in the Padthaway trial in season 3 (2015-16). C= Control, Early Trim= early trimming on the eastern side, ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and Complete CC= cover crop in the mid row and under vine. Attributes: FL= flavour, AT= After Taste.

Kicker Canes

In all three seasons KC reduced yield compared to C with the exception of K EARLY in S1. KUP, in general, reduced yield most significantly. In S1 the number of canes per m was also lower in all KC treatments compared to C (Table 8.32).

The number of bunches per m was different between C and KC treatments only in S2 where it was lower for all KC treatments and for K+BT in particular. Bunch weight was highly influenced by the use of KC in S2 when it was very low in K EARLY; in S3 all KC treatments had lower bunch weights compared to C. Berry weight was lower in K UP and K + BT both in S2 and S3 compared to C while K Early did not show differences with C. Pruning weight and the number of canes per m were significantly reduced when KC were used both in S2 and S3 (Table 8.32).

Table 8.32: Effect of the use of kicker canes (KC) (C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K EARLY= four kicker canes per vine oriented downward and removed at EL 21, K+BT= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot) on yield and yield components of Shiraz grown in Padthaway on yield and yield components of Shiraz grown in Padthaway applied for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Berry weight	Pruning weight (kg)	Cane/m (#)
2013-14	C	3.26 a	56.55	62.85	0.99	0.58	37.34 a
	K EARLY	2.46 ab	46.70	50.56	0.86	0.43	24.96 b
	K UP	1.89 b	43.74	44.45	0.82	0.51	27.37 b
	K + BT	2.29 b	48.72	46.43	0.89	0.45	25.10 b
	P-value (T)	0.033	ns	ns	ns	ns	< 0.0001
2014-15	C	3.15 a	48.62 a	61.16 ab	0.77 a	0.61 a	34.08 a
	K EARLY	1.89 b	34.45 b	47.44 c	0.79 a	0.28 b	26.64 b
	K UP	1.89 b	35.46 b	59.05 bc	0.72 b	0.30 b	25.83 bc
	K + BT	1.46 b	26.82 c	70.98 a	0.73 b	0.28 b	22.92 c
	P-value (T)	0.006	0.001	0.026	0.001	0.000	0.000
2015-16	C	3.28 a	57.37	60.38 a	0.73 ab	0.70 a	31.20 a
	K EARLY	1.86 bc	42.29	43.38 b	0.78 a	0.32 b	27.03 b
	K UP	1.44 c	38.63	38.29 b	0.66 b	0.28 b	24.78 b
	K + BT	2.15 b	50.95	42.73 b	0.66 b	0.30 b	26.70 b
	P-value (T)	0.001	ns	0.03	0.006	0.01	0.01
	Season (S)	ns	0.000	0.032	< 0.0001	< 0.0001	0.02
	S x T	ns	ns	ns	0.047	<0.001	0.000

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

LAI was different only at EL 12 when it was lower for C; canopy architecture was not significantly different when measured at the other phenological stages (Figure 8.26).

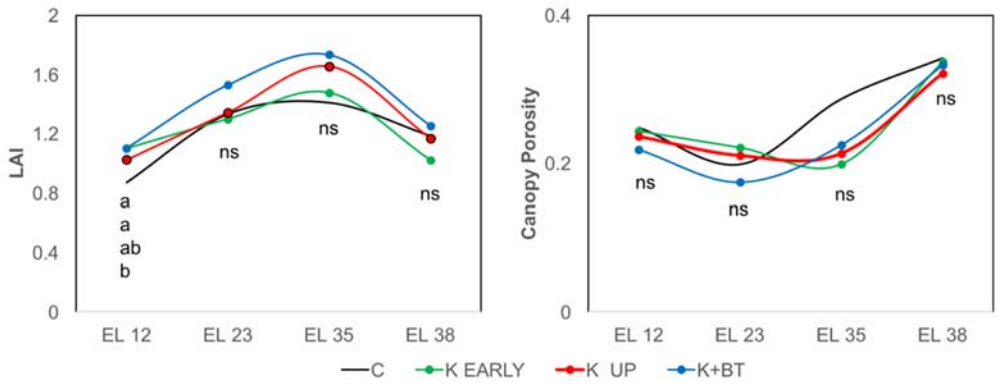


Figure 8.26: Effect of the use of kicker canes in season 3 (2015-16) on canopy architecture (LAI and Canopy porosity) of Shiraz grown in Padthaway. C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K EARLY= four kicker canes per vine oriented downward and removed at EL 21, K+BT= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot. Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Berry chemistry measures were mostly not significantly different between KC and C in the three seasons. Only the tannin content in S1 was higher for K + BT and lower for K UP compared to C while in S3 the anthocyanin content was significantly lower in K EARLY compared to all other treatments (Table 8.33).

Table 8.33: Effect of the use of kicker canes (KC) (C= control, K UP= four kicker canes per vine oriented upward and removed at EL 33, K EARLY= four kicker canes per vine oriented downward and removed at EL 21, K+BT= four kicker canes per vine oriented upward and removed at EL 33-35 with added bunch thinning by leaving one bunch per count shoot) on berry chemistry of Shiraz grown in Padthaway for three consecutive seasons (2013-14, 2014-15 and 2015-16).

Season	Treatment (T)	TSS (Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Iron Reactive Phenolics (mg/g)	Tannin (mg/g)
2013-14	C	22.24	3.31	5.72	2.34	9.16	2.75 b
	K EARLY	22.95	3.30	5.57	2.10	8.48	2.65 bc
	K UP	22.87	3.30	5.53	1.97	7.89	2.45 c
	K + BT	23.12	3.37	5.38	1.99	8.85	3.05 a
	P-value (T)	ns	ns	ns	ns	ns	0.002
2014-15	C	25.75	3.31	6.17	1.98	9.58	2.19
	K EARLY	25.35	3.31	6.33	1.91	9.69	2.17
	K UP	26.40	3.35	5.93	2.03	9.89	2.27
	K + BT	25.91	3.32	6.08	2.34	10.25	2.32
	P-value (T)	ns	ns	ns	ns	ns	ns
2015-16	C	23.15	3.24	5.87	1.95 a	8.86	3.09
	K EARLY	22.74	3.22	5.70	1.71 b	8.32	2.79
	K UP	23.57	3.26	5.38	1.98 a	9.07	2.97
	K + BT	23.51	3.26	5.58	2.01 a	8.75	2.96
	P-value (T)	ns	ns	ns	0.037	ns	ns
	Season (S)	<0.0001	0.001	0.006	0.013	0.001	<0.0001
	S x T	ns	ns	ns	0.01	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Effect of late pruning

Late pruning was applied for two consecutive seasons, 2014-15 and 2015-16 and in both of them it significantly reduced yield, the number of bunches per m and bunch weight while berry weight was not affected. Pruning weight was lower in LatePR only in S1 (Table 8.34).

Table 8.34: Effect of late pruning (LatePR) on yield and yield components of Shiraz grown in Padthaway for two consecutive seasons (2014-15 and 2015-16).

Season	Treatment (T)	Yield/m (kg)	Bunch/m (#)	Bunch weight (g)	Berry weight (g)	Pruning weight (kg)
2014-15	C	3.14 a	48.60 a	64.35 a	0.77	34.06 a
	Late Pr	0.92 b	25.23 b	35.74 b	0.76	26.49 b
	P-value (T)	< 0.0001	< 0.0001	0.000	ns	0.006
2015-16	C	3.28 a	57.50	60.25 a	0.73	31.11
	Late Pr	1.54 b	50.68	30.27 b	0.72	38.22
	P-value (T)	0.000	ns	0.001	ns	ns
	Season (S)	ns	0.000	ns	ns	0.008
	SxT	ns	0.048	ns	ns	<0.0001

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

LAI was measured in 2015-16 and it was significantly lower in LatePR compared to C at EL 23 and EL 35 while by El 38 (harvest) the Late PR canopy fully grew to the C level. No differences were observed in canopy porosity (Figure 8.27).

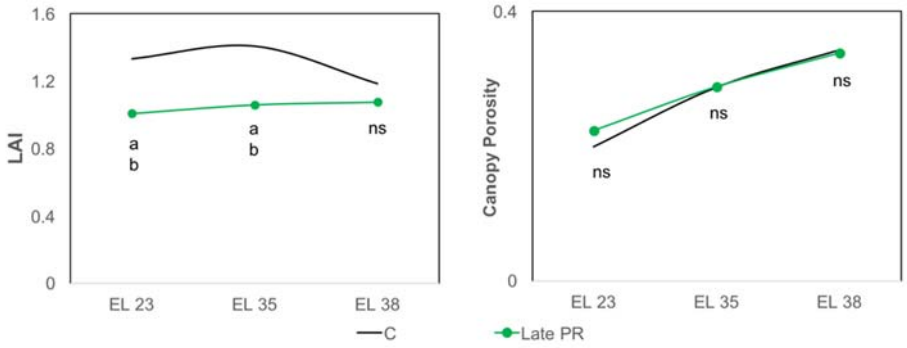


Figure 8.27: Leaf area index and Canopy porosity measured at El 23 (flowering) and El 35 (veraison) and EL #8 (harvest) for the control (C) and the late pruning (LatePR) treatments in 2015-16. Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

In S1, only TA was affected by LatePR, when it was lower compared to C. In S2, TSS and pH were higher while TA was lower in Late PR compared to C while anthocyanins, phenolics and tannins were again unaffected (Table 8.35).

Table 8.35: Effect of Late Pruning (LatePR) on berry chemistry of Shiraz grown in Padthaway in seasons 2014-15 and 2015-16.

Season	Treatment (T)	TSS (°Brix)	pH	TA (g/L)	Anthocyanin (mg/g)	Iron Reactive Phenolics (mg/g)	Tannin (mg/g)
2014-15	C	26.38	3.31	6.17 a	1.98	9.60	2.19
	Late Pr	25.05	3.34	5.30 b	2.18	8.94	2.12
	P-value (T)	ns	ns	0.003	ns	ns	ns
2015-16	C	23.13 b	3.24 b	5.87 a	1.95	8.87	3.09
	Late Pr	27.85 a	3.53 a	4.51 b	2.17	8.65	3.12
	P-value (T)	< 0.0001	< 0.0001	0.001	ns	ns	ns
	Season (S)	ns	0.017	0.02	ns	ns	<0.0001
	SxT	<0.0001	<0.0001	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Wines were made from the LatePR treatment in S3 and higher alcohol content, anthocyanin, phenolic and tannin (epicatechins equivalents) concentrations were found compared to C (Table 8.36).

Table 8.36: Effect of late pruning (LatePR) on wine chemistry of Shiraz grown in McLaren Vale in the 2015-16 season.

Season	Treatment (T)	Alcohol (%v/v)	pH	TA (g/L)	Total Anthocyanins * (mg/L)	Phenolics * (au)	Total tannins ** (mg/L)
2015-16	C	14.80 b	3.96	9.06	559.44 b	47.58 b	1094.72 b
	LatePR	17.59 a	4.10	9.34	790.75 a	68.35 a	1822.88 a
	P-value (T)	0.002	ns	ns	0.004	0.000	0.001

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.
*Determined by the modified Somers assay (Mercurio et al. 2007) expressed as absorbance units (au)
** Determined by the MCP tannin assay (Mercurio et al. 2007) expressed as mg of epicatechin units per L.

When submitted to a panel of assessors for sensory analysis the results from the berries of LatePR were very different from C (Figure 8.28). LatePR was associated with higher dark fruit and jammy flavours and an overall higher flavour intensity. The pulp was sweeter but less acidic. The skins tasted less green

and astringent. The seeds were darker, they crushed more easily when chewed and they were less astringent. Overall the assessors like better the LatePR berries.

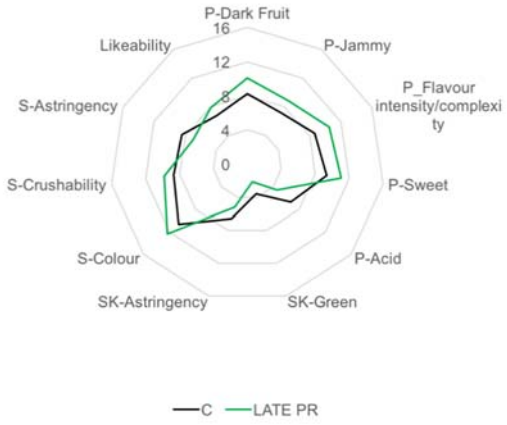


Figure 8.28: Radar plot of significantly different attributes at P ≤ 0.1 by a panel of 12 assessors in the berries of control (C) and late pruning (LatePR) in McLaren Vale in season 2015-16. P= flavour of the pulp, SK = flavour of the skin, S= characteristics of the seeds.

Similar to what was observed for the berries, the results of the wines from C and LatePR were different for many attributes when submitted to descriptive analysis. LatePR scored higher for all the attributes shown in Figure 8.29 and it was also the most liked wine.

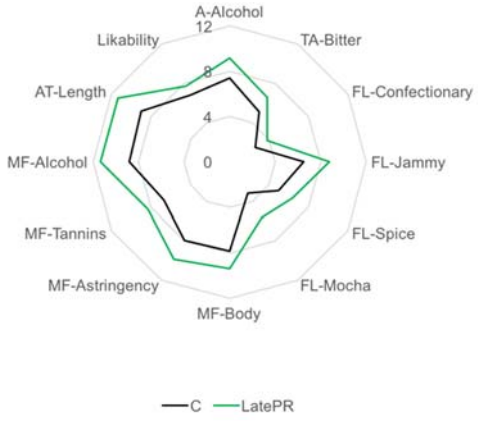


Figure 8.29: Radar plot of significantly different attributes at P ≤ 0.1 by a panel of 12 assessors in the wines of control (C) and late pruning (LatePR) in Padthaway in season 1(2013-14, (a)) and season 2 (2014-15, (b). Attributes: TA= taste, AT= After Taste, A= Aroma, FL= Flavour, MF= Mouthfeel.

Vine balance indices

Vine balance indices were calculated for all the trials and treatments as shown in Table 8.37. The traditional yield/pruning weight (Y/P) ratio measure, also known as Ravaz index, was compared to new indices computed using the LAI measures generated by the VitiCanopy App. In general, for all trials and sites Y/P varied from 9.93 to 1.66. The highest ratios of Y/P were measured in the Padthaway trial with a range of 9.93 to 5.08. The other trials all showed lower indices with ranges of 5.38-3.94 in Barossa, 2.65-1.72 in Coonawarra and 4.98-2.10 in McLaren Vale. The range of Y/LAI was narrower than the Y/P for all phenological stages and trials varying from 3.34 to 0.58. The Coonawarra trial showed the lowest variation of the indices especially when the late season LAI values are considered, confirming the small differences already discussed in yield and LAI between treatments. Of the Y/LAI indices, the one computed using the EL 23 LAI measure presented the widest range of values while the EL 35 measures showed the narrowest range.

Table 8.37: Average vine balance indices shown as the ratios of yield/pruning weight (Y/P) and yield/leaf area index (Y/LAI) calculated for the three phenological stages of flowering (EL 23), veraison (EL35) and harvest (EL 38). Each trial is reported separately and the indices per each treatment are an average of three seasons for the Coonawarra and McLaren Vale and one season for Barossa and Padthaway.

	Y/P	Y/LAI EL 23	Y/LAI EL 35	Y/LAI EL 38
		Coonawarra		
C	2.64	1.40	1.36	1.60
ST	2.65	1.56	1.60	1.67
LP	1.84	0.98	1.19	1.31
BT	1.72	1.03	1.08	1.29
K+BT	1.82	0.57	1.04	1.08
K DOWN	2.23	0.58	0.94	1.15
K EARLY	2.61	1.32	1.21	1.49
K UP	2.34	1.27	1.22	1.63
		McLaren Vale		
C	3.09	2.55	1.84	2.05
ST	2.84	2.86	1.54	1.72
LP	2.81	2.23	1.84	2.02
CC	2.10	1.93	1.18	1.49
Complete CC	4.98	2.50	1.81	1.91
K+BT	3.02	1.18	1.00	0.93
K DOWN	2.14	1.40	1.55	1.43
K EARLY	3.64	1.82	1.68	1.53
K UP	3.75	1.50	1.34	1.25
LatePR	2.54	2.86	0.81	1.01
		Barossa		
C	4.97	2.82	0.93	1.5
ST	3.94	2.45	0.93	1.36
LP	4.63	2.70	1.27	1.59
BT	4.16	2.79	1.10	1.61
EARLY TRIM	5.38	3.34	1.41	1.82
		Padthaway		
C	5.67	2.48	2.32	2.80
ST	5.07	1.96	2.04	2.13
LP	5.45	2.09	2.17	2.32
BT	5.32	1.92	1.73	2.11
EARLY TRIM	9.93	2.76	2.91	3.08
CC	5.08	1.55	1.66	1.73
K+BT	5.29	0.95	0.89	1.15
K EARLY	7.33	1.66	1.47	2.11
K UP	5.90	1.39	1.16	1.57

The relationships between canopy size, canopy growth, vine balance and berry and wine chemistry measures were assessed by Pearson's correlation. Parameters that showed the highest correlation with grape and wine quality measures were included in the correlation matrices: yield (Y), pruning weight (P), LAI and canopy porosity measured at three phenological stages (EL 23, EL 35, EL 38), Y/P, canopy growth rate (GR) calculated as % variation in LAI between two time points (flowering to veraison and veraison to harvest), berry and wine chemistry measures and berry and wine sensory attributes. Vine balance indices were computed for the three seasons as the traditional yield to pruning weight ratio (Y/P) and yield to leaf area index (Y/LAI) at the three above mentioned phenological stages.

Relationships between yield, pruning weight, canopy architecture and berry and wine chemistry

Figure 8.30 shows the statistical relationship between the measured parameters from all trials and the three seasons combined. Yield was negatively correlated with berry TSS, pH both in berry and wine and berry anthocyanins and positively correlated with wine TA. Pruning weight (P) was correlated with more chemistry measures and with higher correlation coefficients compared to Y. P was highly positively correlated with berry TSS, pH, anthocyanins and tannin content while it negatively affected berry and wine TA, wine phenolic and tannin content. Canopy architecture showed greater impact on berry and wine chemistry when measured at flowering (EL23) and harvest (EL38) compared to veraison (EL35). LAI at EL23 negatively correlated with both berry and wine TA, tannins and phenolics while canopy porosity measured at the same time positively impacted on the same measures. The veraison canopy architecture measurement showed a positive correlation between LAI and berry TSS, pH, TA, tannins and phenolics. However, this only translated into the wines as a correlation with pH and phenolics. The porosity measured at EL 35 showed no correlation with any of the measured chemistry but a negative correlation with TA. Contrary to what was observed at flowering, at harvest, higher values of LAI were associated with higher TSS, pH and tannins in the berries and to higher alcohol, pH and anthocyanins in the wines. At the same time point, LAI was negatively correlated with wine TA and tannins. Porosity at EL 38 negatively impacted on TSS and berry and wine pH but a positive relationship with wine TA, phenolics and tannins was observed.

Relationships between vine balance indices and berry and wine chemistry

All of the vine balance indices calculated showed a very similar correlation pattern with some of the berry and wine chemistry; in particular they all negatively correlated with berry TSS, berry anthocyanins and positively correlated with wine TA. Also, with the exclusion of Y/LAI at EL 23, the indices negatively affected berry pH, alcohol content in wine and had a positive correlation with wine tannins. Ten of the 12 chemistry measurements significantly correlated with Y/LAI at EL 38 while only six or seven were correlated with the other three indices.

Relationships between growth rate and berry and wine chemistry

The growth rate (GR) of the canopy was calculated as the % difference in LAI between flowering and veraison (GR 23-35) and between veraison and harvest (GR 35-38). Greater growth between flowering and veraison positively correlated with berry pH, TA, tannins and phenolics. Similarly, wine TA, anthocyanins, tannins and phenolics were positively correlated with GR 23-35. GR 35-38 negatively impacted on berry TA and wine tannins.

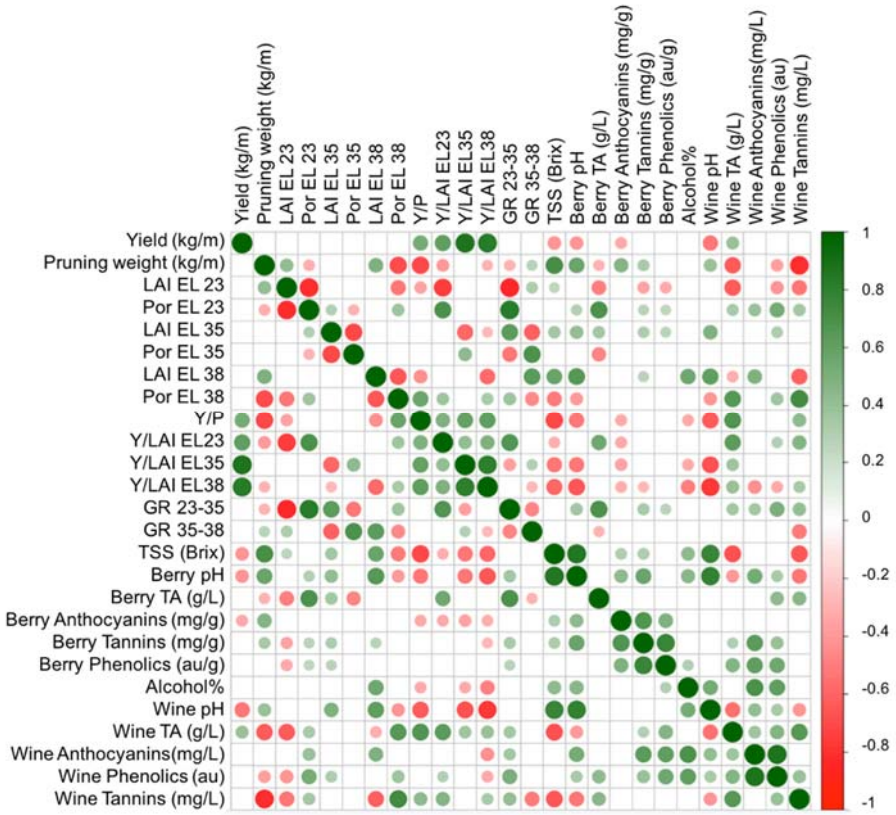


Figure 8.30: correlation map (correlogram) of yield (Y), pruning weight (P), canopy architecture (Leaf area index= LAI and Canopy Porosity= Por), vine balance indices (Y/P, Y/LAI) and growth rate (GR) and berry and wine chemistry measured in all of the Shiraz canopy management trial and in the three growing seasons (2013-14, 2014-15 and 2015-16). Canopy architecture was measured at three phenological stages (El 23, 35 and 38). Only significant Pearson correlations coefficients (P≤0.05) are shown. Green circles correspond to significant positive correlation and red circles to significant negative correlations. The size and colour of the circles is indicative of the level of significance of the correlation.

Relationships between yield, pruning weight, canopy architecture and berry sensory attributes

Figure 8.31 shows the correlogram representing the relationship between yield, pruning weight, canopy architecture and berry sensory attributes for all trials and the three seasons combined.

Yield only mildly influenced some of the berry sensory characteristics such as the red fruit flavour of the pulp and skin and the dark fruit and green flavour of the skin. While pruning weight (P) was highly correlated with many of the attributes. High negative correlations were observed with the pulp dark fruit flavour, sweetness, acidity and the green flavour of the skins. Also, as expected, higher P resulted in greener seeds. P was also positively correlated with the green flavour of the pulp, the detachment of the skin from the pulp and skin disintegration, acidity, dark fruit and red fruit flavours. Also, more bitter seeds were associated with higher P.

The canopy architecture measurements all correlated with some of the berry sensory attributes in different ways. For example, a well establish canopy (higher LAI) at LAI EL 23 resulted in juicier berries while bigger canopies at EL 35 and 38 negatively influenced the same attribute. Similarly, higher values of LAI at EL 23 were associated with softer skins (easier skin disintegration when chewed), higher skin acidity, red fruit flavour and more bitter seeds while the correlation with skin green flavour and astringency was negative. The porosity at EL 38 was the measure that correlated with most of the BSA attributes. Por EL 38 was positively linked to dark fruit flavours and sweetness of the pulp but also to the green flavour in the skins. Higher porosity was also associated with darker seeds. While, the green flavour of the pulp, skin disintegration, acidity, red fruit flavour and seed bitterness were all negatively correlated with Por EL 38.

Relationships between vine balance indices and berry sensory attributes

When vine balance was correlated with berry sensory characteristics, the indices that explained most of the attributes were Y/P and Y/LAI early in the season. Both Y/P and Y/LAI EL 23 were positively correlated with the red and dark fruit flavour of the pulp, the green flavour of the skins and seed colour. Both the indices were also negatively correlated with skin disintegration, acidity and red fruit flavour and to seed bitterness.

Relationships between growth rate and berry sensory attributes

A higher GR from EL 23 to 35 was associated with drier berries, less acidic skins with lower red fruit flavour and less bitter seeds. The same GR was also positively related to skin astringency and coarser tannins and more herbaceous seeds. A positive GR from EL 35 to 38 was associated with higher red fruit flavour in both the pulp and the skin and negatively correlated with pulp acidity and skin dark fruit flavours, skin astringency and the toasted flavour of the seeds.

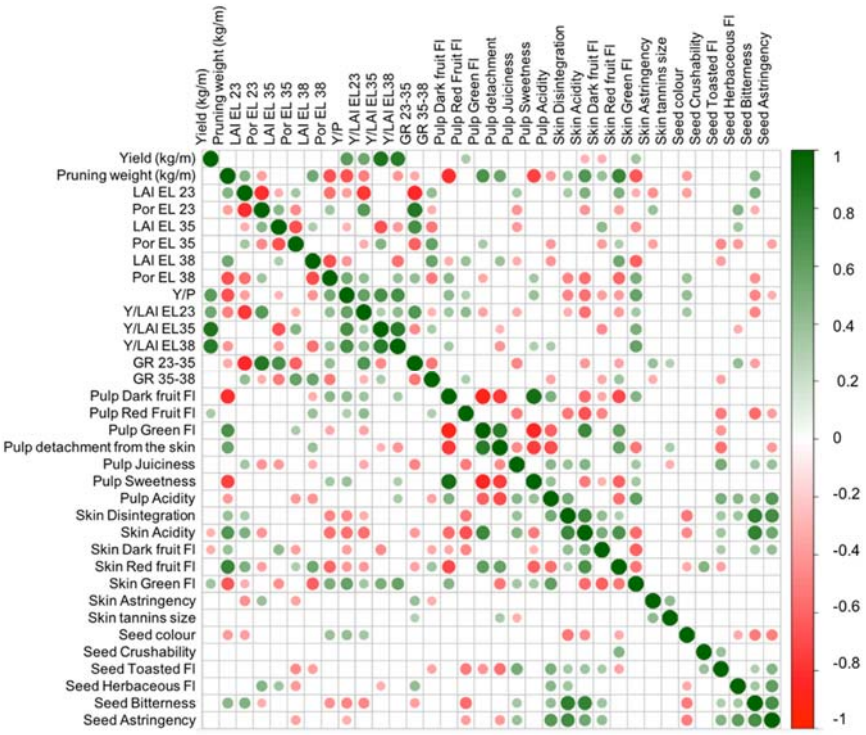


Figure 8.31: correlation map (correlogram) of yield (Y), pruning weight (P), canopy architecture (Leaf area index= LAI and Canopy Porosity= Por), vine balance indices (Y/P, Y/LAI) and growth rate (GR) and berry sensory attributes measured in all of the Shiraz canopy management trials and in the three growing seasons (2013-14, 2014-15 and 2015-16). Canopy architecture was measured at three phenological stages (El 23, 35 and 38). Only significant Pearson correlations coefficients (P≤0.05) are shown. Green circles correspond to significant positive correlation and red circles to significant negative correlations. The size and colour of the circles is indicative of the level of significance of the correlation.

Relationships between yield, pruning weight, canopy architecture and wine sensory attributes

Figure 8.32 shows the correlogram representing the relationship between yield, pruning weight, canopy architecture and wine sensory attributes for all trials and the three seasons combined

Y was negatively correlated with dark fruit aroma, bitter taste and tannic intensity of the wines while the correlation was positive with red fruit aroma. P was highly and positively correlated with peppery and confectionery flavour and negatively correlated with red fruit aroma and alcohol mouthfeel. Canopy architecture measures showed different degrees of correlation with wine sensory attributes; for example, LAI at flowering showed a negative correlation with the astringency and tannic intensity of the wines while porosity at the same phenological stage exhibited a positive correlation. At veraison, the two latter attributes revealed opposite correlations with LAI and Por. LAI EL 38 was highly correlated with the confectionery flavour while porosity was negatively correlated with the latter and to peppery flavour.

Relationships between vine balance indices and wine sensory attributes

All of the vine balance indices were positively correlated with red fruit aroma and negatively correlated with bitterness, confectionery and pepper flavour and astringency and tannic intensity.

Relationships between growth rate and wine sensory attributes

The growth rate from flowering to veraison was only negatively correlated with the pepper flavour while positively to astringency, tannic intensity and length. Confectionery flavour was positively correlated with the GR 35-38 while the correlation was negative with astringency.

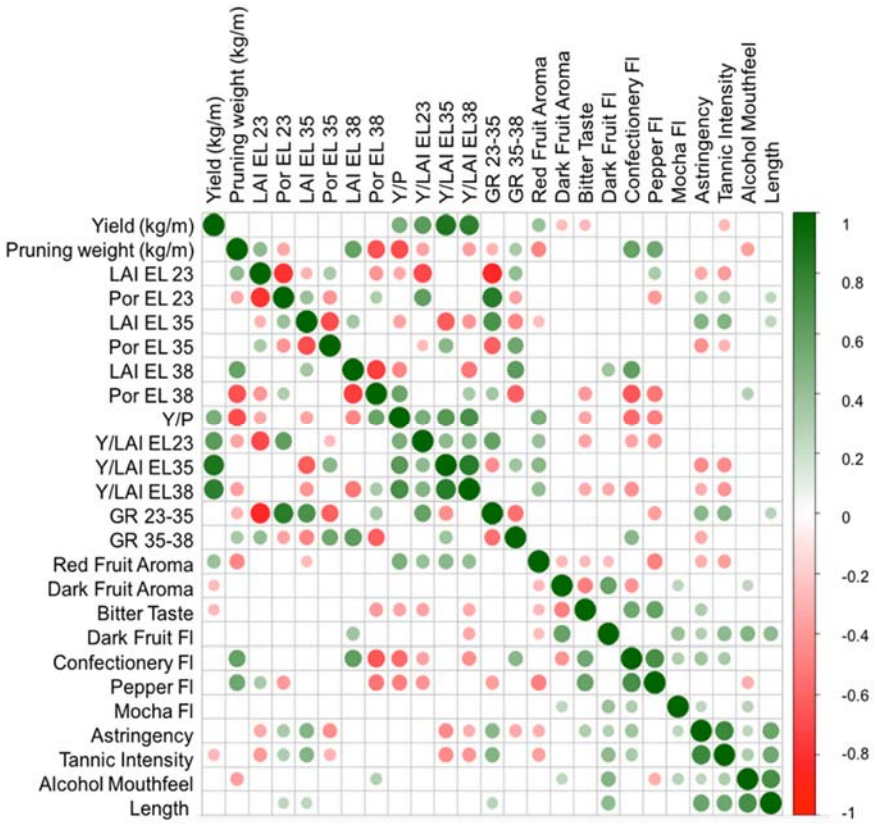


Figure 8.32: correlation map (correlogram) of yield (Y), pruning weight (P), canopy architecture (Leaf area index= LAI and Canopy Porosity= Por), vine balance indices (Y/P, Y/LAI) and growth rate (GR) and wine sensory attributes measured in all of the Shiraz canopy management trials and in the three growing seasons (2013-14, 2014-15 and 2015-16). Canopy architecture was measured at three phenological stages (El 23, 35 and 38). Only significant Pearson correlations coefficients (P≤0.05) are shown. Green circles correspond to significant positive correlation and red circles to significant negative correlations. The size and colour of the circles is indicative of the level of significance of the correlation.

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9 Canopy management trial on Semillon

In an effort to change the ratio between yield and canopy size at a higher level compared to what was achievable using standard canopy management practices in commercial vineyards, a trial was established in the experimental vineyard at the University of Adelaide, Waite Campus. More severe treatments could then be applied such as a reduction of 50% of shoots through shoot thinning; similarly, bunch thinning was applied by removing 50% of the total bunches on the plant. Moreover, a new leaf plucking technique that has been shown to delay ripening on Sangiovese (Palliotti et al. 2013) was trialled at this site.

Materials and methods

Experimental site

The trial was carried out during the seasons 2014-15 (season one, S1), 2015-16 (season two, S2) and 2016-17 (season three, S3) in the experimental vineyard at the University of Adelaide, Waite Campus, South Australia (34°58'3.47"S; 138°38'0.43"E). Measurements were made on own-rooted 25-year-old Semillon vines trained to a bilateral spur pruned cordon with the shoots vertically positioned. Rows were oriented North-South with a vine spacing of 1.8 m and 3 m row spacing. The vineyard was irrigated with in-line drippers discharging 1.5 L/h. The total amount of irrigation discharged in both growing seasons was about 50 mm, with scheduling based on soil moisture readings obtained with a Diviner 2000 (Sentek Environmental Technologies, Kent Town, Australia).

Experimental design

The experiment included four treatments in S1 and five in S2 and S3 and are shown below.

i) Control (C), where no canopy intervention was applied during the growing season;
ii) Shoot thinning (ST) where 50% of the total number of shoots was removed at EL stage 15-17 (Coombe, 1995); Shoots were selected according to their vigour and position on the cordon and the short, weak, double shoots were preferably removed;
iii) Bunch thinning (BT), where 50% of the total number of bunches was removed just after veraison (10 °Brix); Distal bunches on a shoot with two bunches, those on weak and short shoots and smaller bunches were selected for removal;
iv) Leaf plucking (LP) was conducted post-veraison (10 °Brix) according to the method proposed by Palliotti et al. (2013). Leaves were manually removed from the middle third of the canopy, creating a 40-50 cm opening on the canopy as shown in Figure 2.
v) Double nodes (DN) (applied in S2 and S3) where, at pruning, double the number of buds compared to the C were left on the vine.



Figure 9.1: Leaf removal applied above the bunch zone on Semillon at the Coombe vineyard.

In S1, three adjacent rows were selected for the trial. A fully randomised block design was chosen with each treatment repeated once along one row in blocks of three panels of three vines each. All measurements were taken on the middle vine of each panel for a total of three vines measured per treatment replicate.

Canopy architecture, yield components and grape composition

Canopy architecture was measured using the VitiCanopy App (De Bei et al. 2016). In all three seasons images were taken at EL stages 23, 31 and 35 corresponding to flowering, berry pea size and veraison. Two images were taken on each side of the middle vine in each panel at 80 cm from the vine cordon (De Bei et al. 2016).

Harvest date was decided based on the total soluble solids (TSS, °Brix) accumulation in the berries with a target of 23 °Brix to represent commercial harvest levels. Maturity was monitored weekly from EL 35 by collecting a sample of 100 berries randomly selected from the nine plants in each replicate. Total berry weight was measured and then the berries were crushed by hand in plastic bags and the juice expressed, collected in 10 mL tubes and centrifuged at 5000 rpm for five minutes (Hettich Universal, Germany) before TSS, pH and total acidity (TA) (autotitrator; Crison instruments Barcelona, Spain) determination (Iland et al. 2004). TSS was tested with a digital refractometer (BRX-242 Erma inc. Tokyo, Japan). In S1, the trial was harvested at DOY 42 for all treatments while in S2, due to adverse weather conditions and *Botrytis* infections starting to develop on the berries, harvest was carried out when the grapes reached 21 °Brix (Table 9.1). C, BT and ST were harvest on DOY 21 while LP and DN on DOY 29. Similarly, in S3, the treatments were harvested at different DOY which were 54 for BT, 58 for ST and 61 for the other treatments, the TSS ranged from 20 to 23 °Brix (Table 9.1).

Table 9.1 Details of harvest date for Semillon from the Coombe vineyard from three seasons and the applied treatments. C=Control; ST= Shoot Thinning; BT= Bunch Thinning; LP= Leaf Plucking; DN= Double Nodes

Treatment	Season	TSS (°Brix)	Harvest Date (DOY)
C	2014-15	22.2	42
	2015-16	20.2	21
	2016-17	23.0	61
ST	2014-15	22.6	42
	2015-16	20.2	21
	2016-17	20.2	58
BT	2014-15	23.5	42
	2015-16	21.4	21
	2016-17	21.6	54
LP	2014-15	21.6	42
	2015-16	20.4	29
	2016-17	20.0	61
DN	2014-15	-	-
	2015-16	19.4	29
	2016-17	21.6	61

All treatments were hand harvested and the number of bunches per vine and yield per vine were recorded. Cordon length was also measured so that yield and its components could be measured on a per m basis. From yield and bunch number, the average bunch weight was determined. The harvested fruit from three plants per replicate and per treatment was combined into 20 kg vented crates to form one sample per replicate to be used for winemaking. A subsample of 50 berries was collected to measure berry weight and stored at -20°C until tested for phenolic and tannin content. Total grape tannins were measured using the protocol proposed by Mercurio et al. (2007) by the methyl cellulose precipitable (MCP) tannin assay. Total phenolics were determined according to Iland et al. (2004).

At pruning, the weight of all one-year-old wood was collected and weighed in both seasons for each of the middle vines of each treatment replicate.

Berry sensory analysis

In all three seasons, at harvest, from the total of the grapes picked for winemaking, 15 bunches were randomly selected, from these, a sample of 300 berries was collected for berry sensory assessment (BSA) by descriptive analysis (DA). Berries were cut from the bunch rachis with scissors and the pedicel was left on the berries in order to avoid oxidation and colour changes. Descriptive analysis was conducted on the fresh fruit, berries were kept at 4 °C until assessment.

BSA was carried out at the sensory facility of the University of Adelaide at the Waite Campus following the procedure described in Lohitnay et al. (2010) and Olarte Mantilla et al. (2013). The procedure required two stages: 1) training session(s) and 2) evaluation session(s).

The training was conducted according to Olarte Mantilla et al. (2013); briefly, 10 to 12 assessors with previous BSA experience were selected for the DA and trained over three training sessions in S1 and two in S2 and S3, since most of the panellists were the same as in the previous seasons. During the training sessions, the assessors were asked to evaluate berry samples from all the treatments with the aim of reaching an agreement on the number and type of attributes to score during the formal sessions.

The assessors reached a consensus on a list of 24 descriptors and on using a 0-15 line scale with three anchors. The list of descriptors is reported in Table 9.2.

Table 9.2: list of descriptors/attributes assessed by the panellists during the berry sensory analysis with their scale left, middle and right anchor. The attributes are divided in three categories: Pulp Characteristics, Skin Characteristics and Seeds Characteristics.

Attribute	Left anchor	Middle anchor	Right anchor
Pulp Characteristics			
Grape flavour	Low	Moderate	High
Citrus/tropical flavour	Low	Moderate	High
Green/grassy flavour	Low	Moderate	High
Flavour intensity	Low	Moderate	High
Detachment of pulp from skin	Easy to detach	50%/50%	Difficult to detach
Juiciness	All is gelatinous	50%/50%	All is juicy
Sweetness	Low	Moderate	High
Acidity	Low	Moderate	High
Skin Characteristics			
Disintegration of the skins	Easy, homogenous mixture		Very difficult, big pieces
Acidity	Low	Moderate	High
Grape flavour	Low	Moderate	High
Citrus flavour	Low	Moderate	High
Green/grass flavour	Low	Moderate	High
Flavour intensity	Low	Moderate	High
Bitterness	Low	Moderate	High
Astringency	Low	Moderate	High
Tannic intensity	Low	Moderate	High
Tannin size	Soft and silky grains	Medium size grains	High grade sand paper
Seeds Characteristics			
Colour	Green, yellow-green	Brown-green	Dark brown
Crushability	Soft like pepitas	Crunchy like roasted hazelnuts	Brittle like passionfruit seeds
Flavour	Herbaceous		Toasted
Bitterness	Low		High
Astringency	Low		High
Likability	Dislike		Like

During the formal assessment sessions, the panellists were presented with either 12 or 15 three-berry samples in a randomised sample presentation order for each assessor. Each sample was evaluated twice by each assessor, for a total of 24 samples in S1 and 30 in S2 and S3. A custom-built web-based software (cloud.sensorypanel.net/agwine) or a beta version of VitiSense were used to assess samples. Briefly, attributes were presented in the order shown in Table 1 and each attribute was associated with a line bar with a cursor that the assessor could move either using the mouse or by tapping on the screen of a tablet or smartphone or computer. The software collates the data for each session in an Excel file with the sample name in the rows and the assessor name and all the attributes in the columns. At completion of the assessment an Excel file with all the information was downloaded for statistical analysis.

Winemaking

For winemaking, the field replicates were maintained in order to produce three wines per treatment. The fruit was stored for 24 hours in a cold room at 2°C. The day after harvest, the fruit was crushed and de-stemmed using a small scale combined crusher de-stemmer (Grifo Macchine Enologiche, Piadena, Italy). At the crusher 0.2 g/L of potassium metabisulfite was added. The crushed sample was then pressed using a 20L bladder press (Zambelli, Hydro 20, Camisano Vicentino, Italy) and a 4 L aliquot of must was transferred into 5 L food grade fermentation vessels. The ferments were then moved to a controlled temperature growth room at a constant temperature of 14 °C for fermentation.

Ferments were inoculated with 0.2 g/L of commercial dried yeast Maurivin PDM (Maurivin, Toowoomba, NSW, Australia) and 0.2 g/L of di-ammonium phosphate (DAP). Fermentation dynamics were checked daily by measuring the temperature of the ferment and the sugar level with a hydrometer. When the ferments reached 10 °Baume an extra 0.2 g/L of DAP was added. Dry ice was dispersed on the ferment every time the fermentation vessels were opened, to avoid contact with air and oxidation. When the measured sugar level was below -1.5 °Baume (7-8 days after crushing), wines were sulfured to a free level of 30 mg/L and stored in a 2°C cold room. After two weeks, they were racked off the lees, transferred into Schott bottles and cold stabilised at 2°C for an additional two weeks before bottling. Wines were bottled into 375 mL glass bottles and crown sealed. The wines were then stored at a constant 2°C until sensory and chemical analysis.

Wine chemical analysis

The finished wines were analysed for pH and TA as described by Iland et al. (2004) (autotitrator; Crison instruments Barcelona, Spain). The percentage of alcohol (v/v) was determined using an Alcolyzer Wine ME (Anton Paar, Graz, Austria). Colour was determined spectrophotometrically according to Iland et al. (2004). Tannin concentration was determined using the methyl cellulose precipitate (MCP) assay as reported by Mercurio et al. (2007).

Wine sensory analysis

The finished wines were assessed using DA by a panel of assessors as described in Mantilla et al. (2015) and similarly to what already has been described for berries. Assessors were trained for two 2-hour sessions in all three seasons. Training included ranking exercises for taste attributes such as acidity, astringency and bitterness and identification of unknown aroma standards. During the training, the assessors were also asked to try the wines from the trial and reach a consensus on the attributes to score during the formal assessment. The list of attributes is described in Table 9.3.

Table 9.3: List of descriptors/attributes assessed by the panellists during wine descriptive analysis with relative scale left, middle and right anchors. The attributes are divided in categories: Aroma, Taste, Flavour, Mouthfeel and Aftertaste.

Attribute	Left anchor	Middle anchor	Right anchor
Aroma			
Floral	Low	Moderate	High
Citrus	Low	Moderate	High
Confectionery	Low	Moderate	High
Stone fruit	Low	Moderate	High
Tropical	Low	Moderate	High
Grassy	Low	Moderate	High
Dry grass	Low	Moderate	High
Alcohol	Low	Moderate	High
Taste			
Salty	Low	Moderate	High
Bitter	Low	Moderate	High
Acid	Low	Moderate	High
Sweetness	Low	Moderate	High
Flavour			
Floral	Low	Moderate	High
Citrus	Low	Moderate	High
Confectionery	Low	Moderate	High
Stone fruit	Low	Moderate	High
Tropical	Low	Moderate	High
Dry grass	Low	Moderate	High
Mouthfeel			
Body	Thin	Medium	Viscous and mouth filling
Astringency	Low	Medium	High
Tannins	Fine	Medium	Coarse
Alcohol	Low	Medium	High
Aftertaste			

Overall Length	Short	Medium	Long
Fruit length	Short	Medium	Long
Alcohol	Low	Moderate	High
Bitter	Low	Moderate	High

The final assessment was carried out using a similar procedure as the BSA. Assessors were presented with 12 or 15 30 mL wine samples in clear, ISO standard glasses covered with a petri dish. All wines were assessed in duplicate in a randomised, balanced sample presentation order for each assessor. Data was collected using the same custom-built software (cloud.sensorypanel.net/agwine) used to assess the berries.

Statistical analysis

ANOVA, repeated measures ANOVA and Principal Component Analysis (PCA) were performed using XLSTAT Version 2015.4.01.20116 (Addinsoft SARL, Paris, France). Sensory data was analysed using SenPAQ (Qi statistics, UK), a two-way mixed model ANOVA was performed with random assessors. Correlations were analysed using Pearson correlation coefficient and the statistical language R (R Core Team, 2017). The correlations maps between vine balance indices and grape and wine chemistry and sensory attributes were calculated using the R package *corrplot* (Wei and Simko, 2016) and only significant correlations ($P \leq 0.05$) are represented in the maps.

Results

The climatic conditions for the site were sourced from the nearest Australian Bureau of Meteorology weather station located in Kent Town (station number 23090). For comparisons, mean average temperature and rainfall for the growing season, October to April, were calculated for the 30-year average (1983-2013 = long term average (LTA)) and for the three growing seasons of interest, 2014-15, 2015-16 and 2016-17. The Growing Degree Days (GDD) were calculated after Gladstones (2011) with base 10°C and 19°C cut offs. Two of the three growing seasons were warmer than the long-term average with GDD of 1801, 1884 and 1811 for the 30-year average, 2014-15 and 2015-16 respectively. Season 2016-17 temperature sum was lower than average with GDD of 1771. A summary of the meteorological conditions is reported in Figure 9.2. S1 was drier than average with a total rainfall of about 140mm compared to the 198 of the LTA, it also showed a very high mean temperature in February. S2 was again slightly drier than the LTA and was characterised by generally higher mean daily temperatures during the growing season. Interestingly, the total rainfall in all three seasons was higher than the LTA in the month of January. S3 stands out as a very wet season, with a total rainfall of 354 mm, almost 80% more compared to the LTA. October and December were particularly wet with monthly values over 80 mm. Despite the high rain, S3 was colder than LTA only in October and November and warmer in the other months.

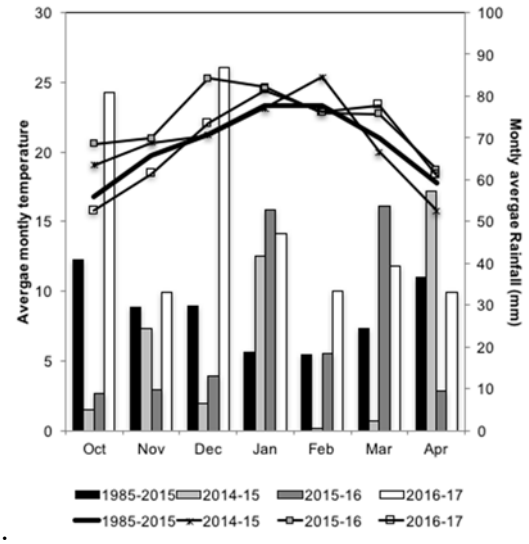


Figure 9.2: Average monthly temperature and rainfall calculated for the growing season October to April for the seasons 2014-15 and 2015-16 and the 30-year long term average (1983-2013).

Table 9.1 shows that harvest TSS varied from 19.4 to 23.5 amongst all treatments and seasons. Harvest date was very different in the three years of the study with differences due to climatic conditions between seasons and applied treatment within season. The climate of the three seasons is shown in Figure 9.2. S1, as discussed above, was hotter and drier than average and harvest was carried out on DOY 42 for all treatments. S2 was slightly wetter than S1, but still below average, and it was the hottest of the three seasons, with a GDD well above the LTA. Due to these hot conditions and coupled with a warmer than average winter (data not shown), the phenology of the vines was brought forward significantly and C, ST and BT vines were harvested as early as DOY 21, 21 days earlier compared to the previous season; while LP and DN were harvested on DOY 29. In S3, due to the wet and cold weather, the phenology was very late compared to the previous two seasons and, if we consider C as a reference, harvest was conducted 20 days later than season 1 and 40 days later than season 2. Harvest started on DOY 54 for BT, 58 for ST and 61 for the other treatments. The great difference in climate between seasons explains the highly significant season effect shown in Table 9.4. Only bunch weight was significantly different when the interaction between treatment and season was tested. Given the high seasonal impact on the study, results are discussed separately for each season.

Effects on vine performance

In S1, when all treatments were harvested at the same time, yield and bunch number were the only significantly different parameters amongst the measured ones (Table 9.4). BT, as expected, significantly reduced yield and bunch number compared to C. Interestingly, ST, despite the large reduction in bunch number did not significantly reduced the yield. In S2 all of the yield components but pruning weight showed highly significant differences in relation to the treatment. Similarly to the previous season, BT and ST had the lowest yield but not significantly different from C. The number of bunches per m of cordon was significantly higher in the DN treatment and ST significantly lower than other treatments.

Bunch weight and berry weight were highest in ST with bunches almost 100g heavier than C. Surprisingly C produced the smallest berries. In S3 yield was variable in the replicates but was not statistically different between treatments. Bunch number was again the lowest in BT and ST however not significantly different from C and while ST had a larger average bunch weight compared to C, BT did not. The smallest bunches were harvested from the DN treatment.

Table 9.4: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and DN: double nodes) on yield and yield components of Semillon grown in the Coombe vineyard, Waite Campus, Adelaide during three consecutive seasons (2014-15, 2015-16, 2016-17).

Season	Treatment (T)	Yield (kg/m)	Bunch number (#/m)	Bunch weight (g)	Berry weight (g)	Pruning weight (kg/m)
2014-15	C	5.5 a	35.3 a	159.2	1.47	0.76
	ST	4.6 a	25.1 bc	183.5	1.50	0.59
	LP	5.7 a	31.9 ab	179.6	1.67	0.68
	BT	2.9 b	19.1 c	152.7	1.53	0.63
	P-value (T)	0.008	0.006	ns	ns	ns
2015-16	C	5.9 ab	39.6 b	142.9 b	1.27 d	0.53
	ST	5.1 b	21.6 c	239.4 a	1.52 a	0.46
	LP	5.6 ab	40.7 b	144.6 b	1.49 ab	0.50
	BT	4.2 b	27.6 bc	148.1 b	1.42 bc	0.46
	DN	7.1 a	61.4 a	116.9 b	1.36 c	0.43
	P-value (T)	0.038	0.001	0.000	0.000	ns
2016-17	C	7.3	35.3 ab	217.3 bc	1.73 c	1.00
	ST	6.6	19.8 b	335.3 a	1.83 bc	0.62
	LP	7.7	35.6 ab	221.8 b	2.10 ab	0.67
	BT	4.5	17.2 b	268.5 b	2.12 a	0.77
	DN	7.9	49.8 a	165.7 c	1.84 abc	0.76
	P-value (T)	ns	0.035	0.001	0.044	ns
	Season (S)	0.000	0.033	< 0.0001	< 0.0001	< 0.0001
	S x T	ns	ns	< 0.0001	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns = not statistically significant.

Effects on canopy architecture

During the three seasons, canopy images were taken at the same three phenological stages corresponding to EL 23, EL31 and EL 35 (flowering, pea size and veraison) (Table 9.5). In S1 only canopy porosity at EL 23 was different between treatments with ST showing the highest and C the lowest values. LAI and porosity were different at all stages in S2; DN showed the highest LAI at EL 23 and 31 while by EL 35 all treatments apart from BT showed similar values. At EL 35 images were taken after BT was applied and since VitiCanopy measures the total Plant Area Index (PAI) rather than LAI, BT showed a lower value due to the removal of 50% of the bunches. At EL 23 and 31 the smallest LAI was measured in ST, as expected, while the canopy porosity was the highest. In S3, at EL 23 ST canopies were smaller compared to all other treatments however no differences were measured after. This could be explained by the warm and rainy weather of the season which stimulated high vigour on the vines and minimised the differences between treatments. Indeed, on average, for all treatments, LAI in S3 was 48% higher than S1 and 50% larger than S2.

Table 9.5: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and DN= double nodes) on yield and yield components of Semillon grown in the Coombe vineyard, Waite Campus, Adelaide during three consecutive seasons (2014-15, 2015-16, 2016-17).

Season	Treatment (T)	LAI EL 23	Canopy Porosity EL 23	LAI EL 31	Canopy Porosity EL 31	LAI EL 35	Canopy Porosity EL 35
2015	C	1.71	0.15 b	1.98	0.169	1.85	0.17
	ST	1.54	0.19 a	1.79	0.196	1.43	0.185
	LP	1.55	0.17 ab	1.79	0.196	1.67	0.195
	BT	1.54	0.17 ab	1.67	0.212	1.68	0.185
	P-value (T)	ns	0.05	ns	ns	ns	ns
2016	C	1.12 ab	0.236 b	1.23 bc	0.198 b	1.38 a	0.226 ab
	ST	0.71 c	0.336 a	1.08 c	0.234 a	1.40 a	0.238 a
	LP	0.99 b	0.277 ab	1.25 bc	0.176 bc	1.38 a	0.221 ab
	BT	1.02 ab	0.238 b	1.43 b	0.176 bc	1.05 b	0.239 a
	DN	1.22 a	0.238 b	1.70 a	0.151 c	1.53 a	0.198 b
	P-value (T)	0.003	0.038	0.001	0.004	0.001	0.05
2017	C	1.53 a	0.185	2.05	0.175	2.92	0.098
	ST	1.09 b	0.215	1.82	0.163	2.71	0.127
	LP	1.42 a	0.191	1.46	0.197	2.37	0.138
	BT	1.40 a	0.179	1.89	0.169	2.57	0.133
	DN	1.49 a	0.187	1.82	0.166	2.79	0.116
	P-value (T)	0.002	ns	ns	ns	ns	ns
	Season (S)	<0.0001	< 0.0001	< 0.0001	ns	< 0.0001	< 0.0001
	S x T	0.048	ns	ns	ns	ns	ns

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Effects on berry and wine chemistry

Harvest TSS was significantly different among treatment in S1 since harvest was carried out on the same day, with the main differences observed between LP and BT (Table 9.6). TA, pH, phenolics and epicatechins were not different. The harvest TA was the highest recorded for the whole duration of the study.

In S2 harvest was delayed by eight days for LP and DN to achieve the target TSS; harvest TSS and pH were not different between treatments. TA was however significantly higher and phenolics and tannins

significantly lower for these two treatments compared to C. DN delayed ripening in 2016 by eight days without yield penalties and also achieved the highest harvest TA.

In S3 TSS in ST and LP was lower than C while pH was not different and TA was lower in LP, BT and DN compared to C.

Table 9.6: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and DN= double nodes) on berry chemistry measurements of Semillon grown in the Coombe vineyard, Waite Campus, Adelaide during three consecutive seasons (2014-15, 2015-16 and 2016-17).

Season	Treatment (T)	TSS (Brix)	pH	Titratable acidity (TA) (g/L)	Total Phenolics (au)	Epicatechins (mg/g)
2015	C	22.2 bc	3.05	10.90	0.91	5.22
	ST	22.6 ab	3.10	10.22	1.02	5.44
	LP	21.6 c	3.09	10.26	0.86	4.79
	BT	23.5 a	3.08	10.91	0.90	5.00
	P-value (T)	0.009	ns	ns	ns	ns
2016	C	20.17	3.29	6.46 b	0.64 a	4.31 a
	ST	20.17	3.27	7.12 b	0.66 a	4.34 a
	LP	20.40	3.36	9.92 a	0.55 bc	3.46 b
	BT	21.37	3.34	6.40 b	0.60 ab	3.83 ab
	DN	19.40	3.44	10.38 a	0.51 c	3.24 b
	P-value (T)	ns	ns	< 0.0001	0.009	0.013
2017	C	23.03 a	3.12	8.52 a	-	-
	ST	20.23 b	3.13	8.95 a	-	-
	LP	19.93 b	3.17	6.91 b	-	-
	BT	21.57 ab	3.15	6.51 b	-	-
	DN	21.63 ab	3.22	6.67 b	-	-
	P-value (T)	< 0.018	ns	< 0.0001		
	Season (S)	< 0.0001	< 0.0001	< 0.0001		
	S x T	0.001	ns	< 0.0001		

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test (P≤0.05). ns= not statistically significant.

Given the difference in harvest TSS, wine alcohol was also different between treatments in S1 and S3 (Table 9.7). pH was the highest in BT in S1 while it was similar in all other treatments, in S2 and S3 it

was the lowest in ST. TA was not different between treatments in S1 while in S2 the highest values were measured for ST and lowest for LP. Only in S2 LP was different from C while no differences between C and the other treatments were observed in S3. Wine phenolics and tannins were not different between treatments in S1 and S2 while in S3 C had significantly higher phenolics compared to all other treatments and the lowest amount was measured in BT.

Table 9.7: Effect of the use of canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and DN= double nodes) on the wine chemistry of Semillon grown in the Coombe vineyard, Waite Campus, Adelaide during three consecutive seasons (2014-15, 2015-16 and 2016-17).

Season	Treatment (T)	Alcohol %	pH	Titratable acidity (TA) (g/L)	Total Phenolics (au)
2015	C	14.53 b	3.12 b	7.61	6.97
	ST	14.12 b	3.13 b	7.78	7.31
	LP	14.12 b	3.14 b	7.93	7.50
	BT	15.51 a	3.19 a	7.36	6.81
	P-value (T)	0.023	0.032	ns	ns
2016	C	13.11	3.32 a	7.76 ab	5.97 b
	ST	12.88	3.12 b	8.00 a	6.58 ab
	LP	12.76	3.38 a	7.35 c	7.04 a
	BT	13.44	3.29 ab	7.58 bc	6.22 ab
	DN	12.24	3.34 a	7.81 ab	5.71 b
	P-value (T)	ns	0.049	0.026	ns
2017	C	13.79 a	2.91 ab	7.90 ab	10.30 a
	ST	11.99 bc	2.88 b	8.32 a	8.54 b
	LP	11.64 c	2.94 ab	7.22 b	7.52 bc
	BT	12.92 ab	2.98 a	7.35 b	7.05 c
	DN	12.66 bc	2.96 a	7.26 b	8.13 bc
	P-value (T)	0.010	0.049	0.040	0.004

Means were separated by ANOVA using Tukey's honest significant difference (HSD) test ($P \leq 0.05$). ns= not statistically significant.

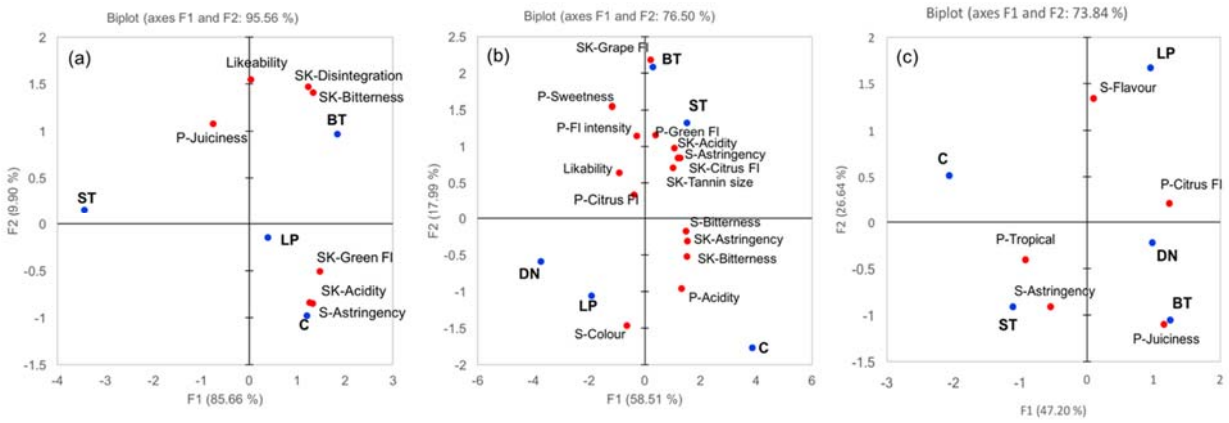
Berry sensory assessments carried out in the three seasons revealed differences between treatments. The PCA in Figure 9.3 shows that in S1 the first two PCs explain 95.56% of the variability in the dataset. PC1 in particular explains 85.66% and is mostly related to differences between ST and all the other treatments. C and, to a less extent LP, were described as having more astringent seeds, skins with more

predominant green flavour and greater acidity. In the opposite quadrant, BT was the most liked treatment, the skins disintegrated easily when chewed however they were bitter. ST was associated with more juicy berries.

In S2, the differences between treatments were clear with as many as 15 attributes judged as different between treatments (Figure 9.3b). The first two PCs explain 76.5% of the variability with 58.5% of variation described by PC1. PC1 separated DN and LP from C and ST. BT characteristics are not explained by PC1. Similar to the previous season, C had greater skin astringency and bitterness, greater seed bitterness and the pulp was more acidic compared to all the other treatments. BT and ST berry samples were scored similarly by the panellists. BT had greater grapey flavour in the skins and both BT and ST were sweeter, had greater citrus and green flavours with more intensely flavoured pulp. ST skins were more acidic, astringent and had coarser tannins. DN and LP had darker seeds and had less astringent and tannic skins and less pulp flavour.

In the last season, the first two PCs explained almost 74% of the dataset variability with PC1 explaining 47% of the variation (Figure 9.3c). PC1 explains the differences between C and ST as compared to LP, DN and BT for pulp flavour, with the latter treatments being associated with greater citrus flavours and the former by more tropical ones. PC2, which explains 26.64% of the variation, explains differences between LP, ST and BT. LP had greater toasted flavour in the seeds compared to BT, ST and, to a less extent, DN. BT and ST, had higher pulp juiciness and seed astringency.

Figure 9.3: Principal component analysis of berry sensory attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the berries of different canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and DN= double nodes) applied to Semillon grown in the Coombe vineyard, Waite Campus, Adelaide during three consecutive seasons (2014-15 (a), 2015-16 (b) and 2016-17 (c)).P= Pulp, SK= Skin, S= Seeds.



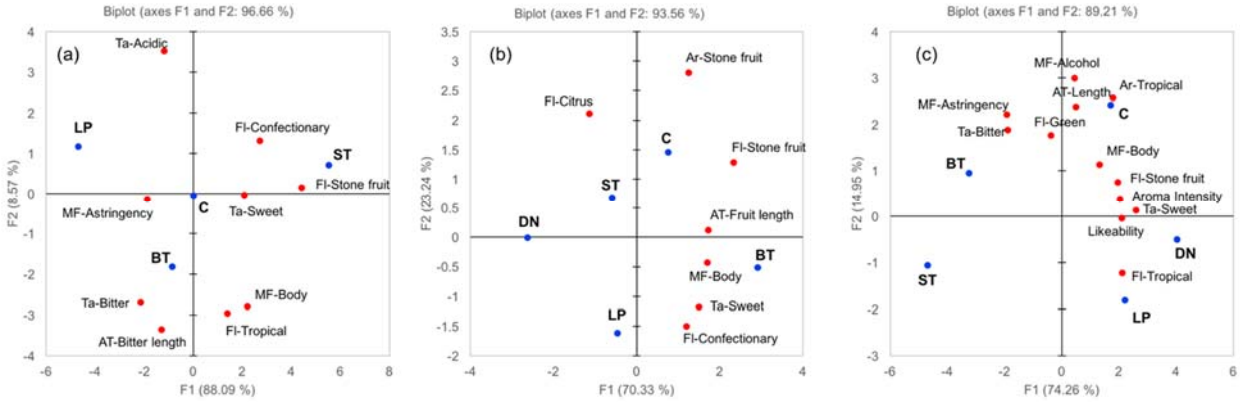
The wines made from the different treatments resulted in sensory differences in all three seasons when evaluated via descriptive analysis (Figure 9.4a). The PCA for S1 uses the first two PCs to explain 88% of the variability. PC1 mostly explains differences between LP and ST with the latter being sweeter, and having greater stone fruit and tropical flavours compared to LP which was described as having

greater acidity, bitterness and astringency. PC2 explains differences between LP and BT with BT being more bitter but also more tropical in flavour and having greater body compared to LP.

S2 PCA explains 93.56% of the variability with most described by PC1 (70.33%) which separates DN from BT while the other three treatments do not show differences (Figure 9.4b). Similar to S1, BT had higher body, greater fruit length, was sweeter and had greater confectionery flavours as opposed to DN. PC2 shows that C compared to LP had greater stone fruit and citrus aroma and flavour, while LP was sweeter with greater confectionery flavour.

S3 PCA shows the greatest differences between treatments (Figure 9.4c). PC1, which explains 74.26% of the variation and shows that BT and ST were more bitter and astringent while DN and LP had more tropical flavours. Also, DN was the most liked wine characterised by more sweetness, greater stone fruit aroma and a generally higher aroma intensity. C, had greater tropical aroma, more body, alcoholic mouthfeel and greater length compared to LP, ST and DN.

Figure 9.4: Principal component analysis of wine sensory attributes found significantly different at P ≤ 0.1 by a panel of 12 assessors in the wine of different canopy management treatments (ST= Shoot Thinning, LP=Leaf Plucking, BT= Bunch Thinning and DN= double nodes) applied to Semillon grown in the Coombe vineyard, Waite Campus, Adelaide during three consecutive seasons (2014-15 (a), 2015-16 (b) and 2016-17 (c)). A= Aroma, TA= Taste, Fl= Flavour, MF= Mouthfeel and AT= Aftertaste.



Vine balance indices

The traditional yield/pruning weight (Y/P) ratio was compared to new indices computed using the LAI measures, measured using the VitiCanopy App (Table 9.8). Y/LAI was calculated for the three phenological stages EL 23, 31 and 35. All indices but Y/LAI EL 35 were significantly different between treatments with the lowest values generally associated with BT and the highest to DN. Y/P values ranged from 13.7 to 6.6 while the Y/LAI range was 5.6 to 2.4.

Table 9.8: Average vine balance indices as the ratios of yield/pruning weight (Y/P) and yield/leaf area index (Y/LAI) calculated for the three phenological stages of flowering (EL 23), pea size (EL 31) and veraison (EL35).

Treatment	Y/P	Y/LAI EL23	Y/LAI EL31	Y/LAI EL35
BT	6.6 c	3.1 b	2.4 b	2.5 b
C	8.7 bc	4.4 ab	3.9 a	3.4 ab
DN	13.7 a	5.6 a	4.0 a	3.7 a
LP	11.1 ab	4.9 a	4.0 a	3.4 ab
ST	10.2 ab	5.4 a	3.9 a	3.2 ab
Pr > F	0.003	0.011	0.003	ns

Relationships between yield, pruning weight, canopy architecture and berry and wine chemistry

The correlogram representing the relationships between yield, pruning weight, canopy architecture and berry and wine chemistry is shown in Figure 9.5.

The correlation between Y and berry and wine chemistry was significant for five of the nine chemistry measures and mostly negative apart from the wine phenolics content which was positively correlated with Y. Pruning weight was highly and negatively correlated with berry and wine pH and positively correlated with wine phenolics.

Canopy architecture was more highly correlated with berry and wine chemistry when measured at flowering (EL23) and veraison (EL35) compared to EL31. In particular LAI at EL23 was positively correlated with TSS, berry TA and phenolics and wine TA and phenolics. It also showed a negative correlation with berry and wine pH. The highest correlations were observed with LAI and Por at EL 35. At this stage higher LAI reduced berry and wine pH, berry phenolics and tannins and wine alcohol while the wine phenolics were positively affected. Porosity showed the opposite correlations with the same measures.

Relationships between vine balance indices and berry and wine chemistry

All of the vine balance indices calculated showed a very similar correlation pattern with some of the berry and wine chemistry; in particular they all negatively correlated with berry TSS and hence wine alcohol while all but Y/LAI EL 35 negatively correlated with berry TA and phenolics (Figure 9.5). Berry pH was positively correlated with all indices but Y/LAI EL 31.Y/LAI EL 35 was highly correlated with wine pH.

Relationships between growth rate and berry and wine chemistry

The growth rate (GR) of the canopy was calculated as the % difference in LAI between flowering and veraison (GR 23-35) and between veraison and harvest (GR 35-38) (Figure 9.5). Faster growth between flowering and veraison was positively correlated with berry pH, TA, tannins and phenolics. Similarly, wine TA, anthocyanins, tannins and phenolics were positively correlated with GR 23-35. GR 35-38 negatively impacted on berry TA and wine tannins.

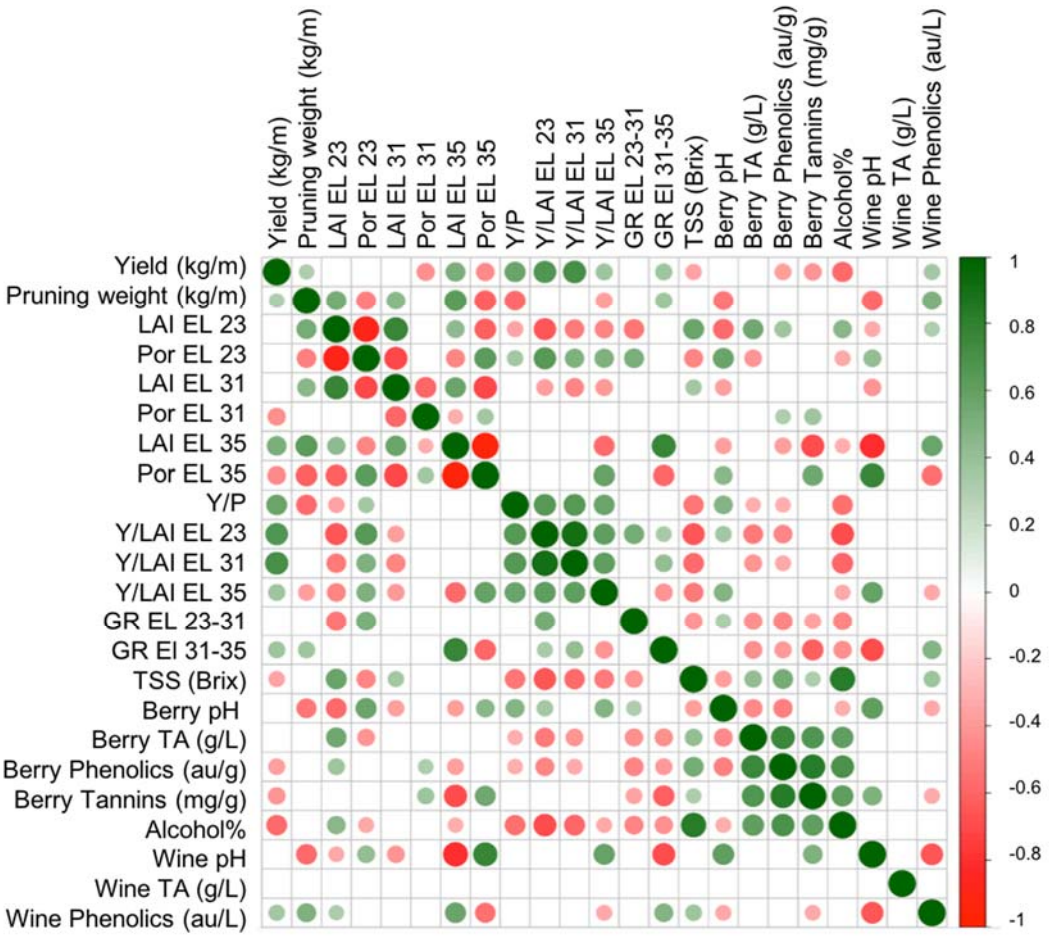


Figure 9.5: correlation map (correlogram) of yield (Y), pruning weight (P), canopy architecture (Leaf area index= LAI and Canopy Porosity= Por), vine balance indices (Y/P, Y/LAI) and growth rate (GR) and berry and wine chemistry measured in Semillon during three growing seasons (2014-15, 2015-16 and 2016-17). Canopy architecture was measured at three phenological stages (EL 23, 31 and 35). Only significant Pearson correlations coefficients (P≤0.05) are shown. Green circles correspond to significant positive correlation and red circles to significant negative correlations. The size and colour of the circles is indicative of the level of significance of the correlation.

Relationships between yield, pruning weight, canopy architecture and berry sensory attributes

Yield only mildly influenced some of the berry sensory characteristics while P was strongly and positively correlated with all of the skin attributes (Figure 9.6). All of the canopy architecture measures apart from Por EL 31 were correlated with berry characteristics. In particular, all the LAI measures were positively correlated with skin disintegration, acidity, citrus flavour and bitterness while the correlation between all these attributes and Por EL 23 and 35 was negative. LAI and Por at EL 35 had the greater number of correlations with BSA.

Relationships between vine balance indices and berry sensory attributes

The vine balance indices mostly showed negative correlations with BSA (Figure 9.6). All negatively correlated with berry sweetness, skin disintegration, citrus flavour of the skin, skin flavour intensity and skin tannin size. The grassy flavour was negatively linked to all but the Y/LAI EL 35 while Y/LAI EL 23 and 31 were positively link to the same attribute in the skin. Y/LAI El 35 also correlated negatively with skin acidity, bitterness and tannin size and with the intensity of the seeds flavour.

Relationships between growth rate and berry sensory attributes

A greater GR from EL 23 to 31 was associated with less sweet berries, with harder skin less citrus flavour and softer tannins (Figure 9.6). GR 31-35 positively affected the tropical flavour of the pulp, the skin acidity, grassy flavour, bitterness and astringency while the relationship was negative with pulp juiciness.

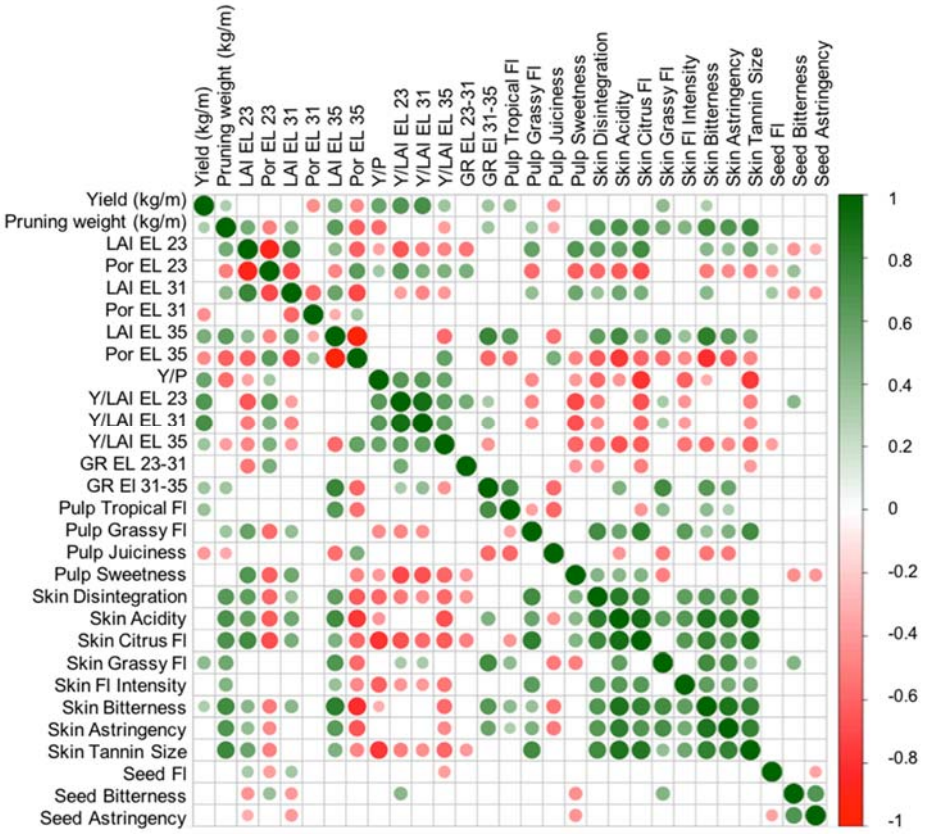


Figure 9.6: Correlation map (correlogram) of yield (Y), pruning weight (P), canopy architecture (Leaf area index= LAI and Canopy Porosity= Por), vine balance indices (Y/P, Y/LAI) and growth rate (GR) and berry sensory attributes measured in measured in Semillon during three growing seasons (2014-15, 2015-16 and 2016-17). Canopy architecture was measured at three phenological stages (EL 23, 31 and 35). Only significant Pearson correlations coefficients (P≤0.05) are shown. Green circles correspond to significant positive correlation and red circles to significant negative correlations. The size and colour of the circles is indicative of the level of significance of the correlation.

Relationships between yield, pruning weight, canopy architecture and wine sensory attributes

Y was positively correlated with wine citrus and tropical aroma and citrus flavour while negative correlations were found with bitter taste, astringency and length (Figure 9.7). Of the canopy architecture measured, Por EL 31 only showed a weak correlation with the bitter taste. A measure of LAI EL 35 showed the strongest correlations with wine sensory in particular, the relationships were positive with citrus and grassy aromas, acidity and citrus flavour while they were negative with confectionery aroma and citrus and dry grass flavour. Por EL 35 negatively correlated with citrus and grassy aroma and flavour and positively correlated with confectionery aroma, astringency and length.

Relationships between vine balance indices and wine sensory attributes

All the indices showed negative correlations with bitterness and dry grass flavour. Only Y/LAI EL 35 correlated negatively with citrus and grassy aroma while all the indices showed strong positive correlations with the confectionery aroma (Figure 9.7). Y/LAI EL 23 and 31 also showed similar negative correlations with dry grass flavour and body and positive with tropical aroma, acidic taste and citrus flavour.

Relationships between growth rate and wine sensory attributes

GR 23-31 showed a weak negative correlation to body (Figure 9.7). GR EL 31-35 was highly and positively correlated with citrus, tropical and grassy aroma, acidic taste and citrus flavour while the correlation was negative with body and length.

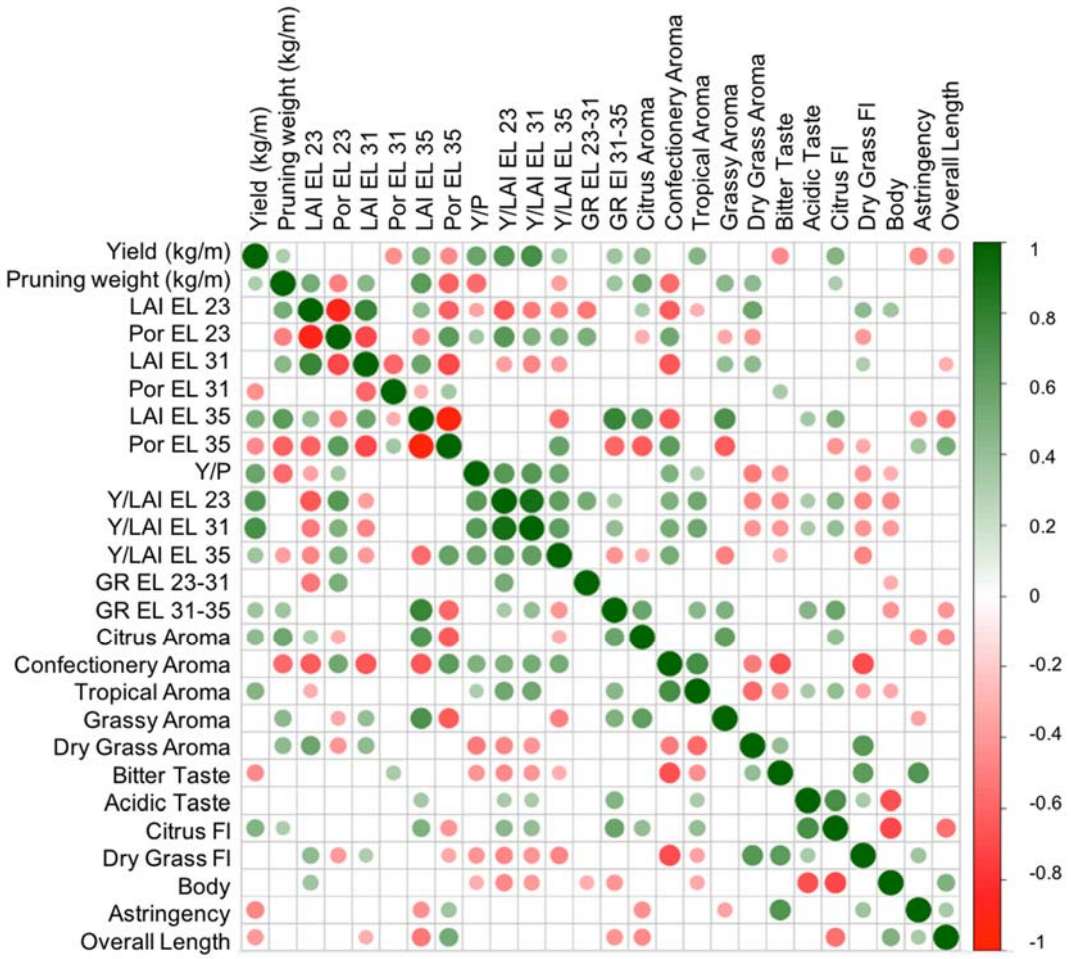


Figure 9.7: correlation map (correlogram) of yield (Y), pruning weight (P), canopy architecture (Leaf area index= LAI and Canopy Porosity= Por), vine balance indices (Y/P, Y/LAI) and growth rate (GR) and wine sensory attributes measured in measured in Semillon during three growing seasons (2014-15, 2015-16 and 2016-17). Canopy architecture was measured at three phenological stages (EL 23, 31 and 35). Only significant Pearson correlations coefficients (P≤0.05) are shown. Green circles correspond to significant positive correlation and red circles to significant negative correlations. The size and colour of the circles is indicative of the level of significance of the correlation.

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10 Near infrared (NIR) calibration of vine water potential

Feasibility of using Near Infrared Spectroscopy to measure water status of Cabernet Sauvignon and Shiraz

Precision irrigation can be achieved in grapevines using physiological measurements of vine water status. The current methodologies of assessing vine water status using plant based sensors are expensive and time consuming, notwithstanding the significant know-how required for their use and interpretation. An easy and accurate assessment can be performed using the Scholander pressure chamber to measure the leaf or stem water potential; however, this method is destructive, slow, labour intensive and requires the use of high pressure gas cylinders, with their inherent handling risks. Near Infrared (NIR) spectra from grapevine leaves can be calibrated against the traditional, vine water status measurements performed using the Scholander pressure chamber (Scholander et al. 1965). In the NIR spectrum of a leaf there are wavelengths strongly influenced by the water present in the leaf material. With statistical interpretation, water status of the plant can be determined and verified against the pressure chamber.

During the growing season 2011-12 a trial was established in a commercial vineyard to investigate the use of near infrared spectroscopy (NIR) as a commercial tool for estimating vine water status based on De Bei et al. (2011). De Bei et al. (2011) demonstrated that calibration models for the prediction of grapevine water status from the near infrared spectral properties of leaves could be built and the accuracy of these models could be high. However, the same study also noted that the accuracy of the calibration models for estimating SWP from NIR spectra is variety, location and phenology dependent. Taking these factors into consideration, measurements were taken throughout the season on both Cabernet Sauvignon and Shiraz vines using the ASD fieldspec instrument which has a wavelength range of 350-1830 nm and a spectral resolution of 1 nm.

Results from the first season using the fieldspec were very satisfactory, as reported in Figure 10.1 and in line with De Bei et al. (2011). However, despite the accuracy obtainable with the instrument used (fieldspec), after using it for a whole season it was clear that such an instrument requires know-how for correct use (highly trained operators required), it is not fully portable, it requires the use of a laptop connected to the instrument and it is cost-prohibitive (AUD$60,000), so that its use in a commercial vineyard was limited.

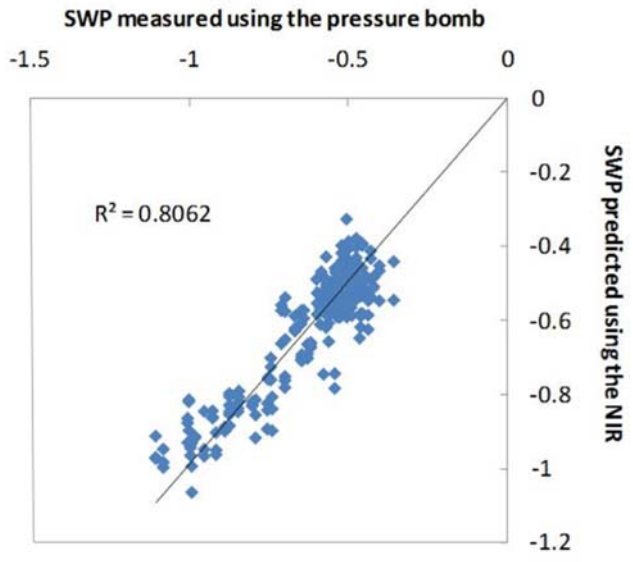


Figure 10.1: NIR predicted midday stem water potential (SWP) versus reference data obtained using a pressure chamber in Cabernet Sauvignon in the Coonawarra wine region.

The University of Adelaide, through the 'vineyard of the future' initiative, purchased a new NIR-based instrument, the Thermo Scientific MicroPHAZIR. This instrument offered the advantage of being more affordable (AUD$25,000), highly portable, light, does not require trained operators, ease of use, and ease in downloading results. However the spectral range is only 1600-2400 nm and the spectral resolution 8nm. A trial was established in the Coonawarra region during the growing season 2012-13. Grapevine water potential and NIR data were collected at key phenological stages on multiple Cabernet Sauvignon and Shiraz blocks. TWE personnel were involved in in-field data collection and UofA personnel conducted the data processing and analysis.

Calibrations were developed for both Cabernet Sauvignon and Shiraz. Models were developed using 'The Unscrambler' software (version 10X, CAMO ASA, Norway), in order to apply spectra pre-processing when needed and perform principal component analysis to detect patterns in the data. The software was also used for outlier detection. Once a good model (High R^2 and low standard error of prediction (SEP)) was obtained, data were transferred to the MicroPHAZIR software in order to rebuild the model and install it in the unit. Once a model is installed in the unit, the instrument will display on the screen a result as water potential (MPa) when pointed at a leaf. When using the MicroPHAZIR it was evident that models were not as accurate as those obtained using the ASD fieldspec. Models obtained with spectra from the ASD unit always resulted in a higher R^2 and lower SEP which also meant a better prediction of new data when the model was used. The highest R^2 obtained with the MP was 0.74 however when that model was applied, it failed to predict new data producing an R^2 in the validation of 0.23. Figure 10.2 shows the correlation between SWP measured using the pressure bomb and the prediction displayed by the MP.

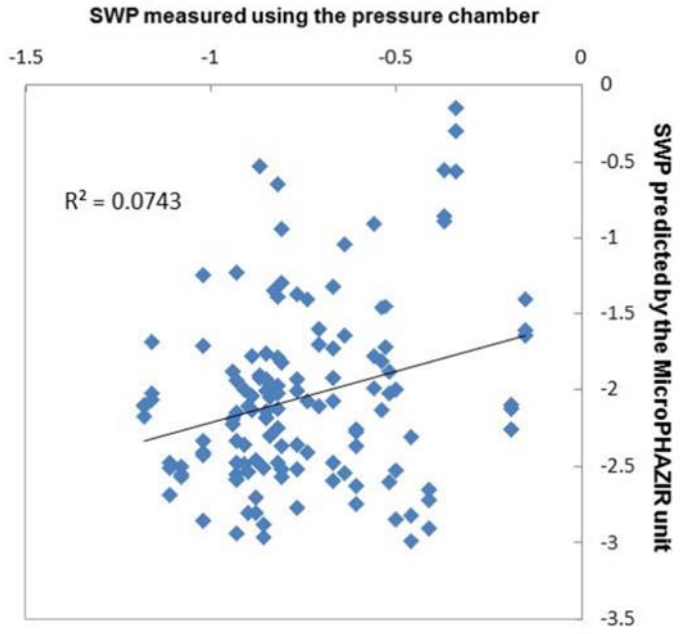


Figure 10.2: Correlation between midday stem water potential (SWP) measured using the pressure chamber and the results obtained by the MicroPHAZIR when a prediction model is installed in the unit.

We believe that the small wavelength range measured by the instrument, 1600-2400 nm, despite containing the main water peak in the NIR region (1930 nm), is not adequate to obtain reliable calibrations like those reported by De Bei et al. (2011) using the ASD fieldspec. Also, the low resolution of the MP might be causing a reduction in model accuracy.

The trialled instrument failed to produce reliable and applicable results. However, new instruments and new analysis techniques have come to the market since 2014. Research is ongoing on the feasibility of using NIR spectroscopy in the vineyard. A recent GiESCO conference report from Dr Maria P. Diago from the University of La Rioja, Spain, showed some good results by using NIR on-the-go from a moving vehicle (5 km/h). Values of R^2 above 0.83, 0.75 and 0.66 were obtained for calibration, cross-validation and prediction and the standard error of the prediction (SEP) was between 0.139 and 0.152 MPa. These results are promising however no NIR tools are yet available for growers to assess water status of the grapevine.

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11 Outcomes and Conclusions

Determine canopy parameters that indicate optimal vine performance and wine quality and evaluate how effectively these can be manipulated using management techniques.

Vine performance was manipulated using a series of management techniques in five vineyards located in different wine regions. In the experimental trials in collaboration with Treasury Wine Estates, timing of management practices and harvest dates were decided by the local vineyard managers and/or viticulturists. Also, some of the treatments applied were region-specific.

Vines responded differently to the same treatments depending on the region and season. In general, and as a three-season average, the traditional canopy management practices (leaf plucking, shoot thinning and bunch thinning) only produced minor effects on vine performance. Shoot thinning applied using industry standards was mostly ineffective in changing yield, yield components and berry and wine chemistry and sensory attributes; it is however an expensive management practice. Intrieri and Poni (1995) reported that shoot thinning a spur-pruned cordon can require up to 50-60 hours per ha. Leaf plucking did not show any effects in the Barossa and Coonawarra vineyards while only minor effects on yield were observed in Padthaway and McLaren Vale. In all cases, VitiCanopy was unable to show a significant change in LAI or canopy porosity from the shoot thinning or leaf plucking applications. When both these treatments were applied at a higher rate in the experimental Semillon vineyard at the Waite campus, significant changes in LAI and canopy porosity were captured using VitiCanopy which translated into significant effects on yield and yield components and also significant changes in fruit and wine sensory. This highlights that VitiCanopy effectively captured changes in LAI and canopy porosity and can be a useful tool to assess the outcome of a management intervention. It would be interesting to use VitiCanopy to assess canopies that have had mechanical shoot thinning or leaf plucking as this may remove more leaf area. When changes in canopy architecture were observed this was mostly evident at the time of the management application but tended to disappear towards the later stages of development. This phenomenon has been previously described in various cultivars as growth compensation from the retained shoots (Dokoozlian 2010, Myers et al. 2008) even when the shoot reduction was as high as 50% (Bernizzoni et al. 2011) as in this study. In the Semillon vineyard, the shoot thinning, as expected, showed a lower LAI and higher porosity in the early phenological stages, compared to control however the yield did not differ due to a compensation in bunch weight and berry weight for the shoot thinned vines. These changes translated into lower phenolic content of the wines and berry sensory characteristics associated with greenness, acidity and higher astringency. The wines made from the fruit of shoot thinned vines were different from the control in all seasons but the significantly different attributes were season-dependent.

Bunch thinning applied as per the industry standard only had a minor effect on vine performance. There was an obvious reduction in the number of bunches per metre in all sites, however no changes were

detected in yield due to changes in bunch architecture (higher bunch weight) which compensated for the loss of bunches. Only in Padthaway was yield reduced in response to bunch thinning. The effect on grape and wine chemistry and sensory was also very minor. Palliotti and Cartechini (1998) showed that for bunch thinning to reduce yield, the intensity should be at least 40%, which was never applied in the commercial vineyards included in this study. When the same treatment was applied in the Semillon vineyard at a level of 50%, a yield reduction was observed compared to the control, lower number of bunches with no compensation in bunch weight until the third season of application where an increase in berry size was observed. The wines made from the fruit of bunch thinned vines were different to the control and were described as more bitter, with more body and a longer aftertaste in all three seasons.

A cover crop is normally used as a management practice to suppress excessive vine vigour (Giese et al. 2015, Guerra and Steenwerth 2011), which is generally associated with inferior fruit quality (Smart and Robinson 1991) and increased disease pressure (Dry and Loveys 1998; Rotem and Patti 1969). Both in McLaren Vale and Padthaway, the cover crop treatments achieved the results sought by significantly reducing vigour (lower LAI) and increasing canopy porosity as reported in previous literature (Tesic et al. 2007). A strong effect was also observed in pruning weight, bunch number and bunch weight, which were all significantly reduced. Only in one of the three seasons, in McLaren Vale, did the cover crop treatment show an effect on berry chemistry as an increase in tannin and phenolic content, which has been previously documented as an effect induced by the more open canopies (Dokoozlian and Kliewer 1996, Keller and Hrazdina 1998, Spayd et al. 2002). Conversely, in the first season of the Padthaway trial, the cover crop reduced the amount of anthocyanin, tannin and phenolic compounds in the berries. Berry sensory assessment, in McLaren Vale, showed that the cover crop treatment compared to the control had a higher dark fruit flavour, astringency and bitterness; similarly, the wines from the cover crop treatment were higher in dark fruit flavour, astringency, tannic intensity and length compared to control however, the control wines were more liked. These differences were also observed in Padthaway where the cover crop treatment reduced yield in all seasons due to a reduction in the number of bunches on the vines and a reduction in bunch weight by the third season of application. Wines were only made in season three and they did not differ from the controls for chemistry but they were described as more jammy in flavour and more liked when judged during the descriptive analysis. A study from Wheeler et al. (2005) on Cabernet Sauvignon found similar results; wines obtained from plots with a cover crop had riper aromas and flavours compared to the control and in general the wines from vines grown with cover crops obtained higher overall ratings.

Sacrificial or kicker canes are extra canes left on the vines at pruning with the aim to reduce shoot vigour. The literature on sacrificial canes is scarce and a study by Longbottom et al. (2003) has shown that the devigorating effect is evident only when four or more kickers are left on the vines. In this study, the use of four sacrificial canes per vine generally resulted in a significant decrease in yield and LAI especially after the third season of continuous application, when a carry-over effect was evident. The

effect was more significant when kickers were removed later in the season rather than at flowering. Surprisingly, no significant changes were observed in the chemistry and sensory outcomes from this practice. Longbottom et al. (2003) also found that kickers did not influence berry chemistry. If kicker canes are used to reduce vine vigour, the results obtained here suggest that the number of sacrificial canes retained and the timing of removal should be carefully considered. Moreover, the carry over effect observed after three seasons of application suggests that kickers should not be used on the same vines for more than two consecutive seasons. It should also be considered that cover crops could be applied to supress vigour without the negative effect of increasing vine variability and at a potential lower labour cost compared to sacrificial canes. Lastly, as observed by Bramley and Lamb (2003) and Bramley (2010) vineyards are managed on the assumption of uniformity but it is well known that all agricultural systems present various levels of variability. Managing this variability is the basis of precision viticulture which considers vineyards as a group of zones with different characteristics and thus requiring different management or zonal management for efficient use of inputs, programming of grape harvest, yield forecast etc (Bramley and Lamb 2003, Bramley and Hamilton 2004, Martínez-Casasnovas and Bordes 2005). In this study, it was observed that sacrificial canes created a high variability in yield and canopy architecture between vines that may lead to more inconsistent batches of fruit. An increase in variability between vines could result in management issues around the application of irrigation, fertilisers, crop protection and sampling strategies which, being at the vine level, would be more difficult to overcome even with the use of precision viticulture tools.

Pruning after budburst, (EL 9-11) (Coombe 1995) was evaluated as a possible strategy to delay ripening and hence counteract the compression of the harvest period that has been reported as an effect of climate change (Petrie et al. 2017, Palliotti et al. 2014). Late pruning, similarly to sacrificial canes, had a strong effect of reducing vine vigour. Moreover, a large yield loss was observed compared to the control treatments after the first season. Gatti et al. (2016) observed a similar yield loss due to reduced number of bunches per vine and berries per bunch when pruning Sangiovese at the phenological stage BBCH17 (Lorenz et al. 1995) which corresponds to EL 14 (Coombe, 1995). Similarly, Petrie et al. (2017) showed that delaying pruning beyond EL9 reduces yield but if carried out before this phenological stage no yield effects were observed. A study on Merlot in New Zealand showed a yield increase associated with late pruning carried out when the apical shoots on the canes were about 5 cm long (Friend and Trought 2007). Gatti et al. (2017) infer that pruning at EL 14 might trigger severe carbohydrate limitations that can cause pre-developed inflorescence primordia to revert to tendrils and hence yield loss. Both in McLaren Vale and Padthaway differences were also observed in chemistry and sensory attributes of both grapes and wines however these differences could be due to the fact that the late pruned vines were generally harvested two weeks after the control and at a higher sugar level. From these results, and taking into account the large yield reduction observed, it is suggested that in these trials late pruning, at EL 9-11, was not effective in delaying ripening. Moreover, it generated a high variability in yield

between vines and in phenology within the same vine; it was observed that, within the same vine, bunches were at different stages of ripening.

Vine Balance

The correlations found in this study showed that yield is a poor indicator of the final grape and wine chemistry. While it is believed that there is an inverse relationship between yield and quality (Bravdo et al. 1984), the contrary has been demonstrated numerous times (Reynolds et al. 1986, Preszler et al. 2013). Interestingly, Chapman et al. (2004) found that the impact of yield on wine sensory attributes depended on the method by which crop was altered. In this study, canopy architecture measures, such as LAI and porosity correlated better than yield with some of the grape and wine chemistry and sensory attributes, demonstrating that canopy architecture measured using VitiCanopy early in the season could be indicative of the final grape and wine chemistry measures. For example, it was observed that a higher canopy porosity at flowering is linked to more favourable grape and wine chemistry measures such as titratable acidity, tannins and phenolic content. Not surprisingly, pruning weight also correlated with chemistry and sensory attributes in a similar way to LAI at harvest. Both these measures were found to be more indicative of the final quality than yield.

When the ratios between canopy size, pruning weight and yield are calculated as indicators of vine balance, it was observed that Y/P and Y/LAI produced very similar correlations with berry and wine chemistry, especially when the flowering LAI measure was used. Also, Y/P and the simple porosity measure at harvest consistently showed very similar correlations with chemistry and the two variables were very highly correlated. However, the simple measures of LAI and porosity obtained with VitiCanopy correlated similarly or sometimes even better than the above-mentioned vine balance indices with the advantage of being easier to measure and that they can be taken earlier in the season thus allowing for management decisions to be made accordingly. It was also observed that the early season canopy architecture measures are better indicators of grape and wine quality than the veraison measures.

Canopy growth in grapevine is typically high in spring, decreases during summer and stops at around veraison (Matthews et al. 1987). In this study, growth rate was calculated as the percentage growth from flowering to veraison and from veraison to harvest and it seemed to explain some of the final grape and wine quality outcomes. It has been previously reported that early leaf area reductions can delay the onset of veraison and extend the veraison-ripening period (Howell 2001). This study showed that the establishment of a good canopy early in the season, here indicated by a greater growth rate, correlates positively with grape and wine chemistry measures. Conversely, a greater late season growth rate, from veraison to harvest, is detrimental to quality. This suggests that canopy growth should be promoted only until veraison. Calculating growth rate from budburst to flowering, which was not included in this study, might also give good indications on final quality.

Vine balance can be effectively measured using new indices that calculate LAI and canopy porosity using VitiCanopy. These measures of vine balance can be obtained easily and timely compared to a measure of pruning weight or destructive measures of leaf area which, being very time consuming, are currently not used in commercial practice. It needs however to be taken into account that vine balance measures, even when carried out using the easy VitiCanopy App, would still rely on accurate early yield predictions.

Develop an accurate, inexpensive, labour saving toolbox for assessing vine balance infield and deploy this toolbox to the industry.

VitiCanopy has proved to be an easy and effective tool to measure canopy architecture parameters. The positive correlations observed between early measurements of canopy architecture, growth rate and grape and wine quality attributes show that VitiCanopy could be used as a predictive tool for final quality. Moreover, VitiCanopy's ability to deliver processed data in real time allows for proactive management decisions to be made. The geo-referencing of the results offers numerous advantages; implementing VitiCanopy during routine vineyard operations could be practical to assess spatial differences in canopy architecture within a vineyard and can be related to other viticultural management strategies, such as irrigation and fertilisation.

VitiSense, will provide users with an easy tool to perform a structured and geo-referenced berry tasting assessment in the vineyard, amongst other sensory assessments. The plasticity of the tool allows users to assess as few as one attribute and save the results in an Excel file. Combining the use of VitiCanopy and VitiSense can provide easy indications of the links between canopy architecture and grape sensory attributes in a vineyard. The geo-location of the measurements obtained with both tools allows for users to assess the same indicator vines for both canopy architecture and sensory attributes. The spatial and temporal variation of the attributes could be visualised in heat maps, such as those in Figure 1, where the distribution of LAI in the Semillon vineyard at the Waite Campus has been mapped across four rows (Figure 1a). Thanks to the link that was found between LAI and berry acidity when tasted using VitiSense, the latter parameter could be mapped for the same vines, thus showing its distribution across the four rows (Figure 1b). Such maps could be used as decision-making tools to indicate optimum harvest time or fruit allocation in the winery.

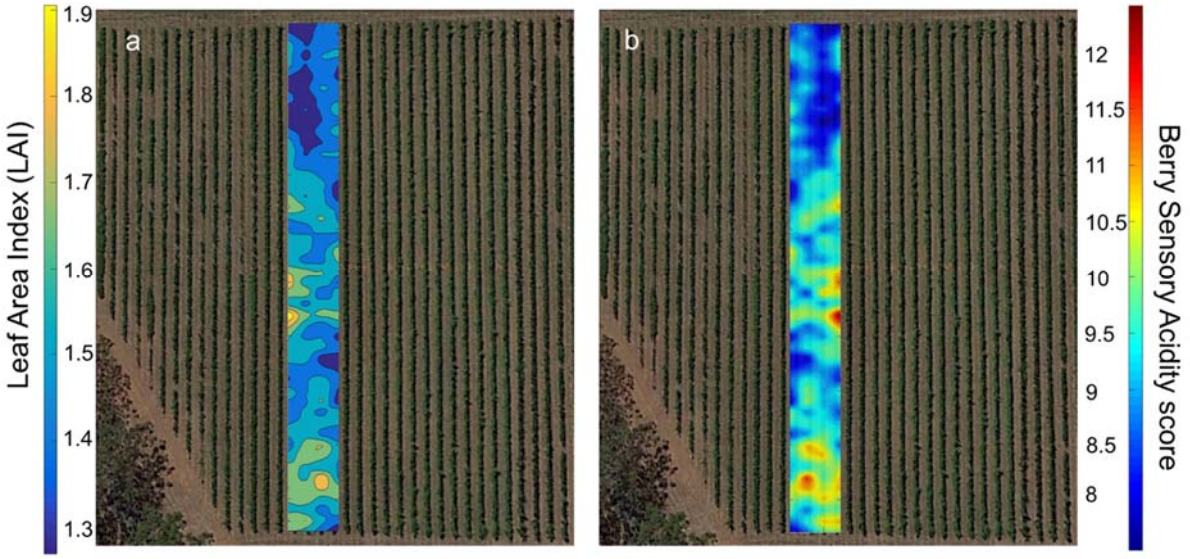


Figure 1: Spatial distribution map showing changes in LAI across four rows in the Semillon vineyard at the Waite Campus measured using VitiCanopy (a) and the corresponding berry acidity perceived by sensory assessment of the grapes from the same vineyard measured using VitiSense (b).

Routine information gathering can also be achieved using VitiCanopy to create a record/history of practices and responses from grapevines in order to make more informed decisions to achieve specific wine styles and vineyard uniformity.

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12 Recommendations

Results from the three season trials on five vineyards in different wine region across South Australia has shown that canopy management strategies and intensity need to be carefully considered. Many commonly used commercial practices and approaches tested in this study proved to be ineffective at changing vine performance, berry and wine chemistry and berry and wine sensory. Practices that reduce canopy vigour were more effective than those that removed leaves, shoots or bunches. Interestingly all of these practices are more expensive to apply than the use of floor management practices such as cover crops or under vine growth (Table 1).

Table 1: Estimated costs of canopy management treatments per ha. Estimates are based on 1800 vine/ha. Source DJs growers, personal communication.

Treatment	Management cost $/ha	Difference with control
Control (only pruning)	1080	-
Cover Crop	1260	+ 180
Bunch Thinning	1350	+ 270
Leaf Plucking	1330	+ 450
Shoot Thinning	1710	+ 630

VitiCanopy proved to be successful in showing whether a management treatment was effective in modifying canopy architecture. In most cases, when VitiCanopy was unable to show a change, the treatment proved ineffective in changing vine performance. Moreover, it was shown that VitiCanopy can be used to calculate canopy growth rate between phenological stages. It was demonstrated that a greater growth rate from flowering to veraison was positively correlated with quality attributes of the grapes and wine, while a greater growth rate between veraison to harvest correlated negatively with quality. In future studies, the growth rate from budburst to flowering, which was not included in this study, will be calculated to explore its implications for final quality.

VitiCanopy offers the advantages of a grower friendly interface, the ability to deliver processed data in real time and the availability of geospatial data with every measurement taken. However, the tool at present has some limitations, such as:

- Limited to validations made up to date: vertically shoot positioned (VSP) and small to medium sprawling canopies.
- It does not allow for batch analysis of the images.
- Similarly to other commercial instruments for measuring LAI, VitiCanopy does not distinguish between leaf and non-leaf (shoots and cordon) material so that often the results are referred to as plant area index (PAI) (Breda, 2003).

VitiCanopy can be improved as follows:

- Develop add-ons that allow for the assessment of different training systems.
- Develop algorithms for dense canopies using wide angle camera lenses.
- Implement algorithms for images taken from the side of the canopy so that the influence of the cordon can be eliminated, and measurements of bunch exposure can be made. Side images would also offer the possibility of mounting the sensor/camera on board a moving vehicle (tractor) so that canopy images/videos can be taken while carrying out routine vineyard operations.
- Develop pruning weight algorithms based on image analysis of canes pre and post pruning.
- Create a web-based platform for batch analysis of the images, data storage, data mapping and visualisation of both current and previous seasons data.
- Explore the potential to implement new algorithms for the analysis of whole vineyard images taken from unmanned aerial vehicles (UAV) or high resolution satellite images.

Future research direction should explore the links between canopy architecture, vine balance and berry quality for different varieties, training systems and wine regions using machine learning modelling techniques. Moreover, given the dependency of vine balance indices on accurate yield estimations, future research should focus on achieving accurate early yield prediction and machine learning based modelling techniques.

Appendix 1: Communication

Articles in scientific and industry journals regarding various aspects of the project have been published (see below). Some of this work has also been presented at the Australian Wine Industry Technical Conferences as well as other national and international meetings, workshops and conferences.

During this project we have had the support and interest of a number of industry individuals and companies. In particular, we have been involved in discussions with grape growers and winemakers in the Coonawarra, Padthaway, Riverland, McLaren Vale, Adelaide Hills, and Barossa Valley regions. Both the proposed research and the results of each season's work and its potential for the industry have been discussed. Discussions and presentations to key personnel in other regions have also occurred. The feedback we have received has been useful in guiding and refining our experimental design and research direction. We will continue to engage with the industry as we progress this work.

Industry and Scientific Presentations (oral and posters)

De Bei R., Fuentes S., Gilliham M., Tyerman S. and Collins C (2017). Practical use of vine balance and new ways to measure it. In Vine balance: what it is, what it does and how to measure it workshop. Nov 30th and Dec 1st 2017, Barossa Valley and Langhorne Creek. In collaboration with CSIRO

De Bei R., Fuentes S., Hook J., Gilliham M., Tyerman S. and Collins C. VitiCanopy: what do the number mean? SPAA (Society of precision agriculture Australia) Precision viticulture workshop. Jun 22nd 2017 Langhorne Creek. Invited speaker.

De Bei R., Fuentes S., Gilliham M., Tyerman S. and Collins C. Canopy management using grower-friendly digital tools. ComBio 2017, Oct 2nd-5th Adelaide. Invited speaker

De Bei R., Fuentes S., Hook J., Gilliham M., Tyerman S. and Collins C. (2017). Grapevine canopy management using the VitiCanopy App. Submitted to the 40th World Congress of Vine and Wine, May 29th – Jun 2nd, 2017; Sofia – Bulgaria. To be published in Bio Web of Conferences (open access journal)

De Bei R., Collins C., Fuentes S. and Scott E. (2016). Grower friendly digital tools for vineyard management. X International Symposium on Grapevine Physiology and Biotechnology. Verona Jun 2016 (poster)

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Industry and Scientific Papers

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Collins C., De Bei R., et al. 2014. Vine balance is driving fruit composition and developing an industry 'toolbox'. Australian and New Zealand Grapegrower and Winemaker. 603: 50-52.

Software Development

VitiSense: an application (App) to record berries and wines sensory analysis results

VitiCanopy: an application (App) for smartphones and tablet PCs to measure grapevine canopy architecture in vineyards. VitiCanopy transforms any iOS devices into effective instruments to measure leaf area index and other canopy architecture parameters. VitiCanopy is available for download at:

https://itunes.apple.com/au/app/viticanopy/id1042914901?mt=8
https://play.google.com/store/apps/details?id=au.com.laicanopy.laicanopy&hl=en

A video guiding users on the use of VitiCanopy is available at: https://www.youtube.com/watch?v=Eqzmuruubm8 and on the Plant Transport and signalling group of the School of Agriculture Food and Wine website: http://www.plantransig.com/techniques/viticanopy/

VitiCanopy was launched for iOS devices in October 2015, and for Android devices in November 2016. The combined iOS and Android download of the App to date (December 2017) is about 3000 units (from Apple Store and Google Play statistics).

The development and launch of VitiCanopy were featured in numerous Australian and international news, newsletters and websites. Figure 1 shows the number of citations VitiCanopy has received in scientific journals and media since its launch in 2015.

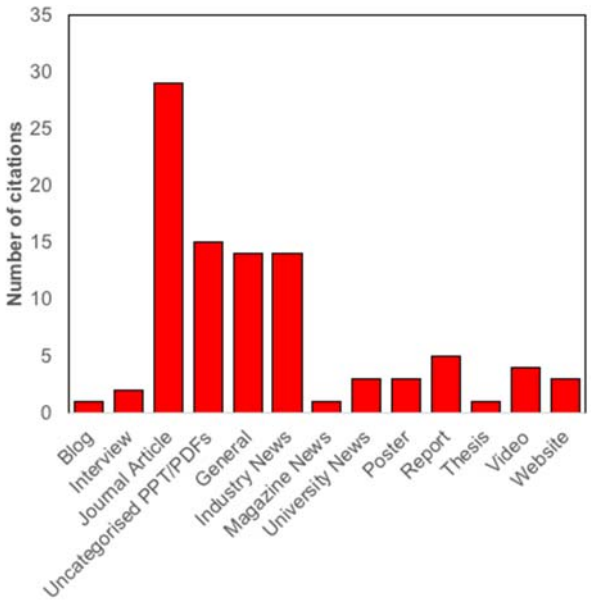


Figure 1: number of citations received by VitiCanopy since its launch in October 2015.

News articles available to the general public appearing in Australian (Table 1) and International (Table 2) general, industry or university magazines discussing VitiCanopy are detailed below.

Table 1: News articles available to the general public appearing in Australian General, Industry or University Magazines discussing VitiCanopy App including the year published, the source and web link.

Title	Year	Source	Link
Wine production controlled through new technology	2016	The Australian Financial Review	http://www.afr.com/news/special-reports/wine-production-controlled-through-new-technology-20160307-gncemc
App to help manage grapevines	2015	PHYS ORG; University of Adelaide	https://phys.org/news/2015-10-app-grapevines.html
Henschke Take Top Billing At Australian Women In Wine Awards	2016	Glam Adelaide	http://www.glamadelaide.com.au/main/henschke-take-top-billing-at-australian-women-in-wine-awards/
New tool for grapevines	2015	Science Meets Business	http://sciencemeetsbusiness.com.au/new-tool-for-grapevines/
New tool to help manage grapevines	2016	expertguide.com.au	http://www.expertguide.com.au/news/article.aspx?ID=2699
VitiCanopy		Plant Transport & Signalling Group	http://www.plantransig.com/techniques/viticanopy/
VitiCanopy		Plant Image Analysis	http://www.plant-image-analysis.org/software/viticanopy
App launched to assess vineyard disease	2016	thedrinksbusiness; Lauren Eads	https://www.thedrinksbusiness.com/2016/01/apps-launched-to-help-fight-vineyard-disease/
Viticulture app part of award-winning research	2017	Wine Australia	https://www.wineaustralia.com/news/articles/viticulture-app-part-of-award-winning-research
Smart app may help to manage grapevines increase wine quality	2015	Technology Org; adelaide.edu.au	https://www.technology.org/2015/10/23/smart-app-may-help-to-manage-grapevines-and-increase-wine-quality/
An app for measuring grapevine canopy architecture	2016	Horticulture Industry Network	http://www.hin.com.au/associations/horticulture-centre-of-excellence/viticanopy
App assists vine control	2015	Murray Valley Winegrowers Inc.: MVW News & Views (Nov 2015)	http://www.mvwi.com.au/items/738/MVW%20News%20&%20Views%20-%20November%202015.pdf
New tool to help manage grapevines	2016	Australian Table Grape Association Inc.; The Vine (Magazine)	http://www.australiangrapes.com.au/wp-content/uploads/2016/03/TV-Mag-JAN-MAR-web-1.pdf
The Data Revolution - Wine Boffins	2017	Qantas Inflight Magazine: Qbusiness	https://www.qantas.com/travel/airlines/spirit-of-australia/global/en
New tool to help manage grapevines	2015	University of Adelaide; News	https://www.adelaide.edu.au/news/news81346.html
Australian women in wine researchers of the year	2016	The Waite (Research Precinct)	https://www.thewaite.org/australian-women-in-wine-researchers-of-the-year/
Wine production controlled through new technology	2016	UoM; Networked Society Institute	http://networkedsociety.unimelb.edu.au/news-events/news/wine-production-controlled-through-new-technology

Table 2: News articles available to the general public appearing in International General, Industry or University Magazines discussing VitiCanopy App including the year published, the source and web link.

Title	Year	Source	Link
汇盛国际开户:APP外包 阿德莱德大学团队开发葡萄 (APP Outsourcing University of Adelaide team development grapes)		Huisheng International	http://www.douji66.com/huodong/24.html
新一代的葡萄培养方面的食用醋酸传感器驱动东西; food-grade acetic acid sensors	2017	Henan Chen food technology co., LTD	http://www.hncgsp.com/news/413.html
Una APP que simplifica la gestión del viñedo	2015	Vinos de Castilla La Mancha (Vinos C-LM)	http://vinosdecastillalamancha.es/una-app-que-simplifica-la-gestion-del-vinedo/, https://vinoscastillalamancha.wordpress.com/2015/11/20/una-app-que-simplifica-la-gestion-del-vinedo/
Nueva aplicación para dispositivos móviles que simplifica la gestión del viñedo	2015	inforwine	http://www.infowine.com/es/noticias/nueva_aplicaci_n_para_dispositivos_m_viles_que_simplifica_la_gesti_n_del_vi_edo_sc_13022.htm#
手机APP也能用于葡萄种植？	2016	wineita.com	http://www.wineita.com/html/2016/zgjybd_0108/1280.html
葡萄種植農福音：手機APP也能評估葡萄園疾病	2016	read01	https://read01.com/KyR0zB.html#.WjDUrd-WY2w
手机APP也能评估葡萄园疾病 (Mobile APP also evaluates vineyard diseases)	2016	iqilu.com	http://wine.iqilu.com/cyqs/jjwh/2016/0111/2660284.shtml
葡萄酒届迎来新技术 可全面监测葡萄树成长 (Wine usher in new technologies to fully monitor vine growth)	2016	www.buuyee.cn	http://www.buuyee.cn/news/133.html
Viticanopy estime la surface foliaire depuis un smartphone	2017	Réussir vigne	http://vigne.reussir.fr/actualites/viticanopy-estime-la-surface-foliaire-depuis-un-smartphone:VDA1F5F2.html
VitiCanopy: une appli pour mesurer la canopée	2015	www.mon-viti.com	https://www.mon-viti.com/filinfo/viticulture/viticanopy-une-appli-pour-mesurer-la-canop%C3%A9e
Smart app might assistance to conduct grapevines and boost booze quality	2015	Global News Connect	http://globalnewsconnect.com/smart-app-may-help-to-manage-grapevines-and-increase-wine-quality/
Factory vs foot-crushing: which wine tastes best?	2017	Sanlam Private Wealth	http://1of1privatecollection.co.za/wine-offers/factory-vs-foot-crushing-which-wine-tastes-best/
OIV News	2017	OIV	http://www.oiv.int/public/medias/5456/oiv-news-16062017.pdf
Australian app to help combat powdery mildew goes global	2017	VINEX	http://es.vinex.market/articles/2017/01/06/australian_app_to_help_combat_powdery_mildew_goes_global
VitiCanopy (Unreleased) is now in Open Beta in the Play Store	2016	Free Press Release	http://www.free-press-release.com/news-viticanopy-unreleased-is-now-in-open-beta-in-the-play-store-1479627934.html
Une application australienne pour piloter la vigne	2017	Vitisphere	https://www.vitisphere.com/actualite-84500-Une-application-australienne-pour-piloter-la-vigne.htm

Awards

2016. Australian Women in Wine Awards. Researchers of the year 2016. The Fabulous Ladies' Wine Society



Appendix 2: Intellectual Property

The intellectual property developed in this project is outlined in the above report. Some information has already been published in refereed or industry journals so that it is freely available. Some remaining work is still being prepared for publication and will be made available as soon as possible. Much of this work has been discussed in other, non-print forums. All results and publications are checked before external discussions for any IP that may be deemed as suitable for protection. As we are trying to develop methods that will have a practical outcome we are very aware of the issues involved with intellectual property protection.

Appendix 3: Staff and Acknowledgements

A number of staff and students worked on this project during the four years it was running. A list of these people is given below.

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Ms Sandra Olarte (UA)
Mr Marcos Bonada (UA)
Mr James Hook (Masters student UA)
Ms Xiaoyi Wang (Masters student UA)
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Ms Catherine Wotton (TWE)
Ms Jana Shepard (TWE)
Dr Paul Petrie (TWE)
Ms Suzanne McLoughlin (TWE)
Ms Amy Richards (TWE)

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Appendix 4: Budget reconciliation

The End of Project Financial Statement was submitted online via Wine Australia's Clarity Investment Management System.