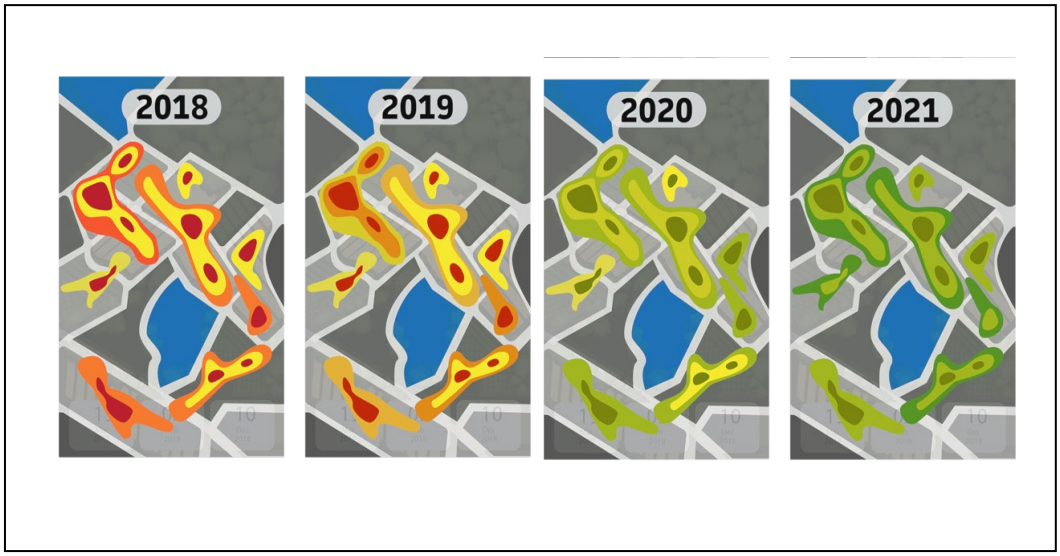
Australian Government
Wine Australia

THE UNIVERSITY of ADELAIDE

DIGITAL TOOLS FOR CANOPY MANAGEMENT TO INCREASE COMPETITIVENESS



FINAL REPORT TO WINE AUSTRALIA

Project Number: **UA1803 1.1**

Principal Investigators: **Dr Roberta De Bei**
A/Prof Cassandra Collins

Research Organisation: **UNIVERSITY OF ADELAIDE**

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Wine Australia Final Report

Project No. UA1803 1.1

Project Supervisor: **A/Prof Cassandra Collins**
Principal Researcher: **Dr Roberta De Bei**

University of Adelaide, Australia

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Table of Contents

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1. Abstract 4
2. Executive Summary 5
3. Background 7
4. Project Aims 9
5. Methods 12
5.1 VitiCanopy redevelopment 12
5.2 Automated image-capture system development 16
5.3 Case studies 18
5.3.1 Case study 1: Semillon canopy management 18
5.3.2 Case study 2: Premium Shiraz vineyards, Barossa Valley 20
5.3.3 Case study 4: Comparisons between VitiCanopy, NDVI and image resolution 21
5.3.4 Case study 5: Chardonnay vineyards in the Riverland region 21
5.3.5 Case study 6: Use of VitiCanopy to assess pruning weight 22
5.3.6 Measuring grape extracts using a spectrofluorometer system 23
5.3.7 VitiCanopy improvements in progress 23
6. Results/Discussion 25
6.1 Climatic conditions 25
6.2 Case Study 1: Semillon canopy management 26
6.2.1 Canopy architecture, yield components and grape composition 26
6.2.2 Canopy PAI throughout a season 35
6.2.3 Canopy PAI same EL stage between seasons 36
6.2.4 Canopy PAI, light interception, canopy temperature and wine aroma 37
6.2.5 Juice elemental analysis 37
6.2.6 AQUALOG Spectrofluorometer analysis 38
6.3 Case Study 2: Premium Shiraz vineyards, Barossa Valley 41
6.3.1 Vineyard 1 41
6.3.2 Vineyard 2 46
6.3.3 Vineyard 3 51
6.4 Case Study 3: Use of VitiCanopy for canopy management decision-making 54
6.5 Case Study 4: Comparisons between VitiCanopy, NDVI and image resolution 55
6.6 Case Study 5: Chardonnay vineyards in the Riverland region 57
6.7 Case Study 6: Use of VitiCanopy to assess pruning weight 62
7. Outcome/Conclusion 65
8. Recommendations 67
9. Appendix 1: Communication 68
10. Appendix 2: Intellectual Property 71
11. Appendix 3: References 72
12. Appendix 4: Staff 75
13. Appendix 5 76

1. Abstract

A more sophisticated version of the VitiCanopy App was developed to make the measure of canopy size and vineyard variability quicker and easier. This was made commercially available with a set of new features including; a mapping tool that shows spatial distribution of canopy size in a vineyard, fast batch analysis of imagery and an easy to use web-based platform for improved visualisation and management decision making. In parallel to software development, a series of case studies were performed to highlight the use of VitiCanopy and investigate the links between canopy size, vineyard variability, vineyard management, fruitfulness, and fruit quality.

2. Executive Summary

To maintain and increase competitiveness in the international market Australian vineyards are required to consistently produce high quality fruit. Canopy vigour and productivity assessments are key factors to determine final fruit and wine quality, however they are difficult to measure and manage in the vineyard using currently available methods, particularly when there is high spatial variability within a vineyard. Previous research at the University of Adelaide (UA) led to the development of VitiCanopy, a mobile app that measures canopy architecture through the analysis of canopy images taken using a smartphone. The geo-referenced VitiCanopy results can be used to assess vineyard variability however, improvements and expansions of the algorithms were needed to make this technology more user friendly and the interpretation of the results more accessible.

The objectives of this project were to:
- Develop and implement add-ons to VitiCanopy that allow for the assessment of additional training systems and vine densities.
- Expand the development of pruning weight algorithms.
- Create a web-based software for batch analysis of images and data mapping, with the option to analyse images from an autonomous canopy capture from moving vehicles.
- Provide information about the links between canopy architecture, vine balance and berry quality for different varieties, training systems and wine regions.
- Achieve accurate early yield prediction through bud dissection and image analysis techniques.
- Develop and deliver an extension strategy to measure and interpret canopy development in vineyards across Australia through seminars and workshops.

VitiCanopy redevelopment: a completely new user interface, enhanced help features, batch analysis of images, cloud server processing and the generation of reports as both files and maps of the spatial variability of plant area index in the vineyard were implemented. This new version of VitiCanopy was launched in February 2022 and can now be downloaded for both Apple and Android operating systems.

Development of pruning weight algorithms: the relationship between pruning weight measured in the vineyard and the cover value obtained from VitiCanopy analysis was assessed for three commercial and one experimental vineyard. Results produced coefficients of determination (R^2) ranging from 0.92 to 0.96 to demonstrate that images of dormant vines can be processed using VitiCanopy and results used to assess pruning weight and its distribution in a vineyard.

VitiCanopy Web: a web version of VitiCanopy is now available for users already registered within the mobile app. This web version allows for analysis and visualization of results using the more powerful CPU of a computer and with the added comfort of a bigger screen.

Collection of images from moving vehicles: the implementation of a vehicle mounted system has been explored and a prototype based on a Raspberry Pi computer developed to enable the autonomous collection of images in the vineyard. The functionality of the Raspberry Pi tool is based on the current VitiCanopy application.

Information on the links between canopy architecture and vine performance for different varieties, training systems and wine regions: Trials were established in an experimental Semillon vineyard, five commercial Chardonnay vineyard blocks in the Riverland Region of South Australia and three premium Shiraz vineyards in the Barossa Valley. Results from these trials have been reported as case studies. In the experimental vineyard, canopy management strategies were applied to modify the canopy size for three consecutive seasons. Results confirmed the ability of VitiCanopy to capture the differences in canopy size imposed by the treatments. Moreover, strong links between canopy size, canopy temperature and light interception, yield components and berry and wine sensory and chemistry were found. The spatial variability of all these parameters, in the trial, was also mapped. The commercial Shiraz vineyards were used as case studies to demonstrate how VitiCanopy could assist identifying areas of different performance, assess variability within and between seasons, create a history of a site and assess the outcome of canopy manipulations. Grape chemistry and sensory attributes and reproductive performance were all assessed for the identified areas of different performance and showed strong links amongst all these measured parameters. This information could be used to direct vineyard management decisions.

Bud dissection using image analysis techniques: the link between canopy size and bud fertility was investigated using bud dissection analysis and image analysis. This information can aid in early yield estimation and canopy management decisions. These techniques are accessible by industry through a commercial bud dissection service offered at the University of Adelaide.

Extension strategy: the dissemination of results was affected by the COVID-19 pandemic however, findings have been presented through online conferences and workshops, through communication with the growers involved in the project and other industry practitioners, through meetings with Wine Australia and the Industry Reference Group and through publications both in open access scientific journals and Australian and international industry magazines.

This project was funded by Australia's grapegrowers through their investment body Wine Australia. Special thanks to the growers that allowed access to and data collection in their vineyards in the Barossa Valley and Riverland Regions. We greatly appreciate the contribution of the industry reference group and the wine industry participants for testing and for the feedback on the redeveloped VitiCanopy. We would also like to thank The University of Adelaide and in particular Ben Pike for his assistance with the Semillon trial. We are thankful to all the staff and students of the University of Adelaide that have helped with data collection and for generally being a great team.

3. Background

Vineyards are variable. Variability can be managed (used or reduced) to increase vineyard profitability as understanding vineyard variability allows for targeted management to apply inputs efficiently and deliver consistent grape quality to the winery. To maintain and increase competitiveness in the international market Australian vineyards are required to consistently produce high quality fruit. Canopy vigour and productivity assessments are key factors to determine final fruit and wine quality, however they are difficult to measure and manage in the vineyard using currently available methods, particularly when there is high spatial variability within a vineyard.

The assessment of vineyard variability can be challenging; a possible approach relies on monitoring leaf area, canopy vigour and canopy growth. However, current methods for canopy monitoring are based on basic and subjective visual observations, manual procedures, expensive remote sensing, or the use of instrumentation which can be destructive, time consuming, expensive and is impractical outside of academia. Previous research at the University of Adelaide (UA) led to the development of VitiCanopy, a mobile app that measures canopy size and porosity (gaps within the canopy) through the analysis of canopy images taken using a smartphone (De Bei et al. 2016). This application not only accurately (R^2 = 0.9) measures canopy architecture but it was also found that canopy architecture parameters can be correlated to grape quality attributes (chemistry and sensory) (De Bei et al. 2019; De Bei et al. 2020; De Bei et al. 2022).

The delivery of more efficient and cost effective tools for vineyard management in the form of mobile apps has been well accepted by practitioners worldwide. The advantages of these tools are: grower friendly interface, the ability to deliver processed data in real time and the geospatial data availability for variability mapping of data within a vineyard. The first version of the VitiCanopy App was easy to use, highly portable and provided real time results. However, it used a multi-step process to obtain a measurement that was cumbersome and error-prone. Additionally, the in-app information provided limited guidance on how to use the tool, manipulate the settings parameters and visualise and understand the results. To make this technology more user friendly and to ease the interpretation of the results some improvements and expansions of the algorithms were needed.

Suggested improvements included features to increase flexibility, generate accurate data for different training systems and vine densities and include pruning weight estimation. A web-based platform, based on the algorithms used by VitiCanopy, was proposed to allow higher processing capabilities to batch-analyse several images taken in the field and the option of GIS generated maps of plant area index and other architectural parameters. The inclusion of a mapping tool, would allow other information to be mapped, and spatial variability assessed by users. Furthermore, this web-based platform could analyse images collected using a remote capture system.

Previous Wine Australia funded project (UA 1803) demonstrated that the use of such novel digital technologies may help advance the understanding and practical application of concepts such as vine balance. Vine balance, fruit exposure and wine quality are the direct result of a complex set of interactions between varietal, environmental and management factors, which traditionally have been translated directly from experimental results into practice in a subjective and informal manner

(Gladstones 2011, Reynolds 2010). UA 1803 delivered information on the correlations between new measures such as LAI/Y and Canopy Porosity/Y and fruit quality – both through chemical composition and fruit grade at harvest which is directly related to income. While fruit grade correlated strongly to canopy architecture measures, little is known about final wine quality. This could be investigated with targeted chemical analysis of grapes and wines (e.g. phenolics, amino acids, organic acids, volatiles) and sensory assessment of berries and wines and then mapped in the web-based platform.

In addition, other studies from the same group at UA have identified a relationship between the size of the inflorescence primordia and bunch weight with significant implications for early and accurate yield prediction which were further explored in this project. Furthermore, results from UA 1207 experimental trials (AGW H1502 and collaboration with TWE) have revealed that canopy management affects the percentage of primary bud necrosis (%PBN), for example bunch thinning resulted in a higher %PBN. In other trials, it was demonstrated that this is likely to influence bunch number, size and weight, and hence the final yield (Wang et al. 2020). The link between fruitfulness and canopy management required further investigation to aid in early yield predictions.

This report outlines the developmental process, improvements and additional features made to VitiCanopy, the creation of a web-based platform and the design and development of a remote capture system. In addition, findings from studies comparing chemical and sensory analysis of grapes and wine with canopy development and the relationship between bud fertility and canopy architecture are presented.

4. Project Aims

Outline of project objectives

- To develop and implement add-ons to VitiCanopy that allow for the assessment of additional training systems and vine densities.
- To expand the development of pruning weight algorithms and models to incorporate into VitiCanopy using different training systems and canopy densities.
- To create a web-based software for batch analysis of images and data mapping, with the option to analyze images from an autonomous canopy capture from moving vehicles.
- To provide information about the links between canopy architecture, vine balance and berry quality for different varieties, training systems and wine regions.
- To achieve accurate early yield prediction through bud dissection and image analysis techniques.
- To develop and deliver an extension strategy to measure and interpret canopy development in vineyards across Australia through seminars and workshops. This will showcase the new management tools, results interpretation and promote/increase adoption by the industry.

Planned project outputs and activities

Most planned project outputs and activities were achieved during the project and are outlined in the tables below for each financial year. Changes made to the outputs and activities are as follows;

- Rather than 'VitiWeb' the web-based platform is also called 'VitiCanopy' and is linked directly to the VitiCanopy App.
- Berry Sense is not directly linked to the web platform but all geotagged data can be mapped on the VitiCanopy web-based platform (including sensory data).
- Many of the workshop outputs listed were not possible due to restrictions related to Covid-19.
- A hands-on workshop at the Australian Wine Industry Technical Conference to demonstrate the use of VitiCanopy as well as industry case studies was not possible as it was not selected by the organising committee.
- Machine learning algorithms were developed in Wine Australia funded project UA1803 1.5 due to project relevance and expertise in this team.

2018-19

Output	Target Date	Activity
a. Fruitfulness and canopy management dataset 2018.	30/09/2018	Conduct pruning at the trial sites and collect images for the VitiCanopy pruning weight add-on. Perform bud dissection and image analysis and analyse results.
b. VitiCanopy and BerrySense Apps linked.	31/12/2018	Link the mapping and analysis capabilities of the VitiCanopy and BerrySense platforms.
c. Vineyard dataset for 2019. Knowledge on the relationships between canopy architecture and fruit quality and bud fertility and management practices.	30/06/2019	Collect and collate canopy, bud fertility, grape chemistry measurements and aerial data across all trial sites. Use the machine learning algorithms for testing, including canopy architecture, compositional and sensory objective measures.
d. Prototype of VitiCanopy with new add-ons. Prototype of VitiWeb software. Prototype of bud dissection / image analysis tool.	30/06/2019	Calibrate VitiCanopy for different training systems and vine densities. Calibration of top and side images in different vigour situations and environments. Develop new algorithms for pruning weight and build them into an improved VitiCanopy app. Develop a simple cloud-based software package ('VitiWeb') with the ability to analyse canopy images and aerial images. Test and validate bud dissection / image analysis tool prototype using actual harvest yield data.
e. VitiCanopy and VitiWeb prototypes available to selected practitioners for beta testing.	30/06/2019	Engage industry partners to trial the new software tools, under the terms of a non-disclosure agreement.

2019-2020

Output	Target Date	Activity
a. Fruitfulness and canopy management dataset 2019	30/09/2019	Conduct pruning at the trial sites and collect images to test the accuracy of the VitiCanopy pruning weight add-on. Conduct bud dissections and analyse results. Elucidate the relationship between canopy management and bus fruitfulness.
b. Bud dissection image analysis tool available to industry	31/03/2020	Launch an improved bud dissection image analysis tool to industry as a service for more accurate early yield prediction.
c. Vineyard dataset for 2020. A collection of three seasons of vineyard data Further knowledge on the relationship between canopy architecture and fruit quality and bud fertility and management practices	30/06/2020	Collect and collate canopy, bud fertility and grape chemistry measurements and aerial data across all trial sites. Use machine learning algorithms for the second round of testing, including canopy architecture, compositional and sensory objective measures.
d. Upgraded VitiCanopy app, with add-ons to measure different training systems and pruning weights Fully developed VitiWeb software	30/06/2020	Launch new VitiCanopy app and VitiWeb cloud-based software to industry.
e. Industry and peer-reviewed journal articles. Hands-on industry workshop.	30/06/2020	Extend project outcomes through publications in at least one industry magazine and peer reviewed journal. Deliver a hands-on workshop on VitiCanopy and VitiWeb for industry practitioners Provide information about the links between canopy architecture, vine balance and berry/wine non-volatile, and volatile chemical composition, sensory attributes and quality for different varieties, training systems and wine regions.

2020-21

Output	Target Date	Activity
a. A complete camera system based on Raspberry Pi. An automated image-collection system to be mounted on a quad bike and/or tractor.	30/12/2020	Validation of images collected using the Raspberry Pi system through destructive measures for different training systems. Validation of different camera angles for image capture. Automated image acquisition trials using moving vehicles.
b. Automated estimation of pruning weight through image analysis	30/12/2020	Creation of algorithms for the estimation of pruning weight from canopy images. Validation of new algorithms via destructive pruning weight measures
c. Vineyard dataset for 2021. A collection of four seasons of vineyard data. Further knowledge on the relationship between canopy architecture, its spatial variability in the vineyard and fruit quality, bud fertility and management practices.	30/06/2021	Collect and collate canopy, bud fertility and grape chemistry measurements and spatial variability assessments across all trial sites.
d. A set of daily images and related canopy architecture parameters from one location on Shiraz in the Adelaide Hills	30/06/2021	Collect daily images of a vine from flowering to leaf fall using a commercial fixed camera. The camera is positioned next to a soil moisture probe. The relationship between soil water content and canopy development will be assess during a whole growing season.
e. Industry and peer-reviewed journal articles. Hands-on industry workshop	30/06/2021	Continue to extend project outcomes through publications in at least one industry magazine and peer reviewed journal. Deliver a hands-on workshop on VitiCanopy and VitiWeb for industry practitioners

2021-22

Output	Target Date	Activity
a. VitiCanopy and VitiWeb commercialised and available to practitioners worldwide	30/11/2021	Complete commercialisation process and launch new VitiCanopy and VitiWeb on the market
b. A collection of four seasons of vineyard data analysed in preparation for the final report and publications. Further knowledge on the relationship between canopy architecture, its spatial variability in the vineyard and fruit quality, bud fertility and management practices. Results available to practitioners and the scientific community	31/03/2022	Collate, analyse and interpret canopy, bud fertility and grape chemistry measurements and spatial variability assessments across all trial sites. Prepare for communication to different audiences.
c. Papers published in peer review scientific journals Articles published in Australian and international wine industry journals AWITC workshop on digital tools – VitiCanopy, VitiWeb and automatic Raspberry Pi system Hands on workshops in wine regions Present results at Terroir Climwine Congress in Bordeaux 2022 (COVID-19 dependant)	30/06/2022	Prepare and submit at least three manuscripts to scientific peer reviewed journals Prepare and publish at least two articles in wine industry journals Deliver a hands-on workshop for the 18th AWITC on VitiCanopy, VitiWeb and the Raspberry Pi system. Present "case study" results from different regions. Deliver hands on workshops in the Barossa Valley and Riverland to demonstrate tools and present regional case study results Submit abstract for an oral presentation at the Terroir Climwine Congress in Bordeaux 2022
d. Final Report completed	30/06/2022	Prepare and submit Final Report to Wine Australia, outlining key findings from the project, with a focus on: - Development and validation of digital tools - Case study uses of tools to improve vineyard management

5. Methods

5.1 VitiCanopy redevelopment

The main focus of the project was the redevelopment of the VitiCanopy application.

The first version of VitiCanopy was a free mobile device App, launched to the market as an iOS App in 2015 and an Android version in late 2016. In approximately five years, the iOS version alone was downloaded more than 6000 times with most downloads in Australia, China, USA and Europe. The App provided grape growers and viticulturists with a quick measure of their vine canopy size and porosity by simply taking a photo of a vines canopy. VitiCanopy compared to other methods of canopy assessment was easier to use and highly portable. Moreover, it provided real time results. However, the early version used a multi-step process to obtain a measurement that users described as cumbersome and error-prone. Additionally, the in-app information provided limited guidance on how to use the tool, manipulate the settings parameters and visualise and understand the results.

Feedback was received through industry workshops, publications and beta testing and identified opportunities to improve the user experience within the app and add value for users and increase commercialisation avenues. To make this technology more user friendly and to ease the interpretation of the results some improvements and expansions of the algorithms were needed. Based on feedback a new version was developed and distributed to selected beta testers in 2019.

A series of major improvements were deployed including:

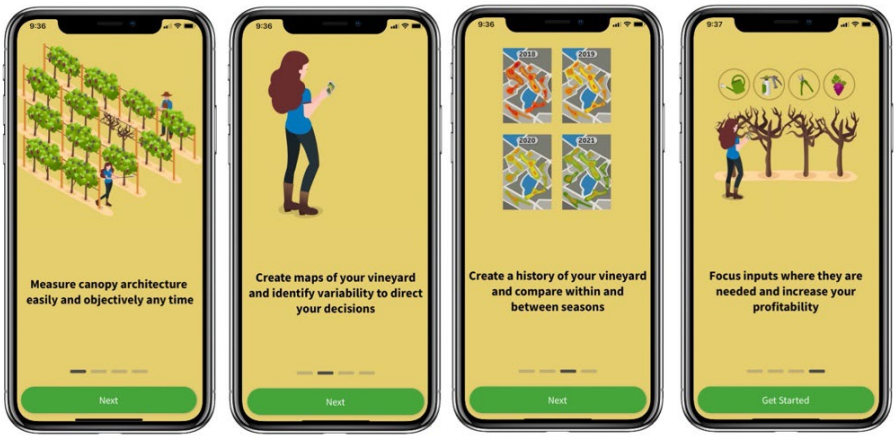
- A new user interface
- User authentication. All users must create an in-app account. This allows the developers to monitor users' geographic location, users' profession and to obtain data on usage (number of sites and number of images).
- Enhanced help features and easy learning curve. A user friendly and intuitive design of the app has been created to make it easier for users to find specific information. Additional guidance is provided through a help function which can be accessed from the general account page and take the users through a series of frequently asked questions (FAQ). The option to 'Contact us' is available if users have specific questions that are not answered in the FAQs.
- Batch analysis. Images are now taken within the app or they can be uploaded from the camera files. Images are analysed automatically.
- Cloud data storage. All images taken are stored in the cloud allowing users to access the images and analysis reports when needed.
- Server processing. Images, once taken, are sent to a cloud server for analysis so that the app does not use computational capability within the phone and its performance is not limited by the phone model, operating system etc. This also has battery charge advantages.
- Reports. By generating reports in the form of maps showing the spatial distribution of vigour in the vineyard, users will be in a better position to make management decisions in response to these results. To the best of our knowledge this is the only smartphone device app able to produce such maps. Maps are created through kriging. Obtaining a similar map was previously only possible using Arc-GIS or similar sophisticated and expensive software. Results can also be downloaded as a .csv file.

A complete overview of VitiCanopy's new user interface and a guide of its features, through screenshots, are presented below.

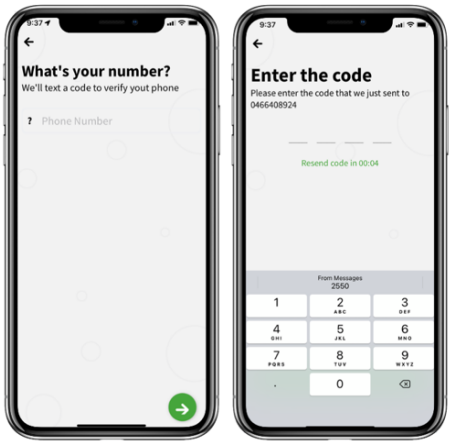
- New home screen with new branding, white VitiCanopy writing on green background. This branding has been maintained throughout the app and the web application.



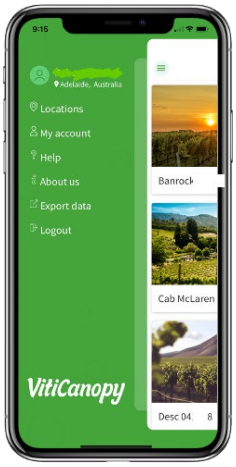
- A quick overview of the app capabilities/what to expect is presented through a series of cartoons. Users are guided through a simple overview of VitiCanopy's functionalities by tapping on "next" until the "Get started" tab.



- By tapping the "Get Started" tab users are presented with a new page that requires the user's phone number to register. A four-digit numerical code is required to complete the registration process.



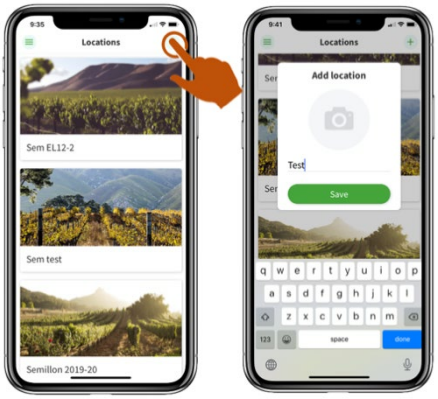
- A user account is created, and the user's information can be found in the "Account" tab. From this menu information on the number of locations and number of images can be accessed together with a "help" function, information about the developers "About us" and the "Export data" function. The option to "Logout" is also included in this tab.



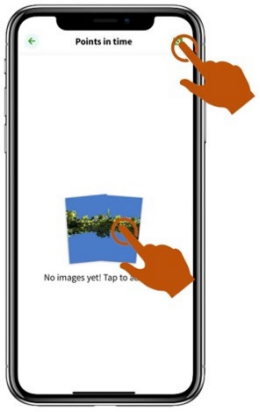
- In the "Help" tab users will find an exhaustive list of frequently asked questions (FAQs). These FAQs have been collated from the feedback received from users and beta testers over the years. For all other questions a "Contact us" tab is available and users can email the team directly. The email is monitored daily and questions are generally answered within 24-48h.



- To start measuring using ViticCanopy users must add a location by tapping on the "+". Once a location has been created, images taken at different time points for the same location can all be stored here. The "Location" page shows all the locations created by the user where images have been taken.

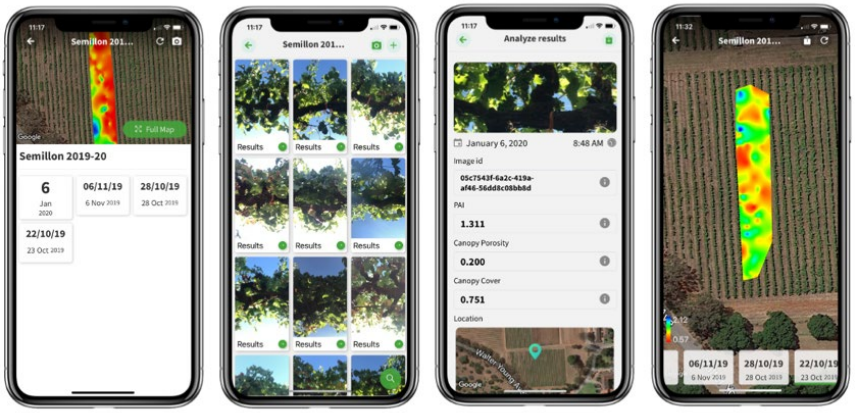


- From the newly created location the analysis process can be initiated on the “Points in time” page. Here a user can start adding image that will be analysed automatically by tapping on either the camera icon or the centre of the screen. Images can also be uploaded from files/camera roll. A maximum of 400 images at a time can be uploaded however, the number of images for each location is unlimited.



- As an example, below is the sequence of results from a Semillon block at the Waite Campus of the University of Adelaide. This block was imaged weekly or fortnightly during the growing season. The first screenshot shows that the location contains four timepoints/dates. By tapping on one of these dates all the images taken and analysed on that specific date are shown. By tapping on each single image, the single results can be viewed and each image is labelled automatically with a unique “Image ID”. By tapping on the green “Full map” tab, the maps of the spatial distribution of the Plant Area Index (PAI) in the vineyard block are shown for each date. All maps can be exported to a nominated email address.

- Results can also be exported as a .csv file to a nominated email account. The email address used to sign in is used by default.



For practical information on how to use VitiCanopy and take images, please watch the YouTube video: https://youtu.be/OmXCELZnwkE

More information is also available on the VitiCanopy website https://viticanopy.com.au/

5.2 Automated image-capture system development

Industry feedback identified that the bottleneck for the use of VitiCanopy technology to be adopted widely is the automation of image collection. Currently the operators/users are required to walk the vineyard and obtain the images using a smart device and a selfie stick. Despite this procedure often taking no longer than 30 minutes/ha it is perceived by the industry as a time-consuming and excessively physical activity, thus impacting on the adoption of the tool within the wine industry. To overcome this issue the automation of the image collection process was investigated. The team made significant progress towards the implementation of a tractor/quad bike camera system that enables the user to be able to acquire images while carrying out other vineyard operations, such as spraying or slashing.

Using a Raspberry Pi computer, camera and control panel system images/videos were acquired automatically in the vineyard. The Raspberry Pi camera connects to a LCD screen that the operator can install in the cabin of the tractor/quad bike (Figures 5.1 and 5.2). A short video showing the system operating on a quad bike in the vineyard is available at this link https://youtube.com/shorts/BsRTga5VJos. The functionality of the Raspberry Pi tool is based on the current VitiCanopy application with the main difference being that images are acquired automatically.

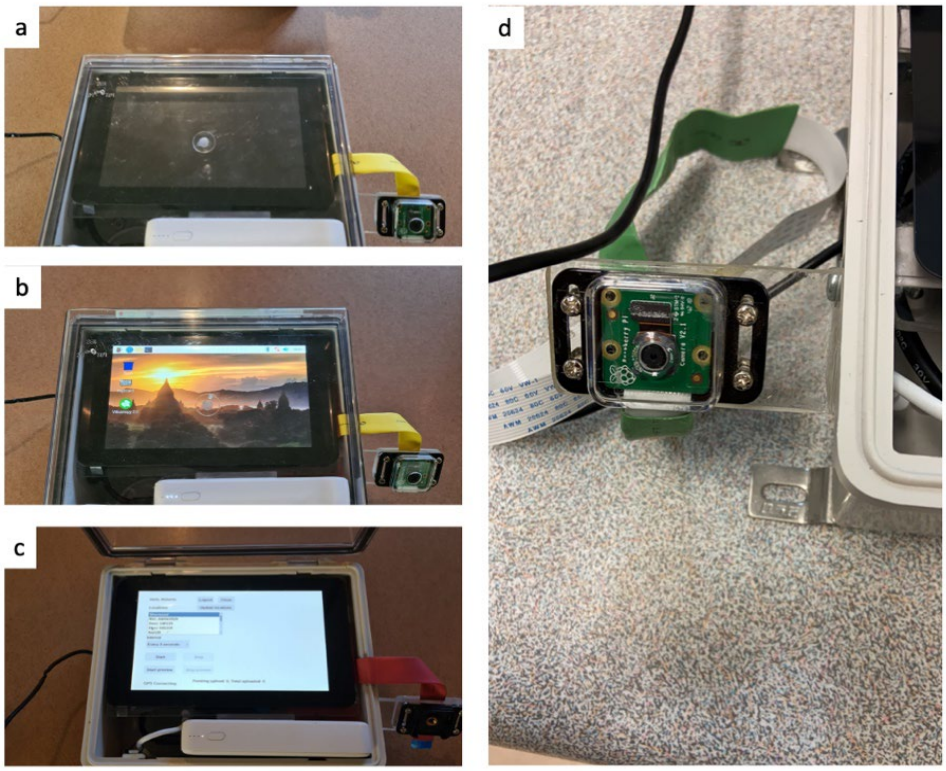


Figure 5.1: Details of the Raspberry Pi system prototype. The system is enclosed in a water and dust proof box (a); the LCD screen is easy to operate, similar to a mobile phone (b) and the set up to take images requires only 2 inputs, the location and the interval, in second, to take the images (c). The camera is attached to the side of the box (a, b, c) and enclosed in its own box (d).



Figure 5.2: Example of the Raspberry Pi system attached to a vineyard vehicle, ready to take images.

The Raspberry Pi system also connects to a GPS receiver so that all the images/videos taken through the Pi are geo-tagged and the information can be used to map the variability in the vineyard.

5.3 Case studies

To demonstrate how VitiCanopy can be used in both a researcher setting and in commercial vineyards, field trials were set up across a number of regions and seasons using approaches. Details of these trials are described below.

5.3.1 Case study 1: Semillon canopy management

A Semillon block in the experimental vineyard of the University of Adelaide, Waite Campus (South Australia) was used for this case study trial. Measurements were taken from own-rooted vines planted in 1990 and trained to a bilateral spur pruned cordon with the shoots vertically positioned. Rows were oriented north-south with a 3m row spacing and a vine spacing of 1.8m. The vineyard was irrigated with in-line drippers discharging 2 L/h and approximately 0.5ML/ha of water discharged in each season. The Semillon trial occupied four adjacent rows; three set up as a fully randomized block design with each treatment repeated once along each row in three panels of three vines each, and one row dedicated to the sprawling canopy treatment. All measurements were taken on the middle vine of each panel for a total of three vines measured per treatment replicate (n=54).

In Season 1 the experiment included six treatments:

1. Control (C), where no canopy intervention was applied during the growing season
2. 50% leaf removal after flowering by removing every second leaf on each shoot
3. 50% leaf removal at veraison (~12 Brix) by removing every second leaf on each shoot
4. Trim at fruit set by trimming every shoot to the second wire to leave an average shoot length of ~ 60 cm (8-10 leaves/shoot)
5. Double node (DN) (or light pruning) where, at pruning, two two-bud-spurs were left at each position instead of one.
6. Sprawling canopy where, in one whole row, wires were not lifted, and the canopy was left to sprawl.

In Seasons 2 and 3, the two leaf removal treatments were replaced with trimming treatments carried out at the same phenological stage. This decision was based on the difficulties encountered when applying the leaf removal treatments and also the impracticality of such a technique when applied commercially.

The measurements recorded for this experimental trial are outlined below.

Canopy architecture was measured weekly using the VitiCanopy App (De Bei et al. 2016). Two images were taken on each side of the vine of interest at 80 cm from the vine cordon. Photosynthetically active radiation (PAR, μmol/m^2/sec) was measured inside the canopy using a Sunfleck PAR ceptometer (Decagon Devices). The readings were taken directly above the cordon, within the cluster zone and parallel to the vine row. The temperature inside the canopy, in the bunch zone was measured for the whole growing season using Tiny tags (Gemini Data Loggers, Chi Chester, UK) that recorded at 15 minutes intervals.

Harvest date was decided based on the total soluble solids (TSS, Brix) with a target of 22 Brix. Maturity was monitored weekly from EL 35 by collecting a sample of 100 berries per replicate. Total berry weight was measured and then the berries were crushed by hand in plastic bags and the juice collected to measure TSS, pH and total acidity (TA). At harvest, the number of bunches and yield per vine were recorded. Cordon length was also measured so that yield and its components could be calculated on a per m basis. From yield and bunch number, the average bunch weight was determined. At pruning, the weight of all one-year-old wood was determined for each treatment replicate.

Berry sensory was carried out both traditionally by collecting samples and tasting in the sensory lab but also directly in the vineyard. At harvest, from 15 randomly selected bunches, a subsample of 300 berries was collected for berry sensory assessment (BSA). BSA was conducted on fresh Semillon fruit (berries were kept at 4 °C until assessment) in the sensory facility of the University of Adelaide at the Waite Campus following the procedure described in Olarte Mantilla et al. (2013) with the approval of the University of Adelaide ethics committee (H2017-054). The assessed descriptors were divided into pulp, skin and seed characteristics and are shown in Table 6.1. The vineyard assessment was also structured so that assessors (n=10) could taste the berries and report the results via the Berry Sense App. All assessors were trained to use the BSA protocol and due to time and resources asked to score five of the BSA attributes in the vineyard (Table 6.1).

Table 5.1: List of attributes assessed by the panellists during the berry sensory analysis of Semillon in the sensory lab (DA) and in the vineyard, with their scale left and right anchor. The attributes are divided in three categories: Pulp Characteristics, Skin Characteristics and Seed Characteristics.

Attribute	Anchors	DA	Vineyard
Pulp Characteristics			
Acidity	Low, High	X	
Tropical flavour	Low, High	X	X
Green/Grassy flavour	Low, High	X	X
Flavour intensity	Low, High	X	
Juiciness	Gelatinous, Juicy	X	X
Skin Characteristics			
Skin disintegration	Low, High		X
Acidity	Low, High	X	
Bitterness	Low, High	X	
Astringency	Low, High	X	X
Green/Grassy Flavour	Low, High	X	
Seed Characteristics			
Colour	Green, Dark brown	X	
Flavour	Herbaceous, Toasted	X	
Bitterness	Low, High	X	
Astringency	Low, High	X	

ANOVA was performed for all yield component and chemistry results. Berry and wine sensory results were analysed using Principal Component Analysis (PCA) and sensory panel performance. All statistical analysis were all performed using XLSTAT Version 2015.4.01.20116 (Addinsoft SARL, Paris, France).

5.3.2 Case study 2: Premium Shiraz vineyards, Barossa Valley

Vineyard 1

A premium Shiraz vineyard in the Barossa Valley region of South Australia was assessed for canopy architecture using VitiCanopy for three consecutive seasons with the aim to create a history of the site, measure vineyard variability and adjust management to achieve higher uniformity within the block.

Vines were trained to a bilateral spur pruned cordon with a sprawling canopy. In winter 2021, 10 rows were re-worked to a cane pruning system. Images were taken on each middle vine of each panel and row (n= 970) and imaging occurred as close as possible to the phenological stages of flowering, fruitset, veraison and harvest in the first two seasons. In 2020-21 images were only taken at harvest while in 2021-22 images were taken at EL 19 just after a major hail event.

Vineyard spatial variability was mapped and the map created at veraison (peak canopy size) in 2019-20 was used to identify three areas of different performance (based on average PAI values) and named “Low”, “Medium” and “High” PAI. Within these zones, at harvest, fruit was collected separately and analysed for berry weight, titratable acidity (TA), total soluble solids (TSS) and pH. Images of bunches randomly selected from each zone were also taken. At dormancy, just before pruning, the same three zones were sampled for 10 node canes (20 canes per zone) for bud dissection analysis. Inflorescence primordia number and size and the incidence of primary bud necrosis (PBN) were assessed.

Vineyard 2

A second Shiraz vineyard managed by the same company/viticulturist as vineyard 1, was assessed for canopy architecture using VitiCanopy for, in this case, four consecutive seasons with the aim to create a history of the site, measure vineyard variability and adjust management to achieve higher uniformity within the block.

Vines were trained to a bilateral spur pruned cordon with a sprawling canopy in this vineyard too. One image for each middle vine of each panel of every fourth row was collected for a minimum of about 900 images collected at each time point. Imaging occurred as close as possible to the phenological stages of flowering, fruitset, veraison and harvest in season two and three while in season one images were taken at veraison and harvest and in 2021 at harvest only. All other measurements were carried out as described for vineyard 1.

Vineyard 3

Canopy architecture (PAI and Porosity) were measured over three seasons in a small (five rows of which four were assessed) rainfed Shiraz block in the Barossa Valley region of South Australia. Images were taken on each middle vine of each panel over four rows for a total of 116 sampling points.

Canopies were imaged on eight occasions: four times in season 2018-19, three times in 2019-20 and at harvest in 2021 (Figure 6.35). All the images collected were then analysed using VitiCanopy and the spatial variability assessed with maps. At harvest 2020 and 2021, five bunches were randomly collected from each of the vines that had already been monitored for canopy architecture (n=116) and bunch weight was measured. On the juice, basic chemistry (pH, TA and TSS) was measured and must samples were then sent to APAL (Australian Precision Ag Laboratory) for elemental analysis. At dormancy (July 2020 and 2021) canes were collected from each of the 116 vines for bud dissection analysis to measure the number and size of inflorescence primordia (IP). Each of these measured parameters were then analysed using ArcGIS and their variability mapped for the whole block.

5.3.3 Case study 4: Comparisons between VitiCanopy, NDVI and image resolution

This trial was carried out to answer the often-asked question of how many images would be required to map block variability. Moreover, in this case, the vineyard owner held NDVI maps of the blocks, the VitiCanopy maps were then compared to NDVI.

A Cabernet Sauvignon and a Shiraz vineyard, located in the McLaren Vale region of South Australia, were assessed just before the 2019 harvest. For the Cabernet block, images were taken by two operators using the VitiCanopy app on two iPhones 8 (Apple Inc., Cupertino, CA, USA). Every vineyard row was imaged (by a different operator) and two images per panel were taken. The results were then mapped using ArcGIS as follows: i) using all the images (n=1184), ii) using images from one iPhone/operator so that every second vineyard row was included in the mapping (n=592), iii) using images from one iPhone/operator and only one image per panel (n=296). The vineyard manager also provided NDVI maps of both the Cabernet Sauvignon and the Shiraz blocks. The Shiraz block was imaged (n=1993) and both VitiCanopy PAI maps were compared to the NDVI images collected in the previous season (2017-18).

5.3.4 Case study 5: Chardonnay vineyards in the Riverland region

In this commercial setting the relationship between canopy size, vineyard variability and grape grade (quality) at harvest was investigated.
For this case study five Chardonnay vineyard blocks belonging to the same farm/company were selected based on the historic knowledge of producing grapes that are consistently graded differently. In particular, block E had proven to consistently produce the highest graded fruit. The vineyard characteristics are reported in Table 5.2.

Table 5.2: Age, soil type, planting density and winery grading of the grapes in 2019 for the five chardonnay vineyard bocks in the Riverland region of South Australia.

Block	Year planted	Soil type	Planting density	Grape grade in 2019
A	1995	Sandy/Loamy	3x2	B/C
B	1995	Sandy/Loamy	3x2	A
C	1995	Sandy/Loamy/limestone	3x2	B/C
D	1995	Sandy/Loamy	3x2	B/C
E	1995	Deep Sand	3x2	A

In these vineyards images were taken in 2018-19 at veraison (all five blocks) and harvest (blocks B, C and E) and all five blocks were imaged at harvest in the following two seasons. The number of images taken at each time point in each vineyard varied with the block size; a minimum of 1000 and maximum of 2500 images.

In 2018-19 grape samples were submitted to the Australian Wine Research Institute (AWRI) analytical services for amino acids analysis. Moreover, wines were made from grapes randomly harvested from all five blocks and the aromatic profiling was analysed through the AWRI services. In 2019-20 bunches were randomly selected from areas of measured high, medium and low PAI values in all blocks, the juice expressed and sent to APAL for elemental analysis. In the last season (2020-21) bunches were again selected from areas of different performance within a block (different PAI values) and berries were subjected to berry sensory analysis.

5.3.5 Case study 6: Use of VitiCanopy to assess pruning weight

The trials were carried out during winter 2020 and 2021 in two locations in South Australia (Australia): the Riverland Region and The Waite Campus of the University of Adelaide. Three commercial vineyards were used in the Riverland region and a Semillon block was assessed in the research vineyard of the Waite Campus. The front camera of an iPhone 8 (Apple, Cupertino CA) and the VitiCanopy application were used to image dormant vines in all four vineyards (Figure 5.3).

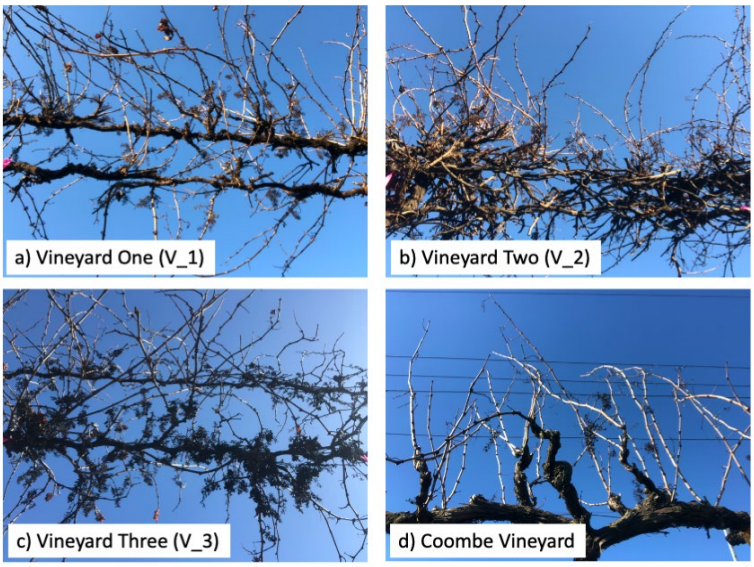


Figure 5.3: Example of images taken before pruning in all four vineyards.

For each of the vines in the trial, a series of images was taken after different levels of pruning. In the Riverland region, where cane number was high (Figure 5.4, a-c), a photo was taken at intervals of 10 pruned shoots while in the Semillon block (Figure 5.4d) three to five shoots were pruned in each photo. The corresponding pruning mass was measured after each photo using a handheld digital scale. Examples of the imaging process with the progression of the pruning are shown in Figure 5.4 (a: V_1; b: Coombe vineyard). A total of 13 vines were imaged in V_1 (115 images in total), 12 in V_2 (40 images), 16 in V_3 (114 images) and 41 vines in the Semillon block (269 images).



Figure 5.4: Example of the images obtained for analysis with VitiCanopy from a) vine in vineyard one (V_1) in the Riverland region and b) a vine in the Coombe vineyard. In the 10-image sequence in (a) 10 shoots were pruned each time and pruning mass recorded. In the nine-image sequence in (b) four shoots were pruned each time and pruning mass recorded.

The canopy cover component (from here on referred to as “cover” only) extracted by the VitiCanopy algorithm was used for all comparisons presented in this study. Cover is defined as the “proportion of ground area covered by the vertical projection of foliage and branches” (De Bei et al., 2016). Pearson’s correlations were calculated using excel to compare the performance of VitiCanopy in estimating pruning mass.

5.3.6 Measuring grape extracts using a spectrofluorometer system

In the second season of the trial an opportunity arose to conduct analyses using a newly purchased spectrofluorometer system (Horiba Aqualog UV-800). The instrument uses the absorbance-transmission and fluorescence excitation-emission matrix (A-TEEM) technique, as reported in a number of recent studies of wine (Ranaweera et al., 2022; Ranaweera et al., 2021a; Ranaweera et al., 2021b; Souza Gonzaga et al., 2021). This approach produces a molecular “fingerprint” of samples according to their fluorophoric molecular and macromolecular components (phenolics, vitamins, and aromatic amino acids) by recording a three-dimensional excitation-emission matrix (EEM) (Coelho et al., 2015). The processed EEM data were combined with multivariate statistical analysis and used for the qualitative investigation and discrimination of grape samples. The samples submitted to A-TEEM analysis consisted of extract of 1 g of grape homogenate in 50% v/v ethanol solution. Before analysis, the extracts were diluted and placed in a 1 cm path-length quartz cuvette to collect EEMs (Coelho et al., 2015).

The processed EEM data was subjected to multivariate analysis with a series of techniques:

- Parallel factor analysis (PARAFAC). This is an unsupervised method that is applied to EEM data to extract the characteristic excitation and emission profiles of the main fluorophores arising from the samples (Lenhardt Ackovićet al., 2017; Ranaweera et al., 2021a; Ranaweera et al., 2021b Souza Gonzaga et al., 2021). The variability of sample EEMs can be explained with a trilinear decomposition model (Cabrera-Bañegil et al., 2017).
- Principal component analysis (PCA) was conducted to identify patterns among the samples and to condense the variables associated with spectroscopic data.
- Extreme gradient boosting discriminant analysis (XGBDA) is a machine learning tool based on a boosted decision tree approach that is not influenced by outliers or non-linear relationships (Ranaweera et al., 2021).

5.3.7 VitiCanopy improvements in progress

VitiCanopy was launched in February 2022 and this gave the team the opportunity to collect further user's feedback and consider some other improvements listed below:

- Ability to map parameters other than plant area index
- Ability for users to add any geotagged .csv file and generate heatmaps.
- Single image analysis without mapping

6. Results/Discussion

6.1 Climatic conditions

Data for this project was collected from 2018 to 2021, encompassing three grapevine growing seasons, 2018-19, 2019-20 and 2020-21. To discuss the general climatic trends of the three seasons weather data collected from the weather station 230909 (Kent Town) of the Australian Bureau of Meteorology has been analysed and presented (Figure 6.1). Season 1 (2018-19) was the hottest of the three seasons with a mean average temperature in January of 25.5°C compared to 22.5°C for the two consecutive seasons. The total GDD was 2384, 2153 and 2151 in season 1, 2 and 3 respectively however, when calculated with base 10 (Gladstone 2011) the temperature summations were identical in the three seasons with a value of 1886. Rainfall in season 1 was also the lowest with only 140 mm from October to April and as low as 45 mm from Dec to harvest. Rainfall in season 2 was slightly higher however, of the 248 mm of rain during the growing season, 102 fell in April, after harvest. In Season 3 rainfall (190mm) was in line with the long-term average (198 mm).

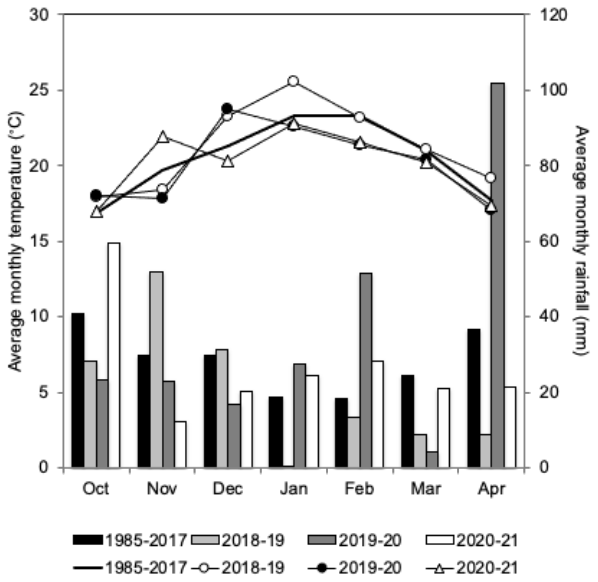


Figure 6.1: Average monthly temperature and rainfall calculated for the growing season October to April for 2018-9, 2019-20 and 2020-21 and the 30-year long-term average (1985-2017).

6.2 Case Study 1: Semillon canopy management

Aim: To assess the impacts of canopy manipulation on fruit yield and quality using VitiCanopy.

6.2.1 Canopy architecture, yield components and grape composition

Canopy manipulations, both direct (leaf removal and trimming) and indirect (sprawling canopy and light pruning - DN) influenced canopy architecture throughout the three growing seasons (Figure 6.2). In season 1, given the higher number of shoots present in the DN vines, the PAI was already higher at the early stages of development (EL 16) compared to both control vines and the other treatments. Interestingly, these canopies also showed high porosity while a denser, less porous canopy was expected. In an unexpected trend, the PAI of sprawling canopies was initially the smallest to then become the largest for the rest of the season. This could be due to the wider space allowed for the canopy to grow given the lack of constriction between the wires. The effect of the early leaf removal was not evident in the PAI measurements however, the late removal caused a considerable reduction in PAI and no recovery was observed for the rest of the season (last measurement at EL 33). No other measurements were taken after EL 33 due to the implementation of over canopy nets for bird control.

In season 2, it was decided to change the canopy manipulations that were applied to the Semillon and replace the 50% leaf removal treatments due to the difficulty in application and the lack of commercial applicability of such a technique. As a result, trimming treatments were then carried out at flowering, fruitset and veraison. As observed in season 1, all treatments had a profound impact on the canopy size measured as PAI using VitiCanopy. The three trimmings pruned all shoots to the wire height thus leaving about 70 cm of canopy and about 8-10 leaves/shoot. This meant that the percentage of canopy removed at each phenological stage was different due to differences in shoot length. As confirmation, the trimming carried out at flowering (EL23) did not have a significant impact on PAI compared to the control as only a few cm were removed. However, the effect was clear for the rest of the season when that canopy stopped growing due to the early removal of the shoot tips and produced the lower PAI values for the rest of the season. Both the trimming at fruit set and at veraison showed a trend towards smaller canopies, however the impact on PAI and porosity was not significant. In line with observations from the previous season the sprawling canopy remained the one showing the largest PAI and lowest porosity.

The canopy architecture measures of 2020-21 were higher throughout the season compared to the previous two seasons. The treatment difference however was similar to the pattern observed in previous seasons with the sprawling canopies showing higher PAI than the other treatments. Similarly, the porosity of the sprawling canopies was much lower throughout the whole season.

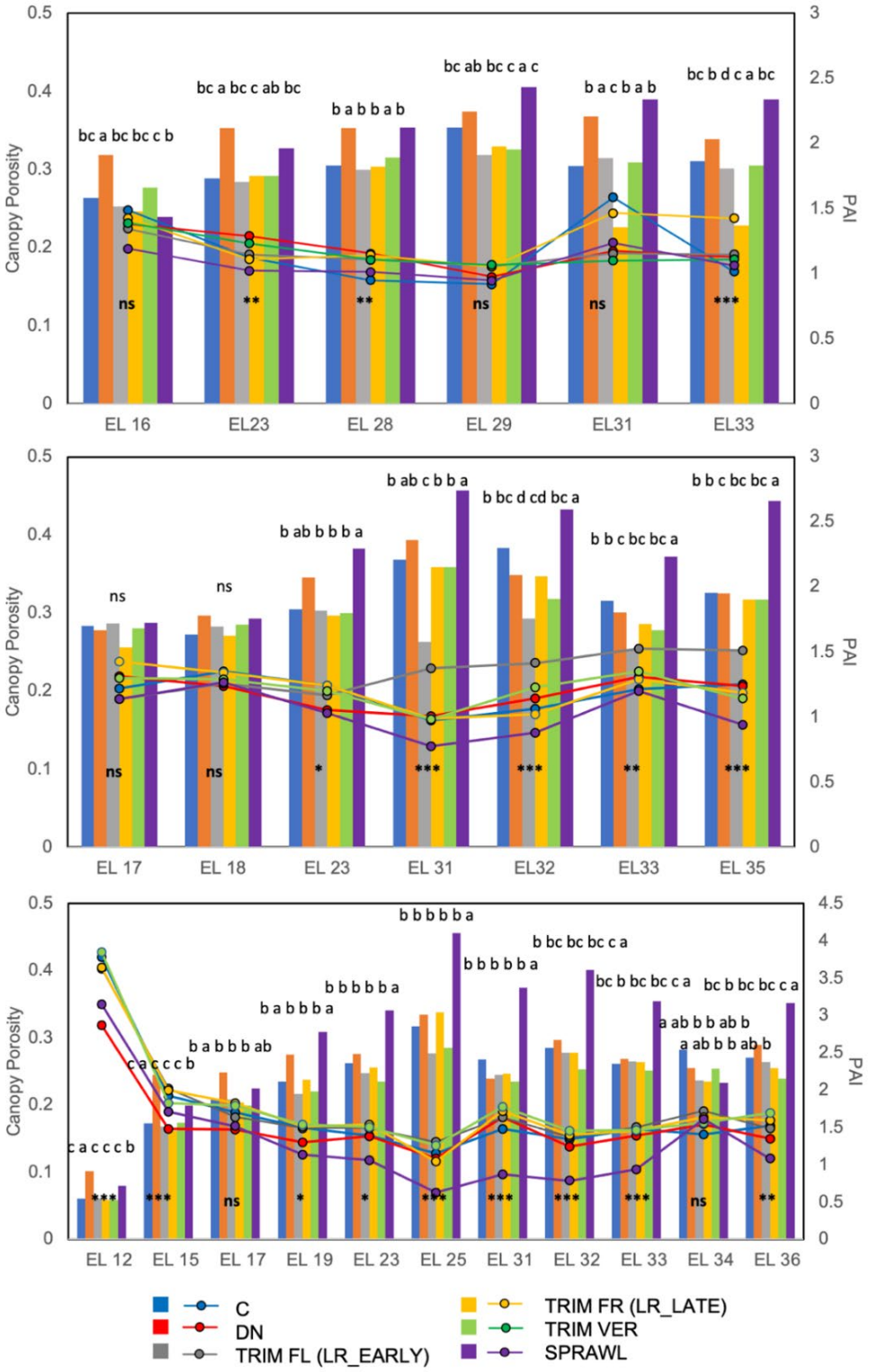


Figure 6.2: Effect of canopy manipulations on the canopy development (PAI) and canopy porosity measured throughout three consecutive growing seasons: 2018-19, 2019-20 and 2020-21. PAI and canopy porosity were measured using the VitiCanopy app at different EL stages (Coombe, 1995). C= Control (dark blue), DN=Light pruning (red), LR-EARLY/TRIM FL (grey) = leaf removal at flowering (season 1)/trimming at flowering (seasons 2 and 3), TRIM VER (green) = trimming at veraison, SPRAWL = sprawling canopy (purple). Treatment effects were analysed using a one-way ANOVA and the means separated with Tukey's test. Different letters at each EL stage for PAI (bars) correspond to means different at $p<0.05$.

The measured light interception at the cordon level/bunch zone is in agreement with the PAI results and indeed a relationship was found between the two parameters measured at EL 33 (R^2=0.48) (Figure 6.3). The sprawling canopy, as expected, showed the greatest values of light reaching the cordon. The nature of such training forces shoots to grow on either side of the cordon hence leaving the cordon itself exposed to sunlight. The effect of early LR, despite not being clear with this measurement either, can be appreciated at EL 31 as a slightly higher interception number compared to the other treatments. However, it is the late LR that shows a greater impact on the canopy/cordon light interception with values close to those observed in the sprawling canopies. This higher light penetration is maintained until EL 33, when the last measurement was carried out.

Interestingly, in season 2, despite the PAI not being greatly affected by the trimming at flowering, the measure of the light intercepted at the cordon level was high and this latter treatment showed greater values at both the measured time points (flowering and close to harvest). The sprawling canopy, also let a larger amount of light through to the cordon as observed previously. This also impacted the canopy temperature that was higher in canopies trimmed at flowering followed by sprawling canopies.

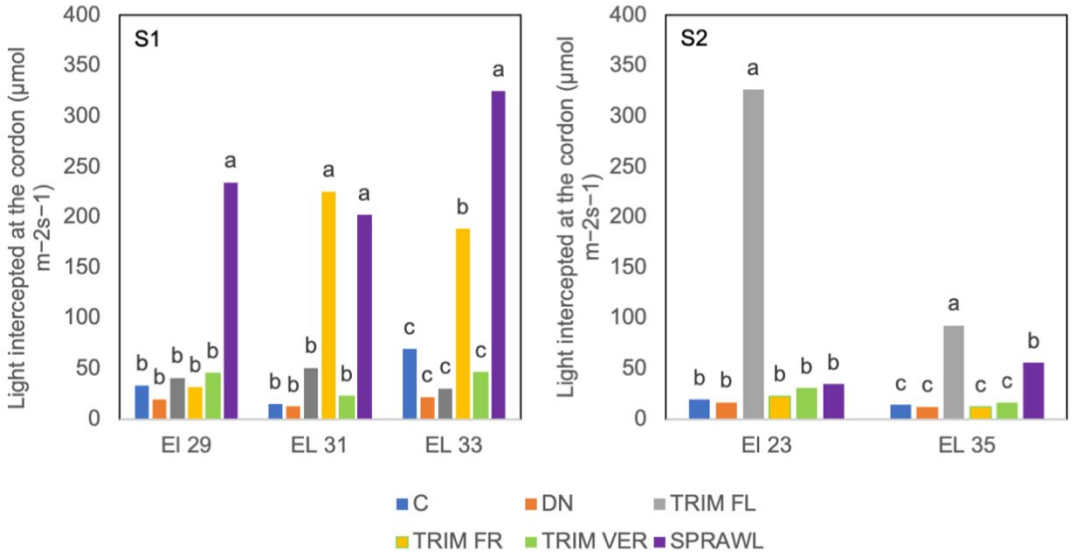


Figure 6.3: Effects of different canopy management treatments on canopy light interception of Semillon for seasons 2018-19 (S1) and 2019-2020 (S2). C= Control (dark blue), DN=Light pruning (red), LR-EARLY/TRIM FL (grey) = leaf removal at flowering (season 1)/trimming at flowering (seasons 2 and 3), TRIM VER (green) = trimming at veraison, SPRAWL = sprawling canopy (purple). Treatment effects were analysed using a one-way ANOVA and the means separated with Tukey's test. Different letters at each EL stage for PAI (bars) correspond to means different at $p<0.05$.

To investigate further the link between canopy architecture and microclimate, temperature sensors were installed inside the canopy of each middle vine of each treatment. Data was collected at 15 minutes intervals throughout the whole growing season from November to February. To present a snapshot of the findings, Figure 6.4 shows the temperature recorded at midday (12pm) and only for days when the differences between treatments were significant (29 days out of 83 total days measured). The temperature measured outside the canopy is also reported for reference for season 1 and is represented in dark blue. Given the open nature of a

sprawling canopy, it comes to no surprise that temperatures were in line with those measured in a completely exposed location in the vineyard. In these conditions temperatures reached above 40°C and on the 24th of January 2019 a midday T of 48.5°C was measured inside the canopy. At the same time the denser control and DN canopies recorded T of 45.9°C and 46.2°C respectively. As a general trend, the bunch zone of the control and DN canopies were cooler for the whole season. The temperature summation of all the significant midday values correlated with the light measured at the cordon level (R^2= 0.61).

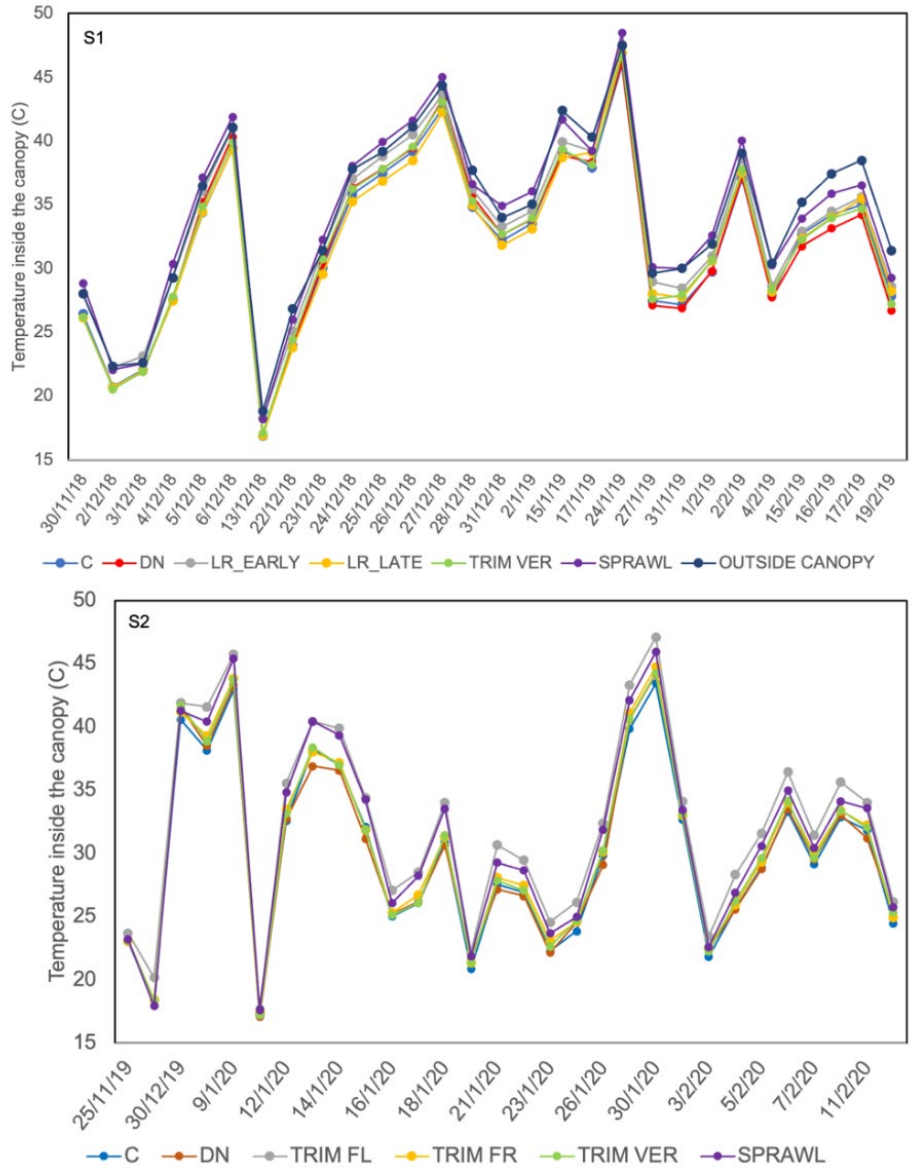


Figure 6.4: Effects of different canopy management treatments on the temperature inside the canopy measured using Tiny tags at 15 minutes intervals throughout the growing season for seasons 2018-19 (S1) and 2019-2020 (S2). C= Control (dark blue), DN=Light pruning (red), LR-EARLY/TRIM FL (grey) = leaf removal at flowering (season 1)/trimming at flowering (seasons 2 and 3), TRIM VER (green) = trimming at veraison, SPRAWL = sprawling canopy (purple). Treatment effects were analysed using a one-way ANOVA and the means separated with Tukey's test. Different letters at each EL stage for PAI (bars) correspond to means different at $p<0.05$.

In season 1, only minor differences were measured between treatments for yield components with the number of bunches/m being higher in the double node treatment, given the higher shoot count (Table 6.2). Yield was not different between the double node treatment and the control due to the double node treatment producing much smaller bunches. Also, the sprawling canopy yield was the lowest in the trial due to lighter bunches. However, the lighter bunches could have been caused by the higher exposure that made them prone to sunburn and more visible to birds when the nets were not yet installed. No other differences were observed in pruning weight, berry weight and berry and wine chemistry, apart from TSS. All treatments were harvested on the same day and while the late leaf removal (50% of leaves removed) achieved the desired effect of slowing down ripening (lower Brix) the trimming treatment carried out on the same day did not. This could be due to multiple reasons: 1) the trimming did not reduce the active canopy enough to impact the overall photosynthesis, similarly to what was observed in De Bei et al. (2019), 2) the vines increased their photosynthetic rate to compensate for the reduction in leaf area (Poni and Giachino, 2000). In season 2, yield components were different amongst treatments with control yielding the highest with over 8 kg/m and the light pruning the lowest, 5.3 kg/m. Bunches/m were not different between treatments hence the yield response was solely related to differences in bunch weight and berry weight, both parameters were indeed highest in control and lowest in the double node treatment. Interestingly, the pruning weight was higher in double node treatment given the higher number of shoots while the two later trimmings reduced the pruning weight considerably.

The last season of the trial saw some differences in yield with the double node treatment producing the heaviest crop (6.1kg/m), the other treatments produced similar yield (3.9-4.6 kg/m) and the lowest yield when vines were trimmed at veraison (3 kg/m). A higher number of smaller bunches was harvested from the DN treatment compared to the control that, instead, produced the heaviest bunches in the trial. Small differences were recorded for TSS with the double node treatment being the lowest and the sprawling treatment the highest. The pH varied from 3.3 when vines were trimmed at veraison to 3.42 when trimmed at flowering. TA was above 6 for control, trimming at veraison and sprawl treatments while it was below 6 in the other treatments.

Table 6.2: Effect of canopy management treatments on the yield components of Semillon grown in the Coombe vineyard of the University of Adelaide, Waite Campus, Adelaide, Australia. The trial was carried out for three consecutive seasons (from 2018 to 2021). C= Control, DN=Light pruning, LR-EARLY/TRIM FL= leaf removal at flowering (season 1)/trimming at flowering (seasons 2 and 3), TRIM VER= trimming at veraison, SPRAWL = sprawling canopy. Treatment effects were analysed using a one-way ANOVA and the means separated with Tukey's test. Means followed by different letters are different at $p<0.05$.

	C	DN	LR-EARLY	LR-LATE	TRIM	SPRAWL
Season 1						
Yield/m (kg)	5.5 a	5.5 a	5.2 a	5.1 a	4.8 a	3.1 b
Bunches/m (#)	27 b	44 a	26 b	29 b	25 b	26 b
Bunch weight (g)	204.5 a	133.5 b	200.3 a	185.3 a	200.1 a	121.3 b
Pruning/m (kg)	1.2 a	1.0 a	1.3 a	1.1 a	1.2 a	1.2 a
Berry weight (g)	1.48 a	1.28 a	1.12 a	1.20 a	1.42 a	1.20 a
Total Soluble Solids (Brix)	23.7 ab	23.7 ab	23.4 abc	22.1 c	24.2 a	22.5 bc
Berry pH	3.35 a	3.31 a	3.32 a	3.32 a	3.39 a	3.32 a
Berry titratable acidity (g/L)	7.51 a	7.72 a	7.51 a	7.64 a	7.22 a	6.72 a
Wine Alcohol (% vol)	14.29 a	13.74 a	14.07 a	13.88 a	14.69 a	13.72 a
Wine pH	3.22 a	3.17 a	3.20 a	3.27 a	3.24 a	3.19 a
Wine acidity (g/L)	5.80 a	5.97 a	5.93 a	5.71 a	5.90 a	6.46 a
Season 2						
	C	DN	TRIM FL	TRIM FR	TRIM VER	SPRAWL
Yield/m (kg)	8.4 a	5.3 b	6.6 ab	7.3 ab	6.6 ab	5.7 b
Bunches/m (#)	33	33	31	29	32	29
Bunch weight (g)	251.9 a	164.6 c	209.1 bc	242.2 ab	207.0 bc	202.7 bc
Berry weight (g)	1.6 a	1.3 b	1.6 a	1.6 a	1.6 a	1.2 b
Pruning/m (kg)	0.94 ab	1.56 a	0.86 ab	0.63 b	0.66 b	0.97 ab
Total Soluble Solids (Brix)	21.4 abc	22.3 abc	22.8 ab	21.1 bc	20.9 c	22.9 a
Berry pH	3.35 bc	3.38 ab	3.23 d	3.28 cd	3.43 a	3.33 bc
Berry titratable acidity (g/L)	5.03 a	4.39 bc	4.11 c	4.87 ab	4.30 c	5.19 a
Season 3						
Yield/m (kg)	4.3 bc	6.1 a	3.9 bc	4.6 b	3.0 c	4.1 bc
Bunches/m (#)	30 bc	58 a	28 bc	36 b	24 c	30 bc
Bunch weight (g)	142.7 a	106.2 b	141.0 a	133.2 ab	122.7 ab	138.4 ab
Berry weight (g)	1.22 ab	1.12 b	1.27 ab	1.36 a	1.1 b	1.16 b
Total Soluble Solids (Brix)	23.0 ab	22.3 b	23.7 ab	23.0 ab	23.7 ab	24.6 a
Berry pH	3.30 b	3.35 ab	3.42 a	3.39 ab	3.30 b	3.33 ab
Berry titratable acidity (g/L)	6.75 a	5.50 b	5.21 b	5.17 b	6.33 a	6.29 a

A Principal Component Analysis (PCA) was performed to visualise the effect of canopy manipulations on Semillon's performance by taking into account all the measured parameters, for the data collected in season 1 (Figure 6.5). The PCA included vineyard measurements of canopy size, light interception, canopy temperature and yield components together with the results of the juice amino acid content and the wine aromatic profiling. Only measurements that were different between treatments ($p<0.05$) were included in the PCA. The first two PCs explained almost 79% of the variability in the dataset. PC1, which explained 51% of the variability and mostly separated the sprawling canopy from the other treatments, the leaf removal in particular. The variables driving the separation along PC1 were mainly related to wine aromas that were all significantly higher in the sprawl. Higher light in the bunch zone and canopy temperature were also drivers of the separation and, as previously discussed were higher in the sprawl. These two parameters pushed the separation of the treatments along PC2 too and separated the double node treatment from the sprawl and the early leaf removal. The double node treatment varied from other treatments in amino acid content with higher cystein and tryptophan levels and lower methionine. High tryptophan levels have been linked to off-flavours in wines which can be observed in this case too (Christoph et al., 1999).

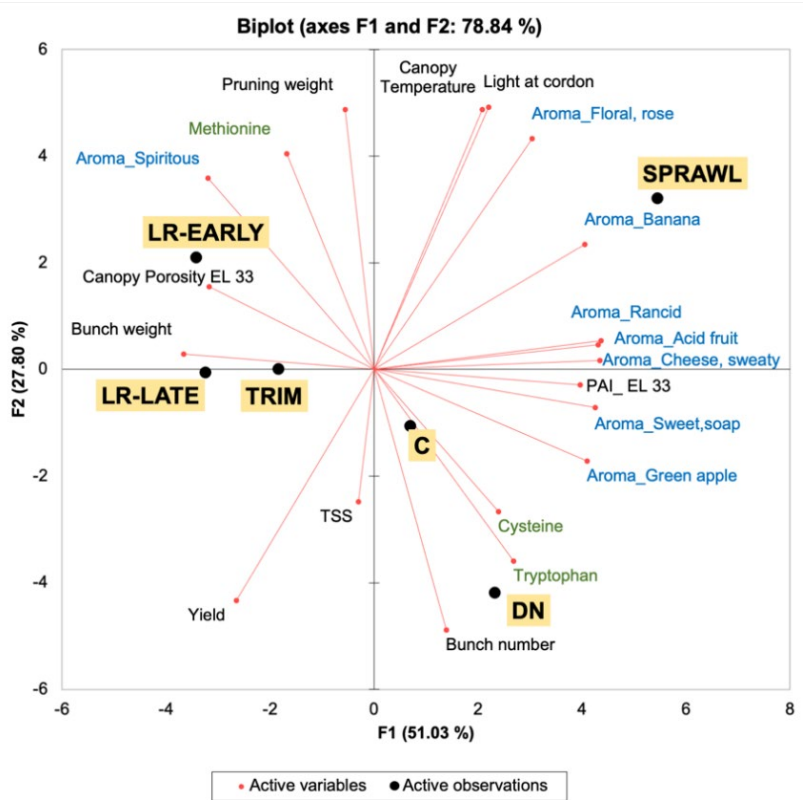


Figure 6.5: Principal component analysis of the parameters of vine performance found to significantly differ ($p<0.05$) between canopy management treatments applied to Semillon in season 2018-19. Parameters included wine Aromas (in blue), aminoacids concentration (in green), canopy architecture (PAI and Canopy porosity), yield components (Yield, bunch weight, bunch number, pruning weight), total soluble solids (TSS), canopy temperature and light measured at the cordon level. C= Control, DN=Light pruning, LR-EARLY= 50% leaf removal at flowering, LR-LATE=50% leaf removal at veraison TRIM= trimming at veraison, SPRAWL = sprawling canopy. TSS= Total soluble solids, PAI= plant area index.

The canopy manipulations, with the demonstrated strong impact on the PAI, light interception and canopy temperature throughout the season also affected some of the wine fermentation products as measured via gas chromatography/mass spectroscopy. In Figure 6.6, three of the strongest correlations obtained are presented. A surprising strong link was detected between the concentration of acetic acid in the wine (volatile acidity-VA) and the canopy temperature, with a trend of higher VA in the wines obtained from cooler canopies. Both the compounds responsible for the aroma of banana (3-Methylbutyl acetate) and floral (2-Phenylethanol) were positively linked with temperature.

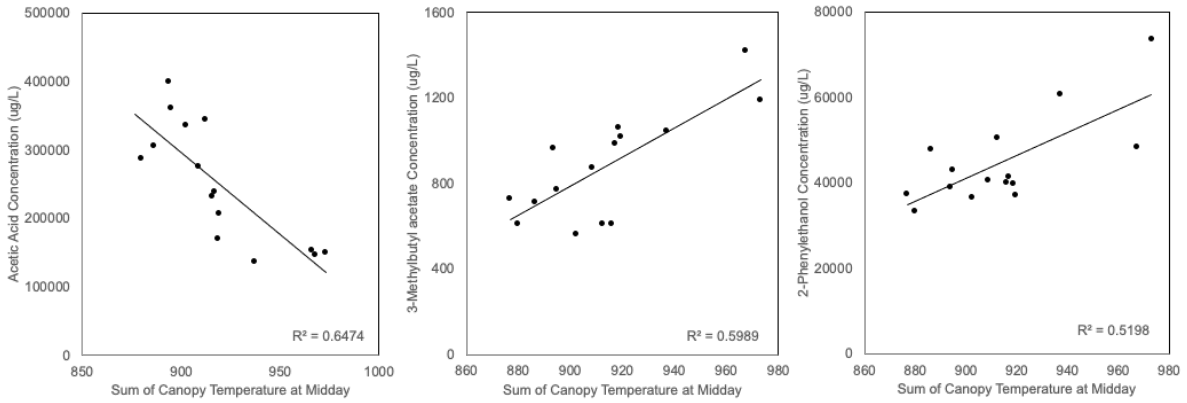


Figure 6.6: Correlations between canopy temperature and a) acetic acid concentration in wine, b) 3-Methylbutyl acetate concentration in wine and c) 2-Phenylethanol concentration in wine. All correlations are significant at $p \leq 0.05$.

From the second season of the trial, the effect of the treatments on the sensory attributes of the berries were investigated both in-field and in through formal sensory assessment in the laboratory. The attributes that were different between treatments in 2019-20 are presented in the PCA in Figure 6.7. The attributes measured in the vineyard have been added as supplementary variables and are presented in blue. There was a good agreement between the BSA in the lab and the simplified BSA in the vineyard. The early trimming treatments were associated to green and grassy characters, higher skin and seed astringency and green, acidic and more citrus-flavoured pulp. All these attributes are normally associated to fruit that is not completely ripe which is consistent with the expected outcome of such treatments; by the drastic reduction of the amount of canopy a delay in the ripening process is expected. However, this effect was not observed in the fruit TSS results.

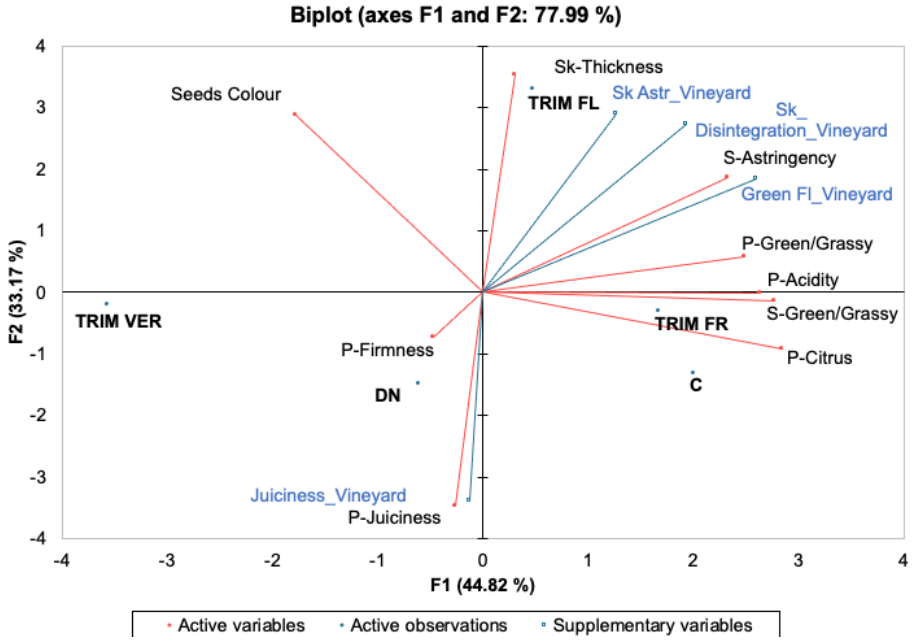


Figure 6.7: Principal component analysis of berry sensory assessment attributes both from the formal assessment (in black font) and from the in-vineyard assessment (blue font) carried out in 2020 on berries from Semillon vines subjected to different canopy management treatments. All the attributes in the PCA have been found to differ between treatments at $p<0.1$. C= Control, DN=Light pruning, TRIM FL= trimming at flowering, TRIM FR= trimming at fruitset, TRIM VER= trimming at veraison, SPRAWL = sprawling canopy. S= seed attributes, Sk= skin attributes, P= pulp attributes Fl= flavour.

In 2021, only three of the five attributes assessed in the vineyard were different between treatments (green font, Figure 6.8) and, together with the attributes assessed during the formal BSA they are represented in the PCA plot in Figure 6.8. The vineyard and laboratory based BSA are in agreement in this season, thus demonstrating the robustness of the in-field assessment. The treatment separation along PC1 (44.15% of the variability explained) was mostly driven by differences between the control and trimming at flowering treatments. In particular, the control was associated to attributes typical of less ripe fruit like green and citrus flavours, higher skin thickness (and less disintegration when chewed), higher acidity and pulp firmness. This treatment had higher PAI both at EL 23 and EL 34 and a higher pruning weight. On the opposite side, the vines that were trimmed at flowering produced fruit with lower scores associated to all the mentioned attributes. Given this treatment had the highest porosity it could be inferred that bunches were more exposed and hence potentially “over ripe”. Further characterised by soft and easy to chew skins and lower green and citrusy berries. Along the second PC the separation between the double node treatment and trimming at flowering, and the control to a lesser extent, is clear and associated to higher flavour intensity in the double node treatment. While the control and trimming at flowering treatments had more acidic and astringent skins.

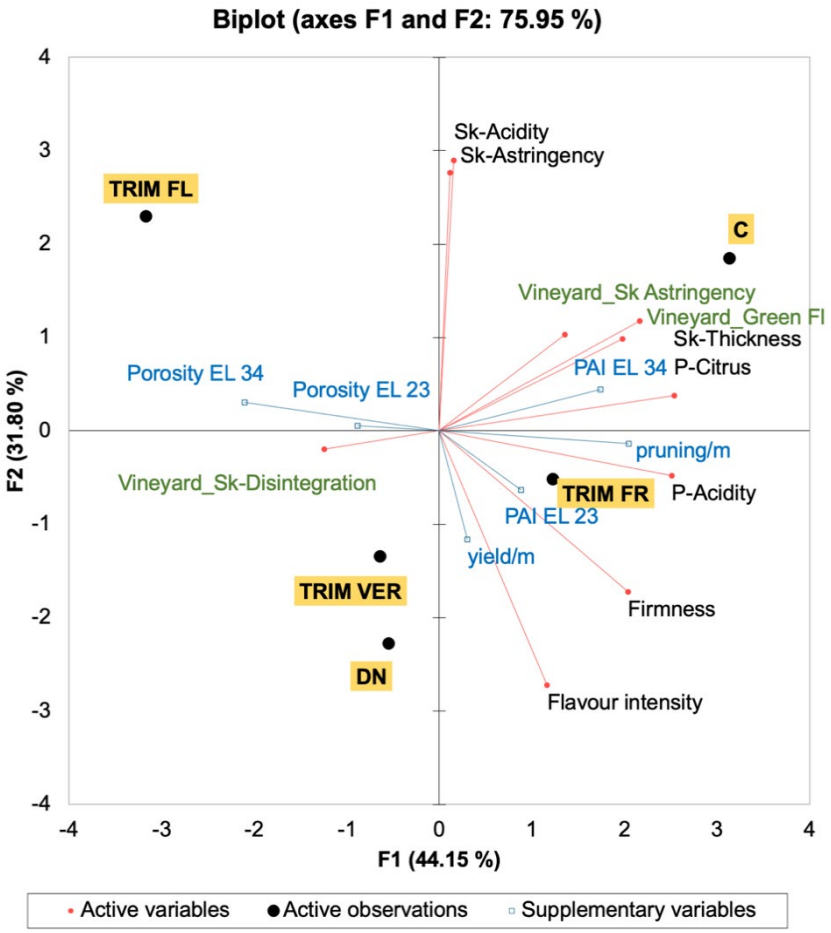


Figure 6.8: Principal component analysis of berry sensory assessment attributes both from the formal assessment (in black font) and from the in-vineyard assessment (green font) carried out in 2021 on berries from Semillon vines subjected to different canopy management treatments. All the attributes in the PCA have been found to differ between treatments at $p<0.1$. C= Control, DN=Light pruning, TRIM FL= trimming at flowering, TRIM FR= trimming at fruitset, TRIM VER= trimming at veraison. PAI= Plant area index, Sk= skin attributes, Fl= flavour.

All data generated by VitiCanopy is geo-referenced and every other measurement carried out on the same vines was also geolocated. This allowed for maps of any of the measured parameters to be created to illustrate their spatial distribution in the vineyard. Below are a few interesting examples obtained from the Semillon canopy management trial.

6.2.2 Canopy PAI throughout a season

The series of maps below represents the spatial variability of the PAI results already presented in Figure 6.5 for season 2018-19. The first measure carried out at EL 16 showed already high values of the PAI with a range from 1.8 to 1.4 (Figure 6.9). The higher values correspond to the location of the double node treatment which was applied to vines on the second last panel of each end of each row (blue areas). This series of maps shows how the canopy management treatments increased the variability in the four rows with most of it related to the high PAI values from of the double node treatment but also from the sprawling canopy values which correspond to the green/blue areas along the left side of the map.

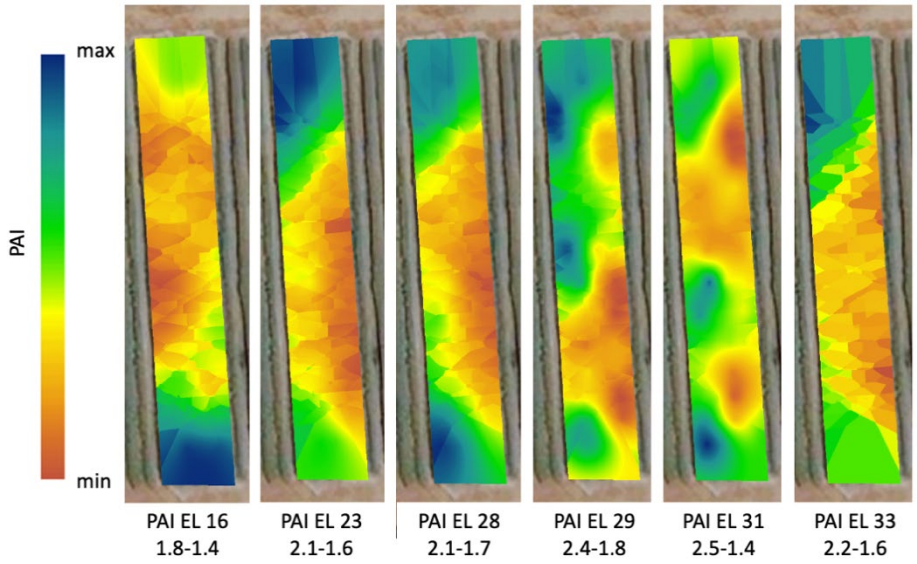


Figure 6.9: Maps of the spatial distribution of PAI in the Semillon vineyard at six phenological stages (El Stage, Coombe, 1995) during the 2018-19 growing season.

6.2.3 Canopy PAI same EL stage between seasons

Vineyard maps of the same block at the same phenological stage (EL 23) for three consecutive seasons are compared in Figure 6.10. Since the variability is imposed through the same canopy management manipulations applied every season, the high similarity between maps was expected. Interestingly, there has been a tendency to higher PAI values throughout the years with the PAI in 2021 reaching values as high as 2.5.

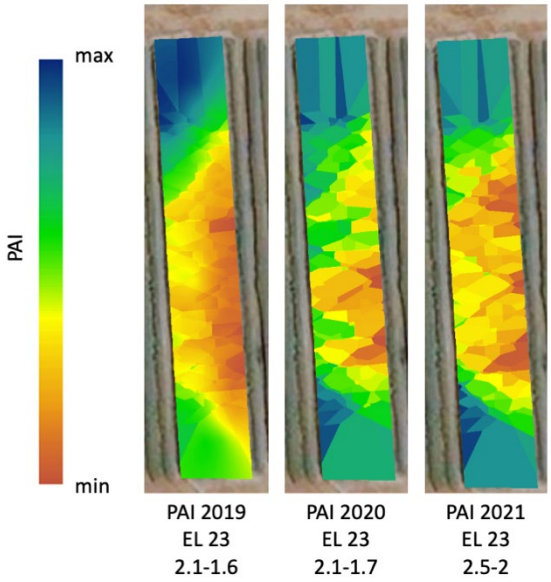


Figure 6.10: Maps of the spatial distribution of PAI in the Semillon vineyard at the same phenological stage (EL 23) (Coombe, 1995) for three consecutive seasons: 2018-19, 2019-20, 2020-21.

6.2.4 Canopy PAI, light interception, canopy temperature and wine aroma.

In 2018-19 an extensive dataset was collected for the trial. In Figure 6.11 below a striking visual representation of the links between canopy PAI, canopy light interception, canopy temperature and wine aroma (in this case the concentration of 2-Phenylethanol was selected) is represented as maps of these attributes spatial distribution in the block. A strong link between high PAI, high light interception, high temperature and high floral aroma in the wine is evident (blue and green areas).

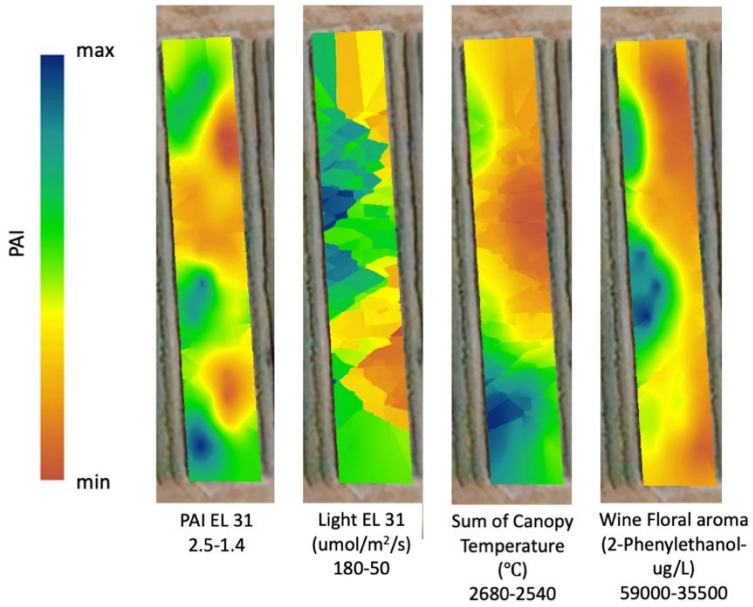


Figure 6.11: Maps of the spatial distribution of PAI at EL 31, light interception at EL 31, canopy temperature and wine floral aroma in the Semillon vineyard in season 2018-19.

6.2.5 Juice elemental analysis

In 2020 must samples from the 54 vines in the trial were sent to a laboratory for elemental analysis (Figure 6.12). A surprisingly high spatial variability of some elements in the juice samples was observed. In particular, the phosphorous content appeared very patchy with areas of very high phosphorous that seem unrelated to any other measured parameters. Calcium too appeared very patchy with an area of high concentration corresponding to the area of low phosphorous. Interestingly, there also appears to be an area at the southern end of the vineyard with high sodium concentration while the rest of the block was consistently low in this element.

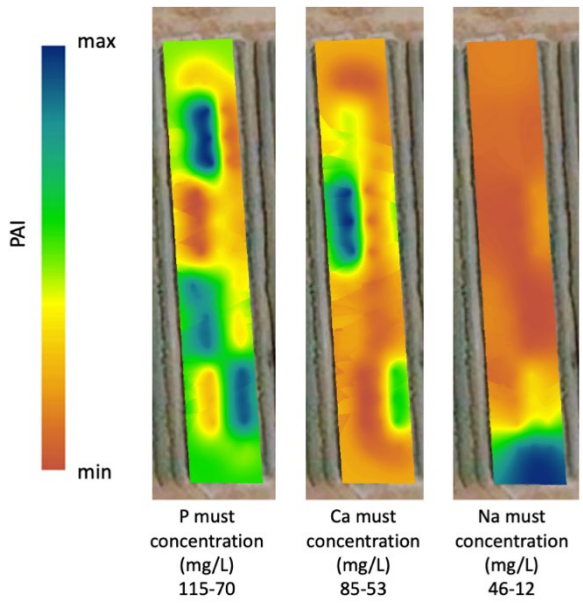


Figure 6.12: Maps of the spatial distribution of three elements (potassium (P), calcium (Ca) and sodium (Na)) measured on juice samples of Semillon from different canopy management treatments in 2019-20.

6.2.6 Aqualog spectrofluorometer analysis

Grape juice samples from harvest 2020 were submitted for Aqualog analysis.

The parallel factor analysis (PARAFAC) model required three components to describe the variability of the excitation emission matrix (EEM). As shown in Figure 6.13, samples did not show a clear separation possibly due to overfitting of all the classes with the same loading of PARAFAC model.

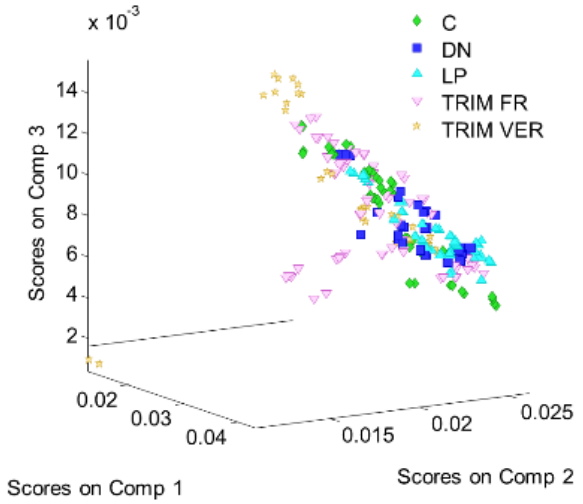


Figure 6.13: Scores from the three component PARAFAC model of EEM data for Semillon samples from different canopy management treatments applied in 2019-2020. C = Control, DN = Light pruning, LP = 50% leaf removal at flowering, TRIM FR= trimming at fruitset, TRIM VER= trimming at veraison.

As an unsupervised method of used to explore the data, PCA was also applied to EEM data. With an auto scale pre-processing, there was no clear separation of samples between treatments (Figure 6.14). Decluttering is an effective way to remove interfering signals, with the value for the clutter threshold (also known as alpha) defining the extent to which the clutter directions are downweighted. As the threshold gets smaller (e.g., 0.1 to 0.001), the extent of de-weighting increases because more variance in the clutter exceeds the threshold. Decluttering by generalised least squares (GLS) weighting (alpha = 0.1) and mean centre preprocessing was applied to the sample EEMs, resulting in a clear separation between samples from different canopy management treatments (Figure 6.15).

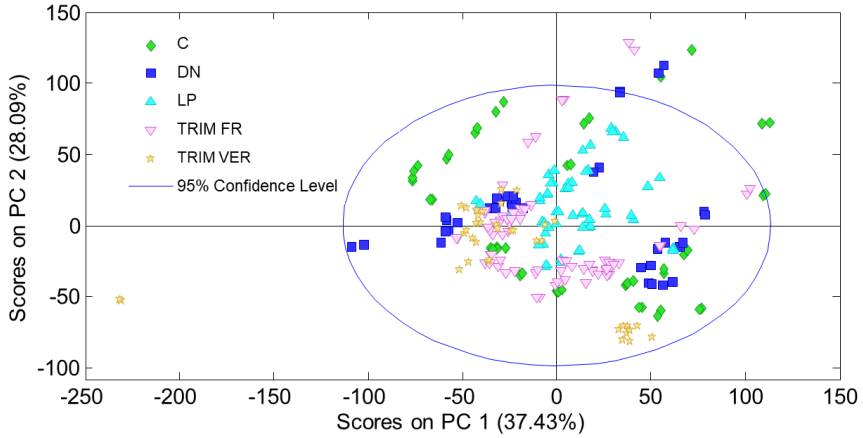
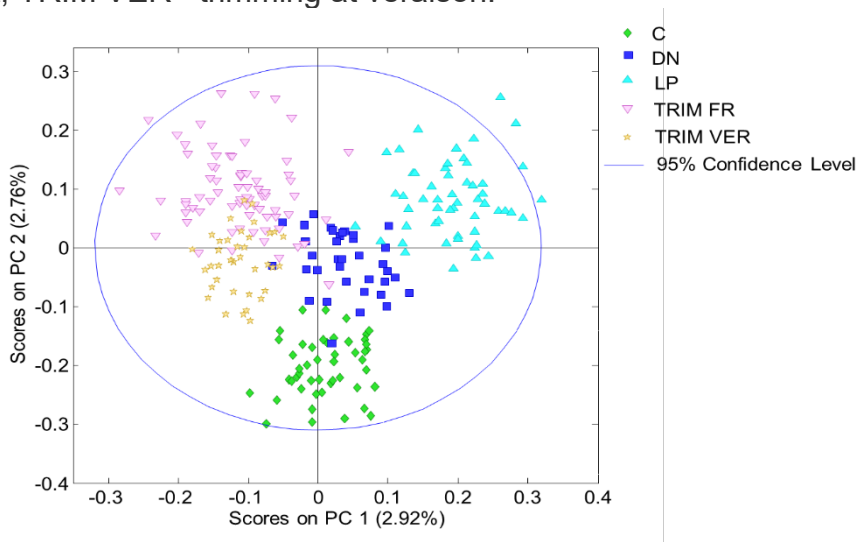


Figure 6.14: Principal component analysis (PCA) score plot without clutter removal of EEM data of Semillon samples from different canopy management treatments applied in 2019-2020. C= Control, DN=Light pruning, LP= 50% leaf removal at flowering, TRIM FR= trimming at fruitset, TRIM VER= trimming at veraison.



(B)

Figure 6.15: Principal component analysis (PCA) score plot with 0.1 decluttering of EEM data of Semillon samples from different canopy management treatments applied in 2019-2020. C= Control, DN=Light pruning, LP= 50% leaf removal at flowering, TRIM FR= trimming at fruitset, TRIM VER= trimming at veraison.

Extreme gradient boosting discriminant analysis (XGBDA) was conducted on the EEM data to determine the classification probability with cross validation. The XGBDA

model built with 10 components from PLSDA dimension reduction using GLS weighting (alpha = 0.1) and mean centre preprocessing showed a 99.2% correct classification according to the treatments. As shown in Figure 6.16, only 2 samples were misclassified out of 248 for the model after cross validation (CV, Venetian blinds method).

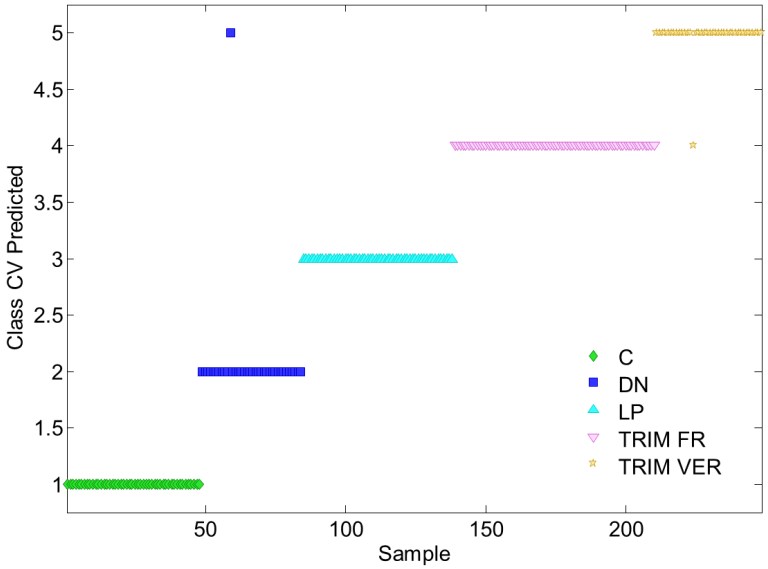


Figure 6.16: Class CV predicted from XGBDA analysis of EEM data of Semillon samples from different canopy management treatments applied in 2019-2020. C= Control, DN=Light pruning, LP= 50% leaf removal at flowering, TRIM FR= trimming at fruitset, TRIM VER= trimming at veraison.

6.3 Case Study 2: Premium Shiraz vineyards, Barossa Valley

Aim: i) to assess vineyard variability within and between seasons and create the history of a site and ii) assess the link between vineyard variability in canopy architecture and vine performance.

6.3.1 Vineyard 1

During the first growing season (2018-19) the vineyard block was assessed at four time points (Figure 6.17). The block variability was high, with areas of very low PAI on the eastern side (as low as 0.48) and higher PAI values on the western end. The overall block variability was consistent throughout the season. Interestingly the maximum and minimum PAI values throughout the season did not fluctuate, remaining in the ~0.5-1 range.

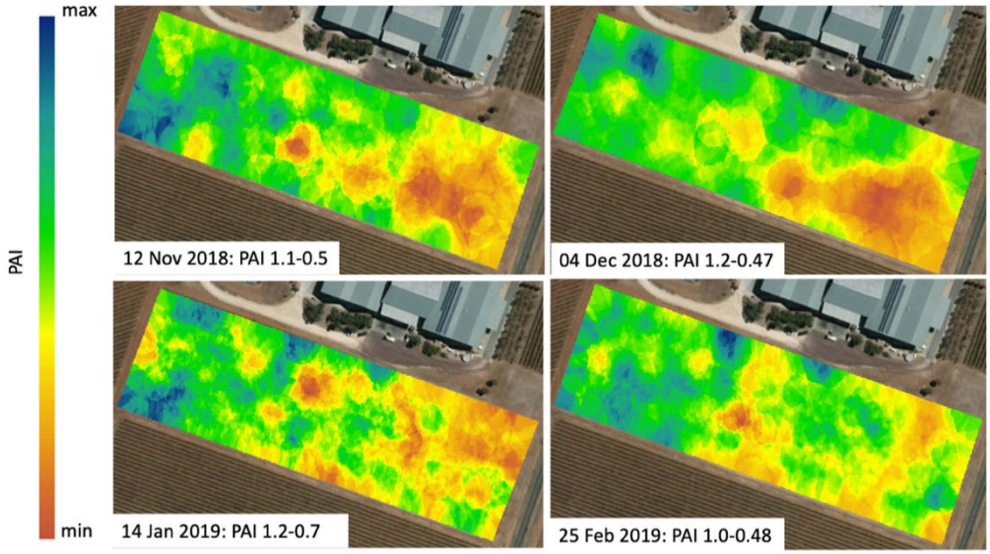


Figure 6.17: Plant Area Index (PAI) maps generated from VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley. Measures were collected at four timepoints during the 2018-19 growing season.

The 2019-20 growing season was one of the hottest and driest of the last decade and this was evident in the canopy development in Figure 6.18. The overall vineyard variability observed in the previous season was less noticeable in this season, however still present with the same pattern. What was interesting in this case is that harvest occurred almost 1 month later than the previous season and the PAI values ranged from 0.1-0.5, which is typically the range of values that can be measured on bare cordons (De Bei et al., 2016). This suggests that these vines had lost significant leaf area across the whole block.

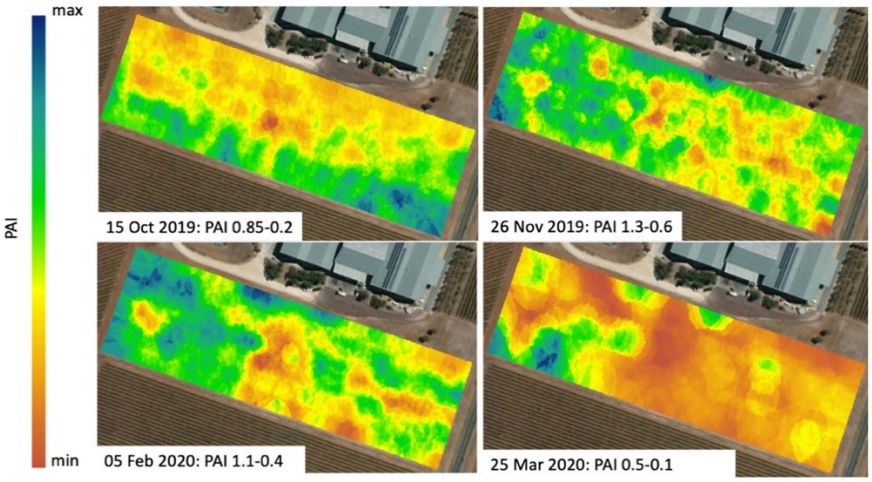


Figure 6.18: Plant Area Index (PAI) maps from VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley. Measures were collected at four timepoints during the 2019-20 growing season.

To appreciate the season effect on the canopy size within the same block and at the same phenological stage the maps of the vineyard just before harvest in 2019, 2020, and 2021 were compared with the same PAI scale/range (same max and min values) (Figure 6.19). The adjusted scale does not allow to appreciate the within block variability in 2020 however what is clear is the effect the very dry season had on the canopies. Harvest 2020 was carried out on vines that were almost bare.

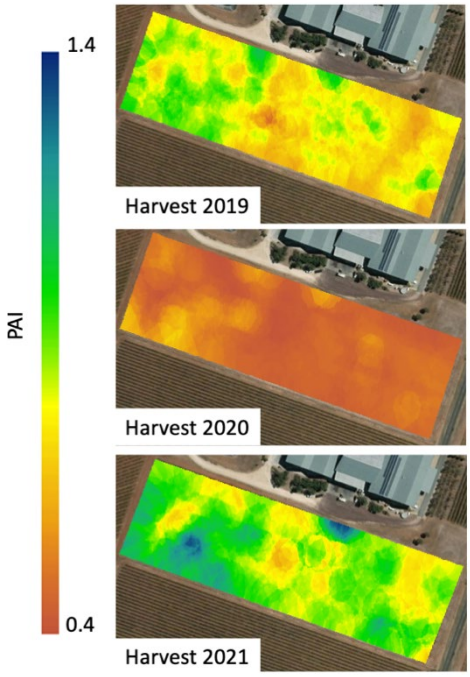


Figure 6.19: Plant Area Index (PAI) maps of VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley. Measures were collected just before harvest on three consecutive seasons.

To explore the effect of vineyard variability in canopy architecture on other vine performance parameters, bunches were sampled at harvest from areas identified as low, high and medium PAI at veraison in 2020. The same areas were sampled at harvest the following year. A map showing the sampling location is presented in Figure 6.20.

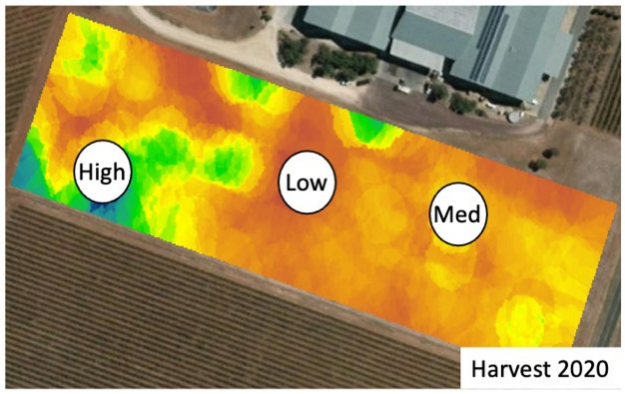


Figure 6.20: Plant Area Index (PAI) map from results of the VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley at veraison in 2020. Areas of low, medium and high PAI were identified and samples were taken from these zones.

A PCA performed on vine performance measures shows a distinct separation between the identified areas of low, medium and high PAI values within the vineyard. PC1 explains 62.5% of the variability in the dataset and it separates the low PAI areas from the high. The attributes driving this separation are numerous; the low areas are characterised by, obviously, low PAI but also high pH, TA and TSS. Interestingly this also corresponded to a greater inflorescence primordia area and larger bunch architecture. On the other side, high PAI was associated to greater TSS 2020, berry weight, bunch weight and inflorescence primordia number in both assessed seasons.

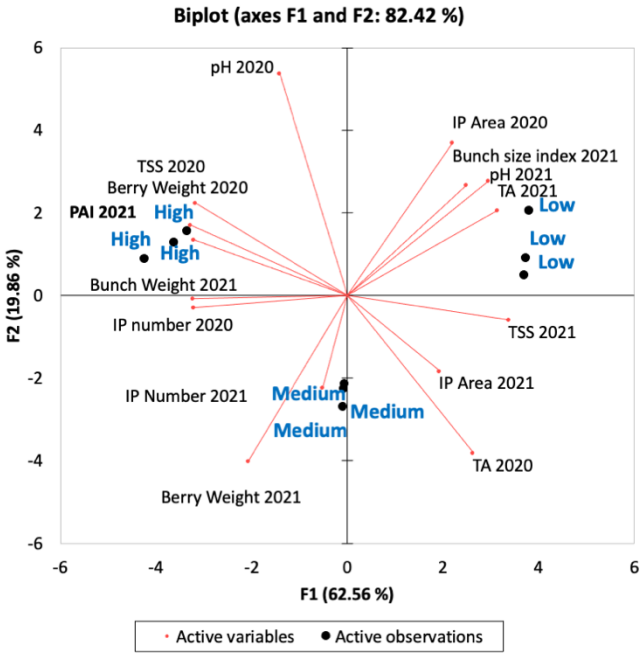


Figure 6.21: Principal component analysis of vine performance measurements collected from areas of low, medium and high plant area index (PAI) (as measured using VitiCanopy at veraison in 2020) found to be different between the three zones ($p<0.05$). TA= titratable acidity, TSS=Total soluble solids, IP=inflorescence primordia.

In 2021, 10 rows within the block were re-worked from spur pruning to cane pruning. In Figure 6.22, a map of the block at EL 15-17 from 2018 (Nov 2018) is compared to the map from the same phenological stage obtained in 2021 (Nov 2021) after re-working was applied (in the blue rectangle). In 2018, a lower PAI was measured in the

southern end of the block. In November 2021, a clear separation in PAI values can be seen in relation to whether the vines were now cane pruned (in the blue rectangle) or spur pruned (higher PAI values).



Figure 6.22: Vineyard spatial variability of PAI in a Shiraz block in the Barossa Valley region of South Australia at the same phenological stage (EL 15-17) in 2018 (left) and 2021 (right). In 2021 the first ten rows on the left were re-worked from spur to cane pruning (in the blue rectangle).

Grape extracts from samples collected from areas in the vineyard of low, medium and high PAI values in the vineyard were submitted for Aqualog analysis. A PARAFAC model with four components was developed with 90% core consistency showing the strength of the model. The score plot of three components (Figure 6.23) showed a tight clustering between the three PAI classes however, the samples collected from areas of high PAI tended to separate from the other two classes.

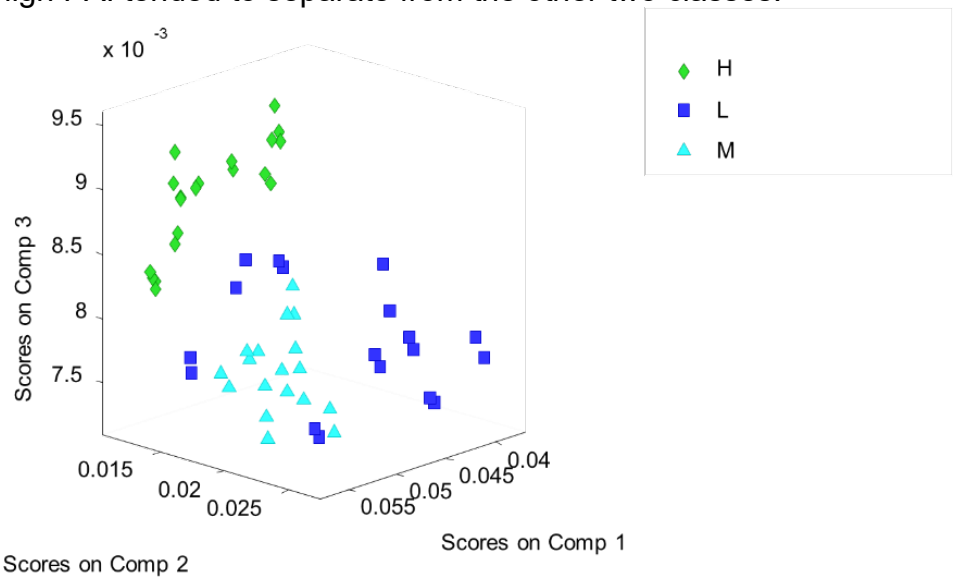


Figure 6.23: Score plot of the first three components of the PARAFAC model of EEM data for samples collected in areas of low (L), medium (M) and high (H) PAI values in a Shiraz vineyard in the Barossa Valley.

A PCA model with four PCs and decluttering with external parameter orthgonalisation (EPO), an extended mixture model (EMM) filter, along with mean centre pre-

processing, showed strong differentiation between samples from different PAI areas (Figure 6.24). PC1 mostly separated high from low PAI samples whereas PC2 tended to separate the medium PAI samples from the other two classes.

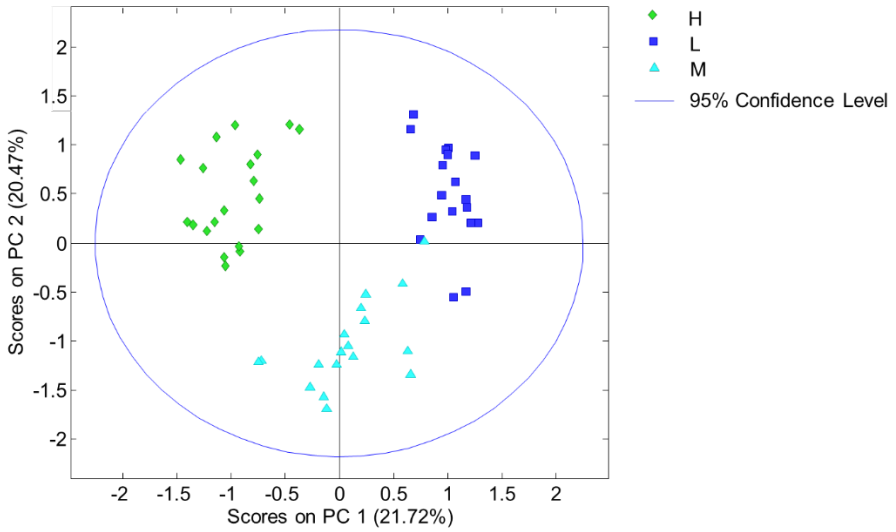


Figure 6.24: Principal component analysis (PCA) score plot of EEM data for samples from different PAI values areas. L= low PAI values, M=medium PAI values and H=high PAI values.

XGBDA modelling was undertaken with four PLSDA components after EPO/EMM filtering and mean centre pre-processing, to validate the exploratory results obtained from PCA and PARAFAC. The XGBDA algorithm enabled the distinction of different PAI value areas using EEM data with 100% accuracy for the CV model (Figure 6.25).

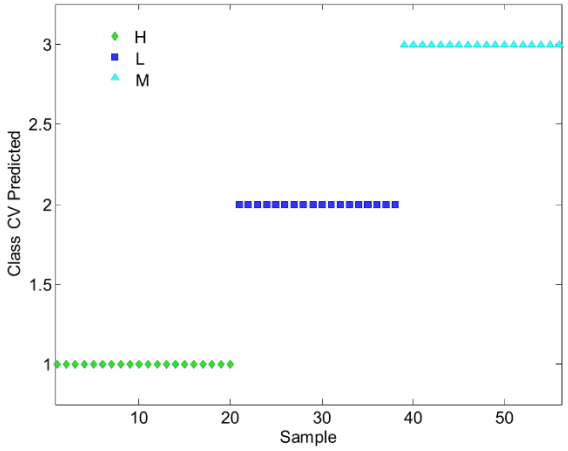


Figure 6.25: Class CV predicted from XGBDA analysis of EEM data for samples from different PAI value areas. L= low PAI values, M=medium PAI values and H=high PAI values.

6.3.2 Vineyard 2

In 2017-18 the vineyard was imaged twice, at around veraison and just before harvest (Figure 6.26). The maps show a similar spatial distribution of the PAI values, with an area of higher PAI from the left corner and expanding through the centre of the block. The range of PAI values measured was also very similar at the two dates with a range between 2.4 and 1.

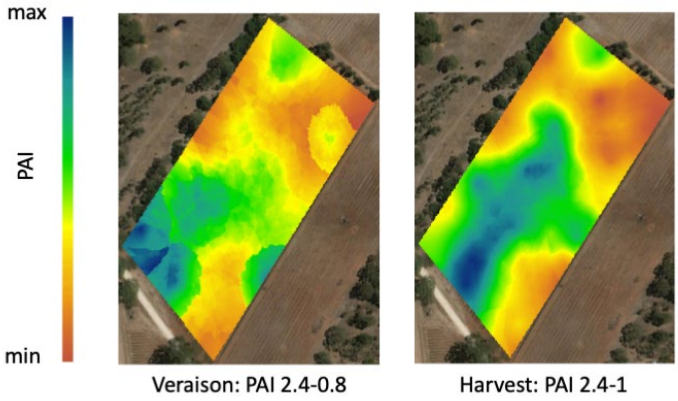


Figure 6.26: Plant Area Index (PAI) maps from VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley. Measures were collected at two timepoints during the 2018-19 growing season.

Season two and three data offered a within and between season comparison for the vineyard block at four stages of the growing season (Figure 6.27). Interestingly the four maps obtained in 2018-19 show an almost identical variability, with areas of inevitable low PAI on the west side of the vineyard most likely due to competition for water with the neighbouring trees and, as in the previous season, higher PAI values throughout the centre of the block. The PAI range measured at each stage not only showed much lower maximum PAI values compared to the previous year but also a loss of canopy from fruitset (max PAI 1.7) to veraison (max PAI 1.5) with the lowest values measured at harvest (max PAI 1.3).

In 2019-20 an early measure was taken in mid-October corresponding to EL 16 followed by a flowering, veraison and harvest measure. The three first measurements did show again a similar variability pattern however, compared to the previous season, a much wider area of low PAI values was noticeable already at veraison. The measurement taken at harvest was surprising, the canopies in the whole block appeared to have lost leaf area with the only area of PAI values above 1 in the top left corner of the block (Figure 6.27).

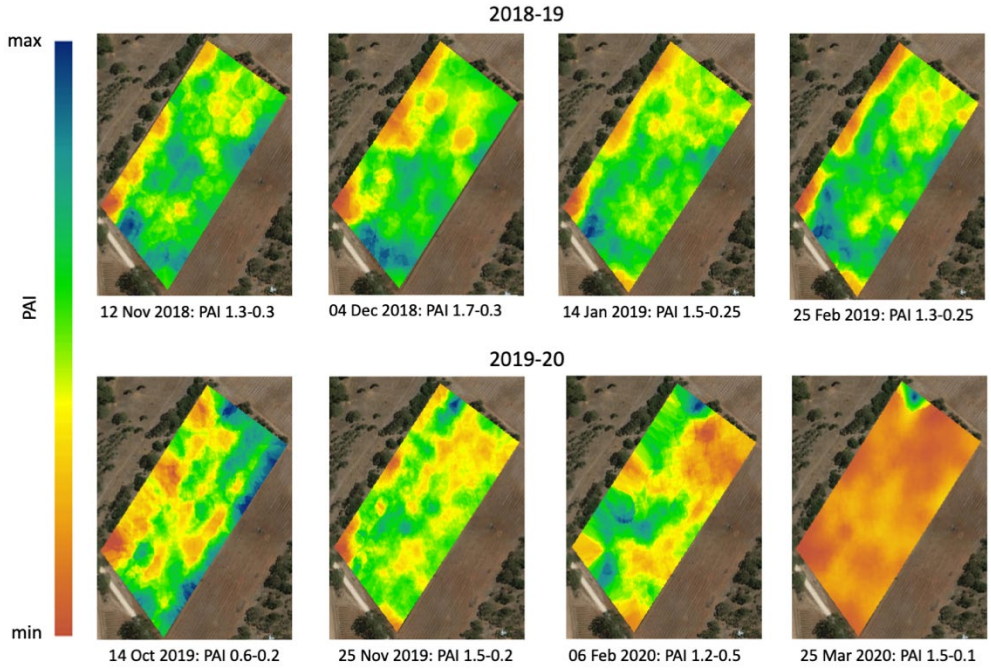


Figure 6.27: Plant Area Index (PAI) maps from VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley. Measures were collected at four timepoints during the 2018-19 and 2019-20 growing seasons.

When these maps were compared at the same phenological stage in different seasons a pattern of decline in canopy size (PAI) was obvious (Figure 6.28). The measurements taken at veraison in 2017-18 showed a consistent distribution of high PAI values in the block with a wide area of values as high as 2.4 (blue area). At the same stage in 2018-19 only a few scattered areas of green were visible, and this completely disappeared in 2019-20. In all three of these seasons there was a tendency to lower PAI values towards harvest which culminated with an almost complete loss of canopy in the hot and dry 2019-20 summer. It can be assumed that in the last season, a more favourable irrigation regime was adopted that was able to not only maintain canopy until harvest but also achieve greater uniformity within the block (2020-21).

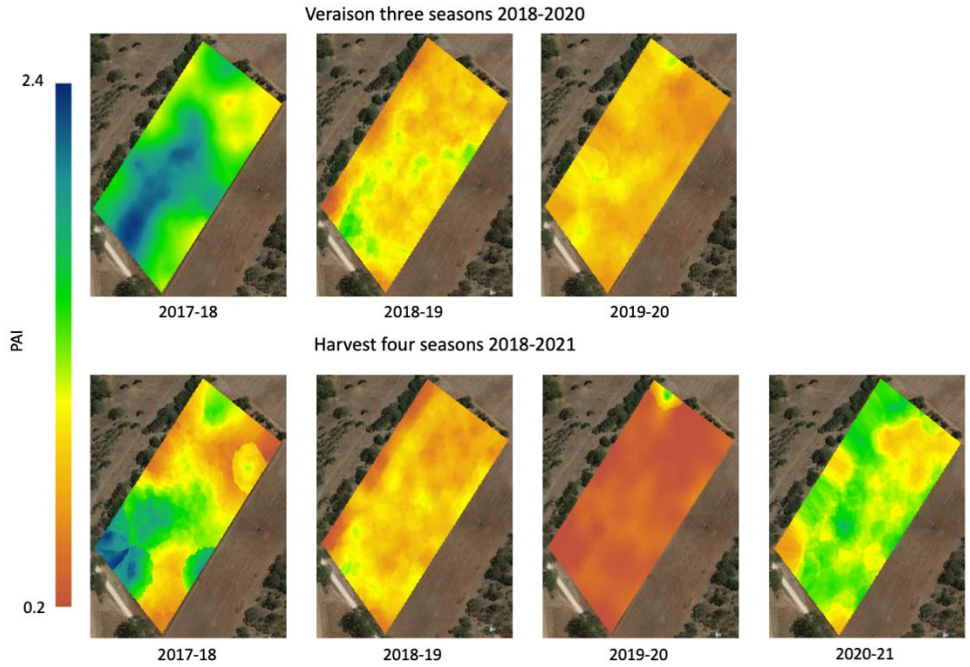


Figure 6.28: Plant Area Index (PAI) maps from VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley. Measures were collected at veraison for three consecutive seasons (2018-2020) and at harvest for four seasons (2018-2021).

To explore the effect of vineyard variability in canopy architecture on other vine performance parameters, bunches were sampled at harvest from areas identified as low, medium and high PAI at veraison in 2020. The same areas were sampled the following year. A map showing the sampling location is presented in Figure 6.29.

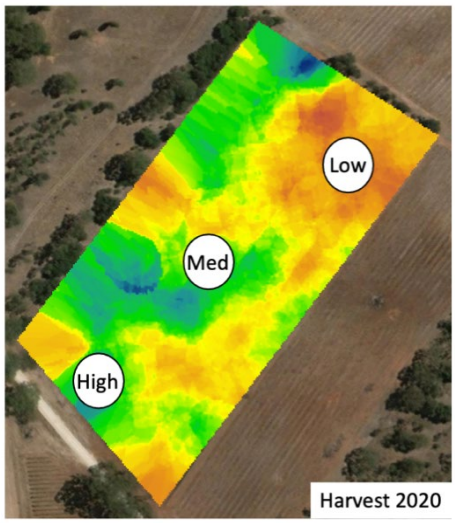


Figure 6.29: Plant Area Index (PAI) map from results of the VitiCanopy analysis of images collected in a Shiraz vineyard in the Barossa Valley at veraison in 2020. Areas of low, medium and high PAI were identified and bunch samples were taken from these zones.

Similarly to the vineyard 1 observations, results from vineyard 2 confirmed a strong grouping of the three sampling areas of low, medium and high PAI when PCA was performed (Figure 6.30). In this case the separation along PC1 (46% of the variability) is linked to differences between zones of low and high PAI. The low zone were characterised by high TSS, pH and TA in 2020 and greater berry weight in 2021 while

on the opposite quadrant, bunch weight in 2021, PAI and berry weight in 2020 were higher in the high PAI zone. The areas of intermediate PAI values showed the highest TSS in 2021 and generally higher values for both inflorescence primordia number and size from bud dissection analysis.

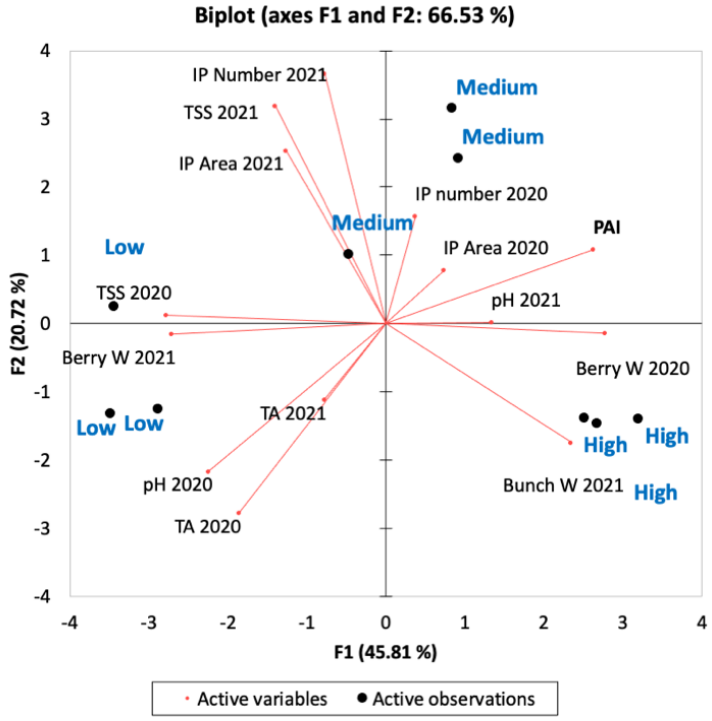


Figure 6.30: Principal component analysis of plant performance measurements collected from areas of low, medium and high PAI (as measured using VitiCanopy at veraison in 2020) and found to be different between the three zones ($p<0.05$).

Aqualog analysis was also performed on these samples, with the EEM data analysed with a four component PARAFAC model. Results did not show a clear clustering of samples according to their PAI values; however, the low PAI values separated from the high ones (Figure 6.31).

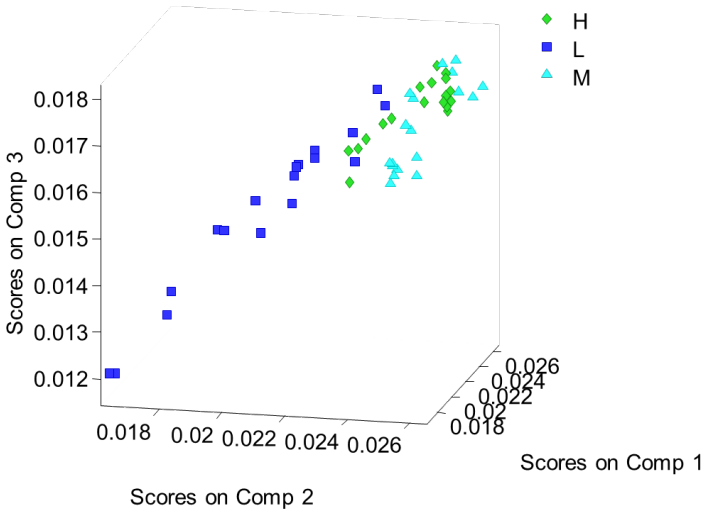


Figure 6.31: Score plot of the first three components of the PARAFAC model of EEM data for samples collected in areas of low (L), medium (M) and high (H) PAI values in a Shiraz vineyard in the Barossa Valley.

A PCA model was built using three principal components (PCs) (GLS weighting with alpha = 0.01 and mean centre pre-processing) that explained about 50% of the total variance for the samples, which were clearly separated according to the different PAI values (Figure 6.32). PC1 separated high PAI samples from the other two classes and PC2 separated low PAI samples from high and medium.

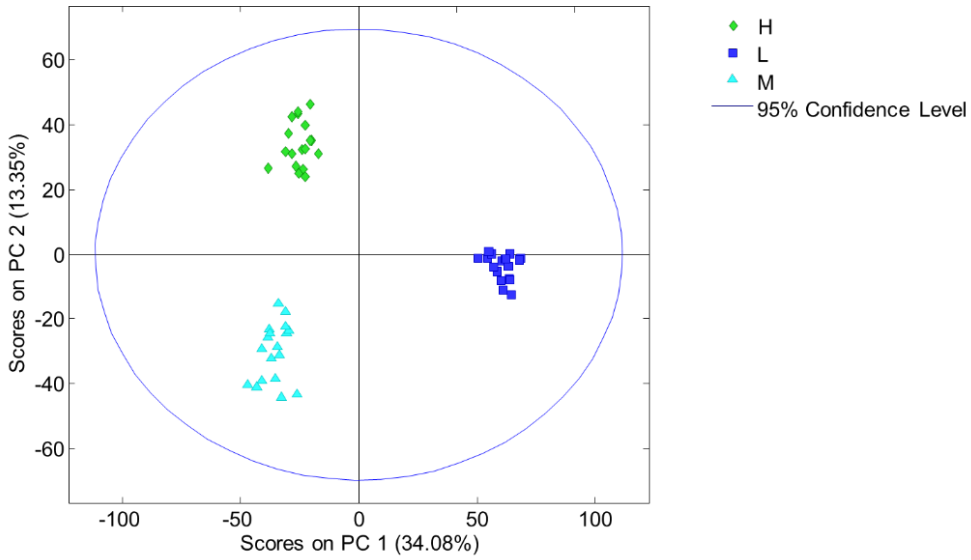


Figure 6.32: Principal component analysis (PCA) score plot of EEM data for samples from different PAI values areas. L= low PAI values, M=medium PAI values and H=high PAI values.

Supervised approach using XGBDA with only mean centre pre-processing and PLSDA compression with 10 components resulted in 100% accuracy in classifying samples according to their vigour (Figure 6.33).

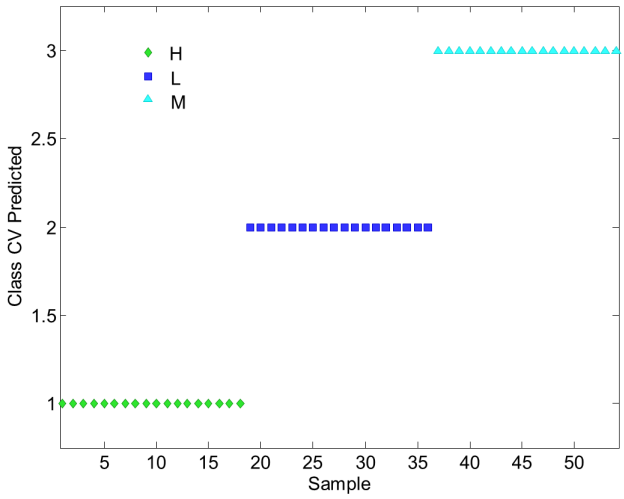


Figure 6.33: Class CV predicted from XGBDA analysis of EEM data for samples from different PAI values areas. L= low PAI values, M=medium PAI values and H=high PAI values.

6.3.3 Vineyard 3

The location of the 116 sampling point is shown in Figure 6.34.



Figure 6.34: Location of the 116 vines (middle vine of each panel in four rows) that were sampled for three consecutive seasons in a rainfed vineyard in the Barossa Valley of South Australia.

Canopies were imaged on eight occasions: four times in season 2018-19, three times in 2019-20 and at harvest in 2021 (Figure 6.35). All the images collected were then analysed using VitiCanopy and the spatial variability assessed with maps. At harvest 2020 and 2021, five bunches were randomly collected from each of the vines that had already been monitored for canopy architecture (n=116) and bunch weight was measured. On the juice, basic chemistry (pH, TA and TSS) was measured and must samples were then sent to APAL (Australian Precision Ag Laboratory) for elemental analysis. At dormancy (July 2020 and 2021) canes were collected from each of the 116 vines for bud dissection analysis to measure the number and size of inflorescence primordia (IP). Each of these measured parameters were then analysed using ArcGIS and their variability mapped for the whole block.

VitiCanopy assessment showed that the vineyard block was somewhat variable with areas of higher PAI values in the middle-top end of the block and areas of lower PAI towards the bottom end. In the first season the range of PAI values varied from 0.5 to 1.2 at each time point to indicate that the canopy size was already established as early as mid-November and only slight variations were observed for the rest of the season. Given this is a rainfed block, the grower was not able to manipulate canopy size through irrigation, however good canopy retention was observed all the way to harvest.

In the following season, a very similar pattern was observed to the point where the two maps obtained from the November data collection looked almost identical. However, despite the variability in the block looking similar, the range of canopy PAI values was almost double in November 2019 compared to November 2018. Lower values were then measured at veraison (04 February 2020) and harvest (25 March 2020). The three PAI maps obtained from the harvest measure in the three seasons confirm, once more, the consistent variability in the block.

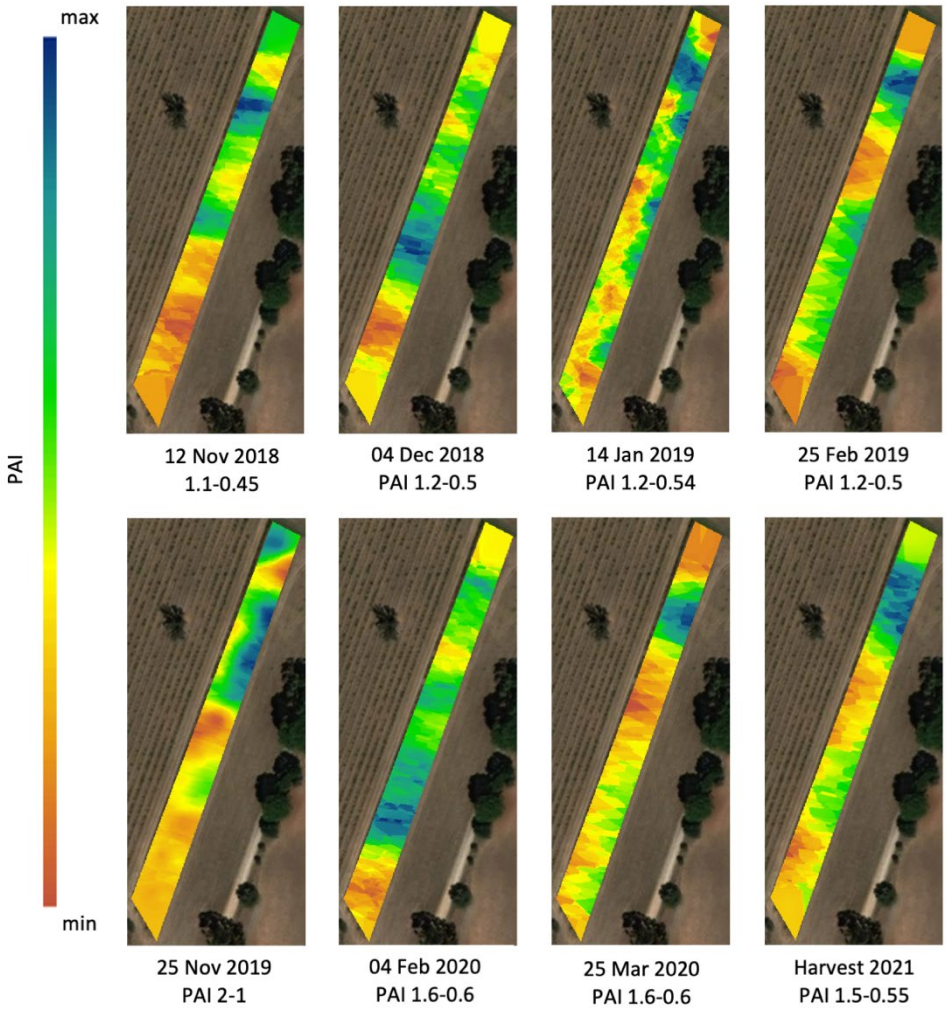


Figure 6.35: Plant Area Index (PAI) maps from results of the VitiCanopy analysis of images collected in a rainfed Shiraz vineyard in the Barossa Valley. Measures were collected at four timepoints during the 2018-19 season, three in 2019-20 and at harvest in 2021.

The dataset available for this vineyard gave us a unique opportunity to assess the relationship between a series of vineyard characteristics without the influence of irrigation.

The series of maps shown in Figure 6.36 displays the variability of some of the measured parameters in the block and their link (or not) with PAI. The last PAI measure (Harvest 2021) and related canopy porosity, have been chosen as reference for all the canopy architecture measures. Considering that canopy size is an indicator of canopy water usage, the Kc of the whole block was calculated by applying the formula proposed by William and Ayars (2005) and the water needs of the vineyard block could be easily visualised at the block scale (Figure 6.36, crop coefficient). A link (R^2= 0.6) was observed between PAI and bunch weight; areas of low PAI produced small bunches and vice versa. In terms of fertility (IP numbers) in the two seasons, the 2020 data showed variability throughout the block, not necessarily linked to canopy architecture however, the bottom end of the block, where PAI was very low also showed low IP numbers in the buds. The 2021 map showed less of a clear pattern.

Juice sugar appeared highly variable and related to PAI with high TSS in areas of low PAI and high porosity (high bunch exposure) and vice versa. The acidity and pH

measures showed a similar pattern. Interesting, results from the juice elemental analysis suggest that there was a link with canopy architecture; areas of low PAI showed a general higher concentration of P, K and Ca.

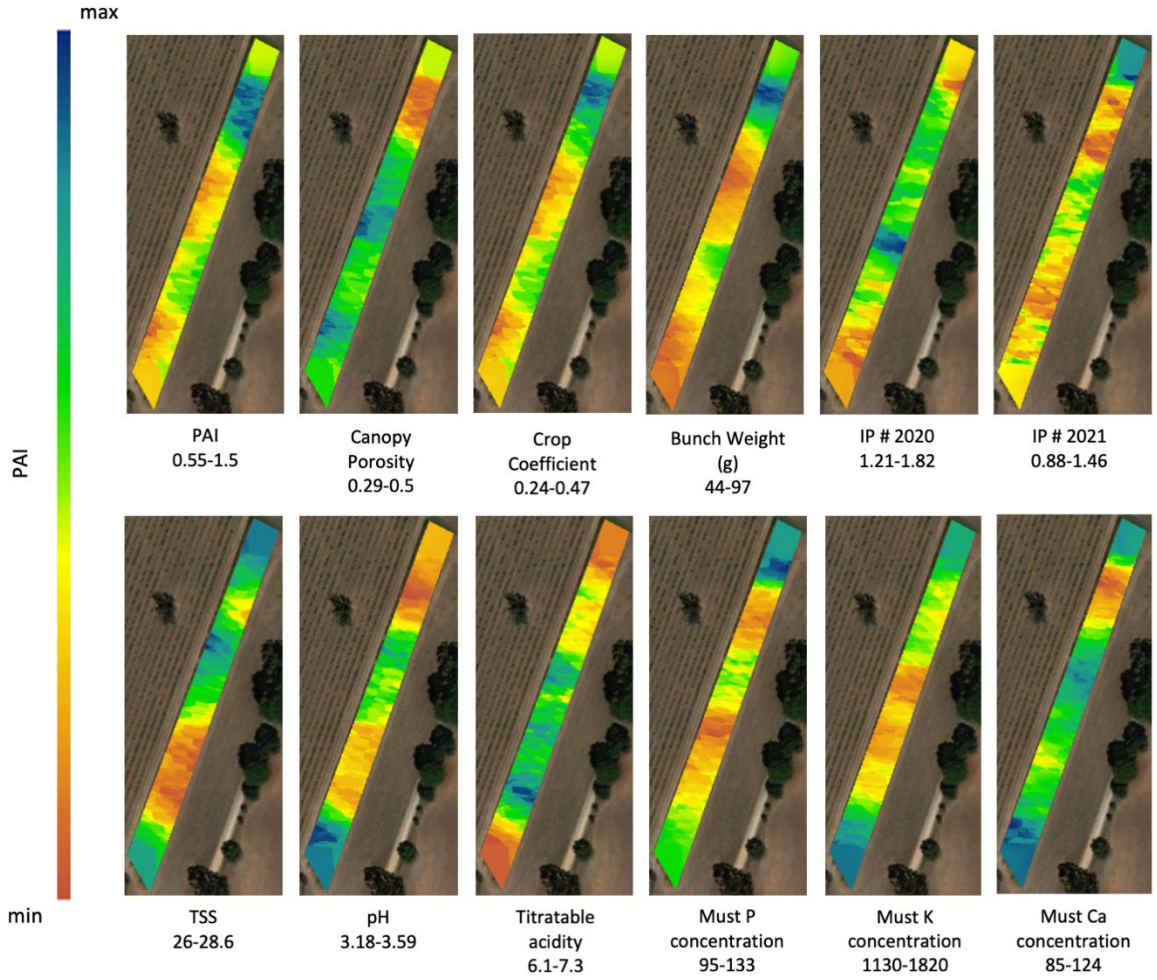


Figure 6.36: Maps of the spatial distribution of different vineyard measurements collected in 2020 and 2021 on 116 vines in of a rainfed Shiraz vineyard in the Barossa Valley.

6.4 Case Study 3: Use of VitiCanopy for canopy management decision-making

Aim: To use VitiCanopy to direct canopy management decisions.

In this simple example on the use of VitiCanopy in a commercial setting, a vineyard manager decided to carry out a leaf removal operation on a block that was deemed very variable.

Before the leaf removal application was carried out in the whole vineyard, a small portion of the block was assessed, a total of 550 images were taken and the resulting maps confirmed the high PAI patchiness of the block with values of PAI as high as 5 and as low as 0.7 (Figure 6.37a). The same block was re-imaged after leaf removal and the resulting map showed that the operator was able to achieve the desired outcome of a more even distribution of canopy PAI in the block. The PAI values ranged from 4.5 to 0.5; these low values were concentrated in the south-east corner of the block and were possibly indicative of a too high leaf removal in that area.

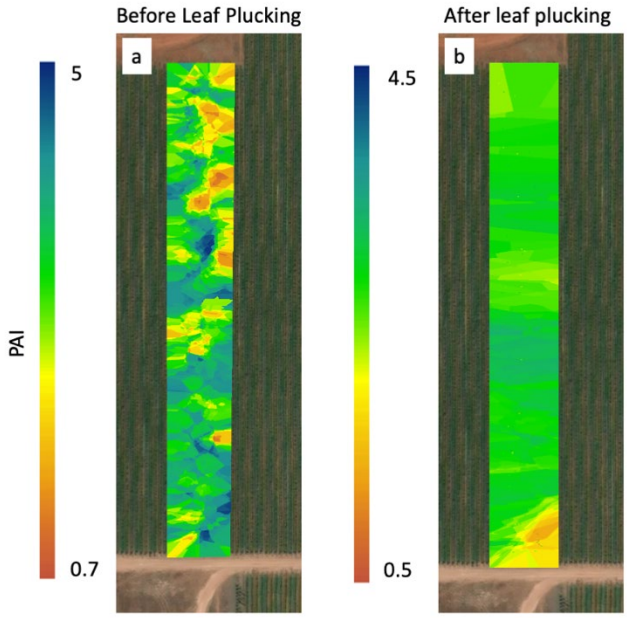


Figure 6.37: Maps of the spatial distribution of PAI in a section of a vineyard before (a) and after (b) a leaf removal application.

6.5 Case Study 4: Comparisons between VitiCanopy, NDVI and image resolution

Aim: i) to answer the often-asked question of how many images would be required to map block variability and ii) to compare VitiCanopy maps to NDVI.

Values of PAI in the Cabernet vineyard varied from 0.9 to 2.6 with areas of lower PAI found in proximity of trees surrounding the vineyard and higher PAI values through the middle part of the vineyard, likely due to differences in soil type (Figure 6.38). Moreover, the three maps with different image densities showed very similar features (Figure 6.38a-c). An expected decrease of resolution can be observed when 296 images were taken (Figure 6.38c) however, the areas of low and high PAI were still easily identified. Negligible differences were observed between the maps generated from 1184 (Figure 6.38a) and 592 images (Figure 6.38b), which indicates that in this vineyard, images taken every second row could be considered sufficient to map the block variability in PAI.

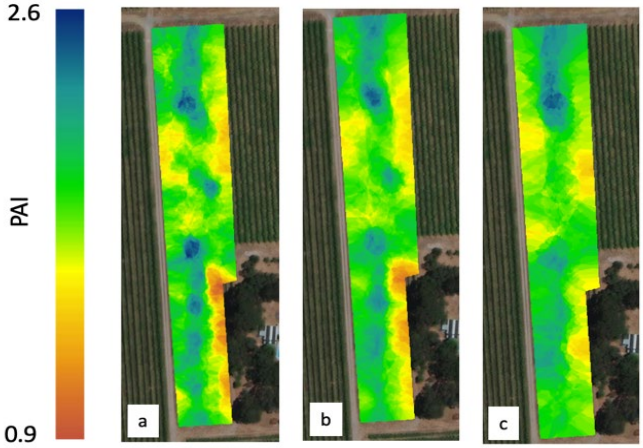


Figure 6.38: Plant Area Index (PAI) maps generated from the collection and analysis of canopy images using VitiCanopy in a 0.7 ha vineyard in the McLaren Vale wine region of South Australia. a) Two images per panel were taken by two operators in all rows (n=1184); b) two images per panel were taken by one operator in every second row (n=592); c) one image per panel was taken by one operator in every second row (n=296).

When maps from images taken at harvest in 2019 were compared to NDVI taken in the previous season, for Cabernet Sauvignon, similar block variability was observed (Figure 6.39). The top part of the block was largely characterised by lower PAI values (orange/yellow on the map) as opposed to the bottom half of the block where green and blue colours indicate higher PAI. The NDVI showed a very similar pattern. Some differences were noticeably related to the maps being acquired in two different seasons; the grower elucidated that the dark blue patch/circle present in the NDVI map was related to an irrigation leak that he was able to spot and fix thanks to the map itself. This is the reason why that patch was not as remarkably blue in the VitiCanopy map however, the effect of the leak was still visible the year after as PAI in that same position was still higher compared to the surroundings.

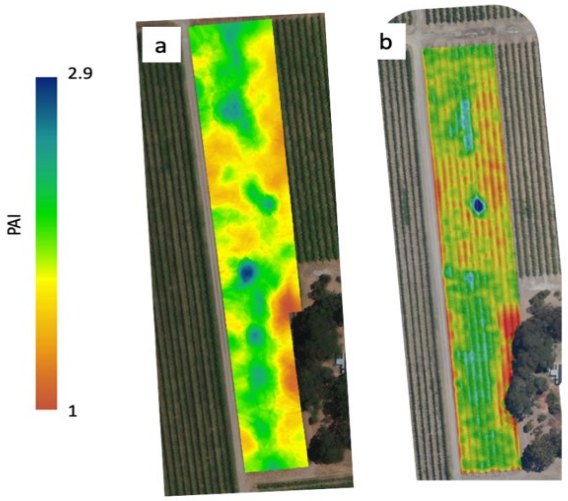


Figure 6.39: VitiCanopy PAI map (a) taken just before harvest in 2019 and NDVI map (b) obtained at around veraison in the previous growing season (2017-18) for the Cabernet Sauvignon vineyard located in the McLaren Vale region of South Australia.

Similarly to the observations made for the Cabernet Sauvignon block, the two maps for the Shiraz showed very comparable results. Despite a general higher uniformity within the block, in this case too, some isolated dark blue “spots” were linked to an issue with irrigation.

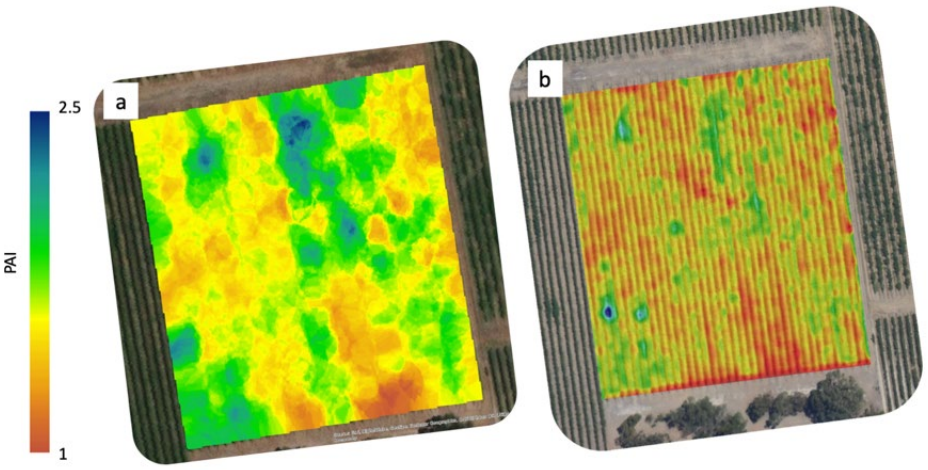


Figure 6.40: VitiCanopy PAI map (a) taken just before harvest in 2019 and NDVI map (b) obtained at around veraison in the previous growing season (2017-18) for a Shiraz vineyard located in the McLaren Vale region of South Australia.

The number of images required to visualise the variation in a vineyard block will depend on the level of resolution needed. Once a high-resolution map is obtained, areas of different performance can be identified, and future assessments can be performed only on a selection of benchmarking areas within the vineyard. In this study, two operators took about 30 minutes to image a whole block (>1000 images) and few differences were observed in the maps when this number was halved. Moreover, VitiCanopy and NDVI maps showed great similarities so practitioners can rely on vineyard PAI maps as an accurate decision-making tool for management strategies to meet production goals.

6.6 Case Study 5: Chardonnay vineyards in the Riverland region

Aim: To investigate the link between vineyard variability in canopy architecture and grape quality (grade).

The 2018-19 PAI maps of the vineyard blocks at two phenological stages, veraison (all five blocks) and harvest (blocks B, C and E) are shown in Figure 6.41. The maximum (6) and minimum (2) PAI values across the five blocks were chosen as the range of PAI values for all blocks in order to appreciate the canopy size differences between them. At veraison the five vineyards showed differences in PAI with block D standing out with the highest PAI values while block B, and even more so E, showed much lower PAI values across their whole surface. Block E showed possible areas of concern toward the eastern edge, lined with trees. The vineyard manager implemented an irrigation strategy aimed to increase PAI in blocks B and E that were deemed too low for the phenological developmental stage. In block C the variability observed at veraison was maintained until harvest and no major changes were observed in PAI across the block. The new irrigation regime for blocks B and C however, achieved the desired effect of increasing canopy size. Block B not only achieved higher PAI values towards harvest but also greater uniformity across the block. In block E, irrigation was able to increase PAI for most of the area but the edges, with the eastern edge remaining unchanged due to competition with trees.

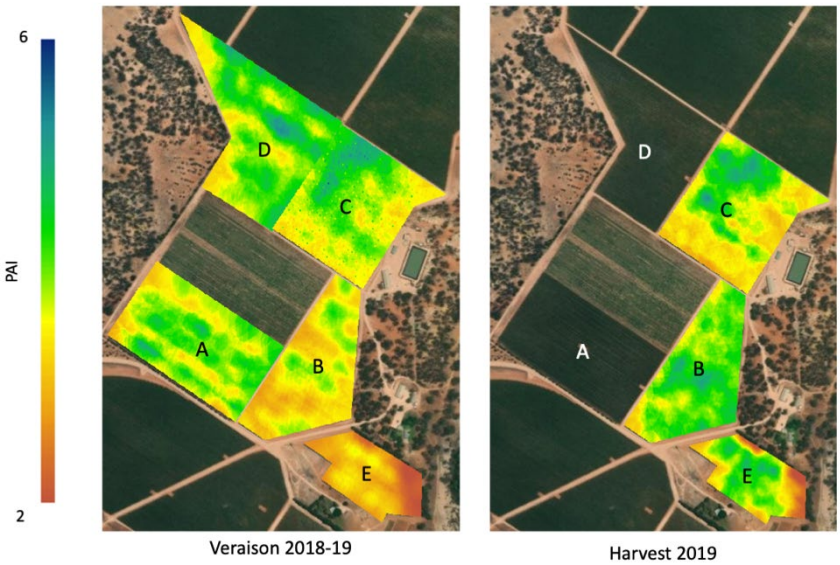


Figure 6.41: Plant Area Index (PAI) maps from results of the VitiCanopy analysis of images collected in five chardonnay vineyards in the Riverland region of South Australia. Measures were collected at veraison (all five blocks) and harvest (three blocks only) during the 2018-19 season.

The canopy architecture differences between blocks seemed to also be the drivers for some of the separations observed in the PCA plot in Figure 6.42. Only significantly different measures of wine aromas, juice amino acid concentrations, juice elemental analysis, wine alcohol, pH and PAI were used for the PCA which explains 85.58% of the variability in the data set. The first PC, which explains 58.64% of the variability, separated blocks A, B and E from blocks C and D. This separation is somewhat linked to the geographic location of the vineyards however, it can also be explained by the PAI measured at veraison. The PAI had the biggest contribution amongst all variables along PC1 where block D had the highest PAI and block E the lowest. Moreover, all

of the amino acids that were found to significantly differ between blocks were higher in blocks E followed by A and B. Similarly, Na, K, Si, Cl, Mn, P and S concentrations measured in the juice were all higher in these latter blocks. PC2 explained 27% of the dataset variability and it separated the blocks mostly on their wine aroma concentrations. Block E, with lowest PAI, produced wines higher in 2-methylbutanoic acid, 2-methylbutyl acetate and 3-methylbutanoic, all linked to undesirable notes of cheese, sweat and nail polish. On the other hand, block A, with the bigger canopies, produces wines with more desirable aromas of green apple, fruit and sweet perfume.

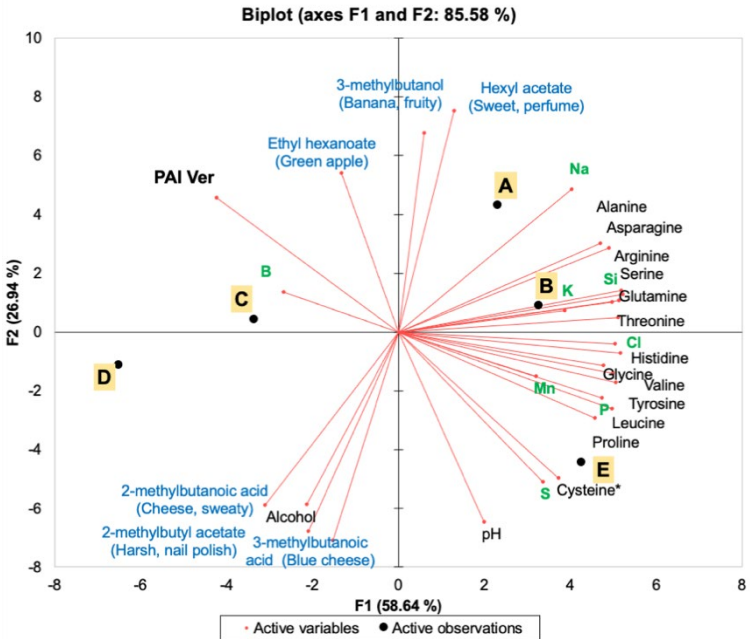


Figure 6.42: Principal component analysis of plant area index (PAI), must elemental analysis results, amino acid concentration and wine aromas in the five assessed vineyard blocks in season 2018-19. Only attributes/measurements found to be different between the five vineyards ($p<0.05$) have been used in the PCA analysis. PAI= Plant area index.

For the following two seasons the five blocks were imaged only at harvest and the results are shown in Figure 6.43. The range of PAI at harvest in 2019 was 6-2 while canopies in 2020 reached a maximum PAI of 3 and minimum of 0.5. This was a result of a very dry winter and a dry and hot summer; small stunted canopies were reported across regions and varieties in this season. At a block level however, very little variability was detected and in a similar pattern observed in 2019 block D produced canopies with the highest PAI values and block E the lowest. A canopy recovery was observed in the following year with values of the PAI at harvest in 2021 as high as 4.5 and minimum of 1.2.

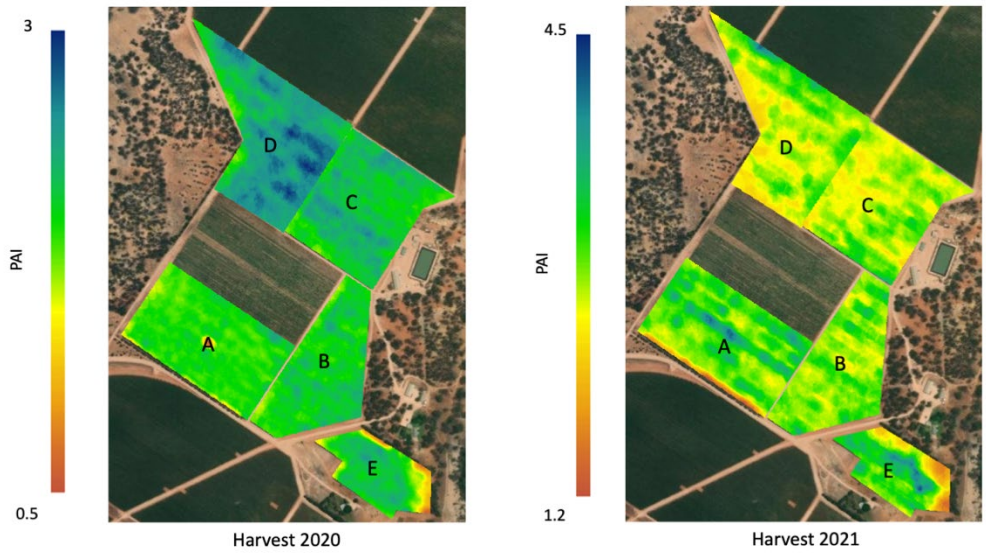


Figure 6.43: Plant Area Index (PAI) maps from results of the VitiCanopy analysis of images collected in five chardonnay vineyards in the Riverland region of South Australia. Measures were collected at harvest in 2020 and 2021.

In 2021 bunches were collected in three blocks (B, C and E) and the fruit subjected to berry sensory analysis. The results (Figure 6.44) show a good separation between high and low PAI value areas for block E while B and C separate as blocks rather than based on their high and low sampling zones. This is however not surprising given the lack of variability in these two blocks while a higher variability could be detected in block E. The results in the PCA showed that fruit from block B and the higher PAI areas of block E were characterised by tropical, floral, fruit and sweet flavours while block C and the low areas of block E were generally greener, acidic with bitter and astringent skins.

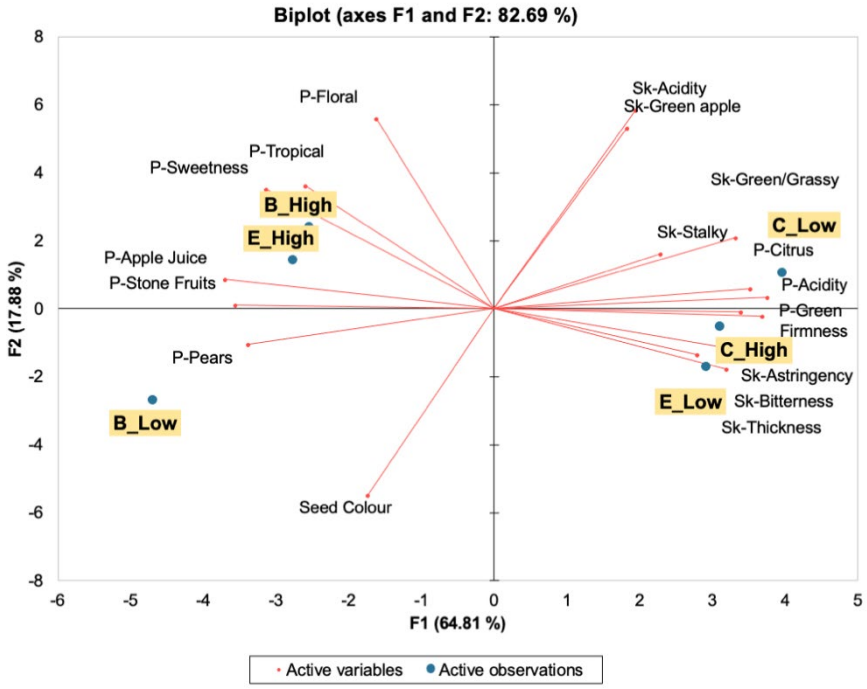


Figure 6.44: Principal component analysis of the berry sensory attributes found to differ ($p<0.1$) between blocks and areas of low and high PAI values within those blocks. The berries for BSA were collected at harvest 2021. P= pulp attributes, Sk= skin attributes.

Aqualog spectrofluorometer analysis was performed on these samples and PARAFAC showed that samples from different blocks clustered relatively close to each other. However, some samples did not group together (E-H and C-L, for example) so that further exploratory analysis was carried out with EEM data using PCA.

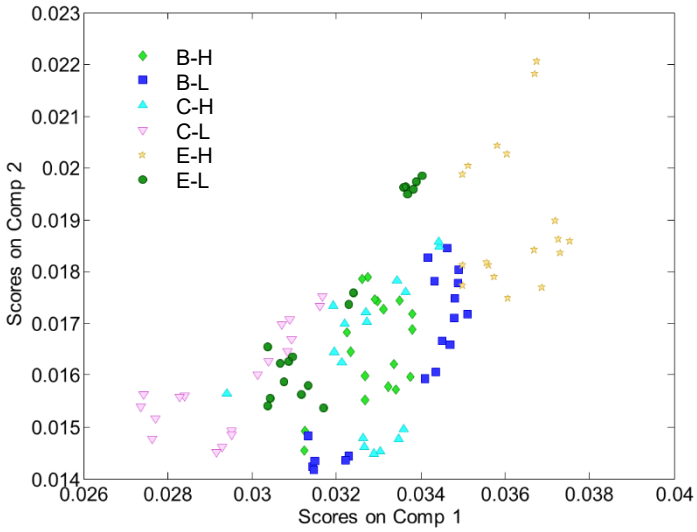


Figure 6.45: Score plot of the first three components of the PARAFAC model of EEM data for samples collected in areas of low (L) and high (H) PAI values in three Chardonnay vineyards (B, C and E) in the Riverland Region of South Australia.

A PCA model was built using six PCs, after decluttering by GLS weighting (alpha = 0.02) together with mean centre preprocessing. Figure 6.46 shows that the first three PCs explained almost 40% of the total variance for the samples (reduced due to decluttering), which were now clustered according to the block and canopy size. This outcome highlighted that the sensitivity of the fluorescence molecular fingerprint was able to differentiate samples not only from different vineyard blocks, but also according to their canopy size (high or low PAI).

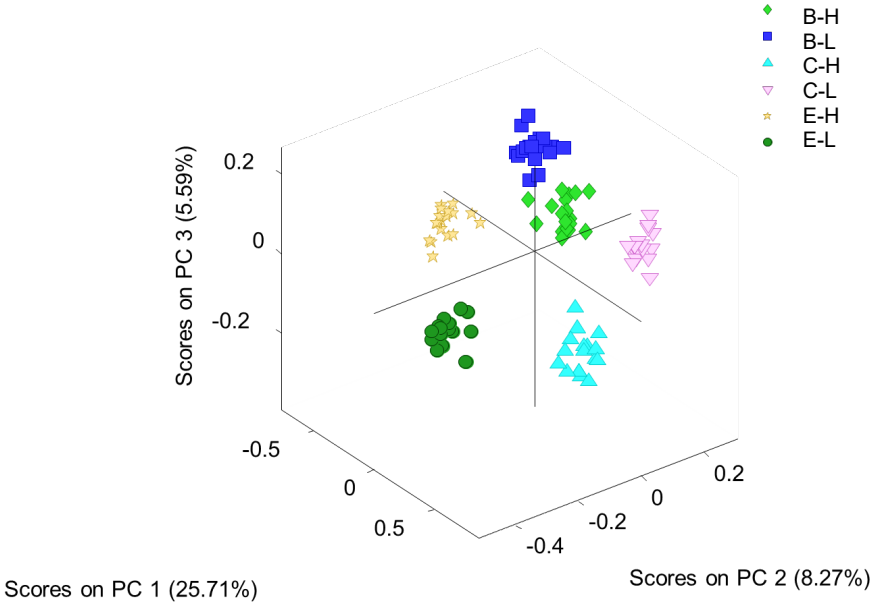


Figure 6.46: Principal component analysis (PCA) score plot of EEM data for samples collected in areas of low (L) and high (H) PAI values in three Chardonnay vineyards (B, C and E) in the Riverland Region of South Australia.

XGBDA was also carried out and the results further validated that samples from different blocks and PAI could be classified based on their EEM (Figure 6.47). The model was built with GLS weighting (alpha 0.02) and mean center preprocessing with PLSDA compression with 10 components. Figure 6.47 shows the class cross-validation prediction probability from XGBDA, with 99.06 % accuracy misclassifying only one sample of E-H as C-H.

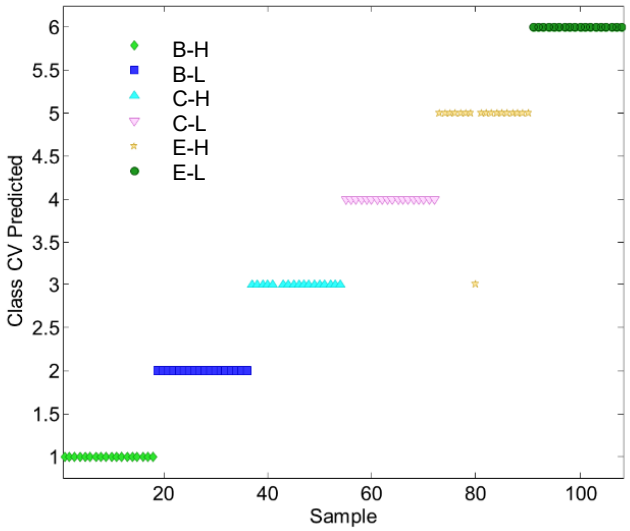


Figure 6.47: Class CV predicted from XGBDA analysis of EEM data for samples collected in areas of low (L) and high (H) PAI values in three Chardonnay vineyards (B, C and E) in the Riverland Region of South Australia.

6.7 Case Study 6: Use of VitiCanopy to assess pruning weight

Aim: To assess the feasibility of using VitiCanopy as a tool to estimate vine pruning mass at dormancy.

Pruning weight is the measure of the pruned wood from a dormant vine and it is used to quantify vine size and vigour (Taylor and Bates, 2012; Rives, 2000). Knowledge of a vineyard's dry matter production, at vine level or at the whole vineyard scale, has considerable implications for vineyard management decisions. This measure can be used as an indicator of vineyard performance. However, pruning weight is not often used in the industry since its measure requires the interruption of the flow of pruning operations making it laborious and time consuming (Taylor and Bates, 2012).

The relationships between real pruning mass and cover values calculated using VitiCanopy for each vineyard site are shown in Figure 6.48 (a-d). A poor correlation (R^2 = 0.25) was obtained for the Coombe vineyard (Figure 6.48a). A number of factors are responsible for this result including the fact that this is a research site and vines have been subjected to different canopy management treatments in each panel for the previous seven seasons; this has created a high plant to plant variability confirmed by both the pruning mass (min 530 g, max 1220 g) and the estimated cover values of the bare cordons (min 0.09, max 0.23). When the more uniform, commercial vineyards were considered, more robust correlations were observed, with R^2 ranging from 0.57 (V_2) (Figure 6.48c) to 0.89 (V_1) (Figure 6.48b). The canopy cover values of the pruned vines/bare cordons (pruning weight=0) confirm the higher uniformity of all three commercial vineyards compared to the Coombe with values in the range 0.09-0.12 for V_1, 0.23-0.34 for V_2 and 0.09-0.14 for V_3. Nonetheless, the results obtained confirm that in the three commercial vineyards the cover value obtained with VitiCanopy is a good indicator of pruning mass.

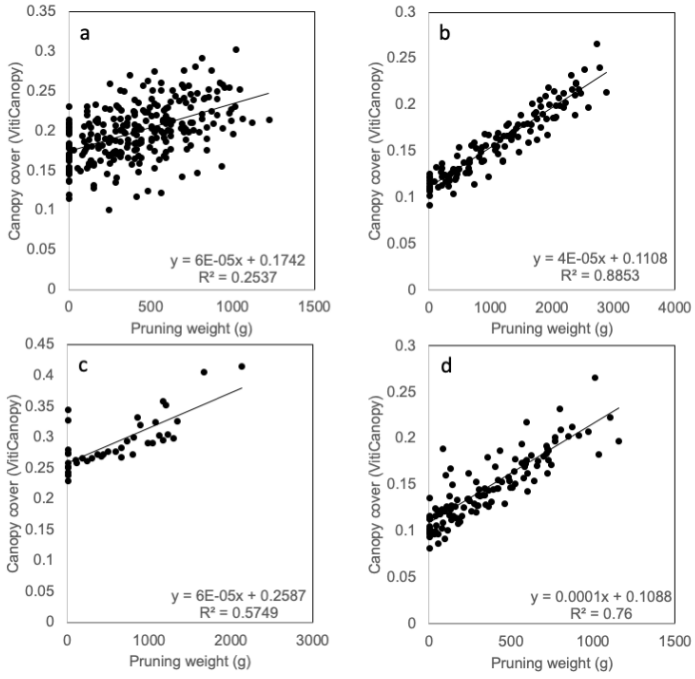


Figure 6.48: Relationships between pruning weight and canopy cover values obtained from VitiCanopy for the four vineyards assessed: a) Coombe vineyard; b) vineyard one (V_1), c) vineyard two (V_2) and d) vineyard three (V_3).

As previously shown and discussed in De Bei et al. (2016), a great improvement of the relationships between real measures and VitiCanopy results can be achieved by subtraction of the cover value of the bare cordon to all the other measures calculated from images within each vine (Figure 6.49). When this simple calculation was applied to the Coombe vineyard images, a great improvement was observed, confirming what speculated above, that the poor correlation obtained in Figure 6.49a was to be attributed to the high variability in the size (cover value) of the bare cordons. When this subtraction was applied to all vineyards in the study the determination coefficients of the correlations improved to values as high as 0.96 in V_2.

In a commercial setting, where vineyard uniformity is more likely to occur, operators could obtain pre and post pruning images for a representative number of vines and extract the average cover value to all the subsequent images within the same vineyard (Figure 6.49). This would allow users to build a vineyard specific calibration that could be used to accurately estimate pruning mass through images. In an experimental setting, personnel might need to capture images of vines before and after pruning to calculate the cover value of bare cordons of each vine.

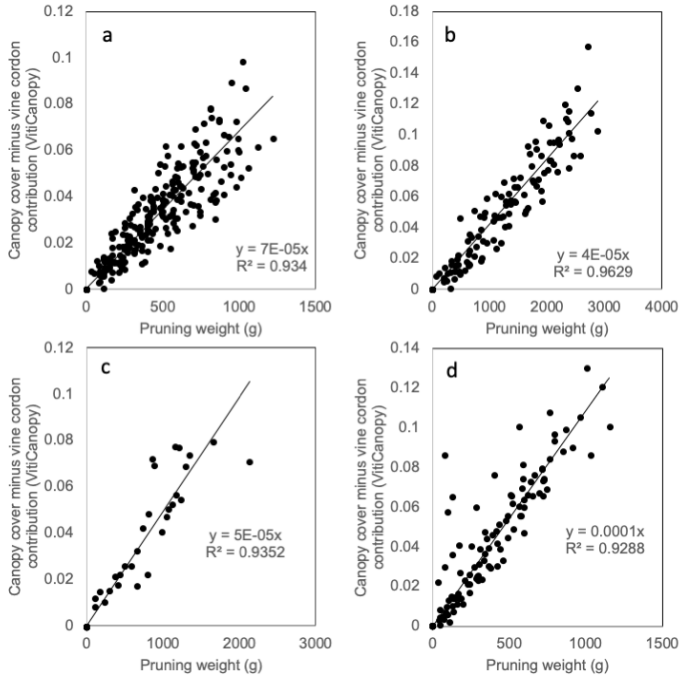


Figure 6.49: Relationships between pruning weight and canopy cover values obtained by extracting the Y—intercept (bare cordon) for each vine for the four vineyards assessed: a) Coombe vineyard; b) vineyard one (V_1), c) vineyard two (V_2) and d) vineyard three (V_3).

Similarly to the measurement and mapping of PAI during the growing season, the pruning weight can also be mapped and an example of the map obtained from a vineyard at dormancy is shown in figure 6.50. The combination of VitiCanopy measurements taken during the growing season (plant area index) and at dormancy (pruning mass) could allow for accurate estimations of vineyard above ground biomass production both at the individual vine level or at the whole block scale; taking viticultural landscapes a step closer to accurate carbon accounting.

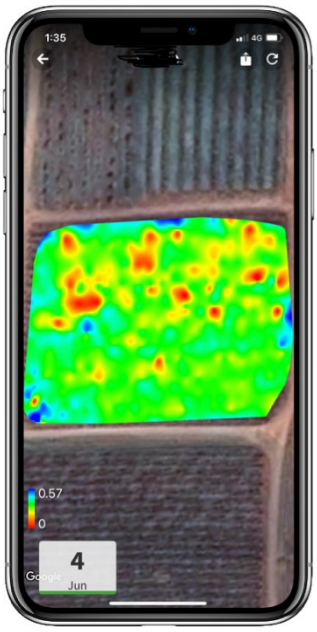


Figure 6.50: Vineyard spatial variability of PAI measured on dormant Shiraz vines in a vineyard in the Riverland region using VitiCanopy.

7. Outcome/Conclusion

This project has generated new knowledge on the relationships between canopy architecture and grape and wine quality for different wine regions and varieties. Moreover, the tool that has facilitated generating this knowledge, VitiCanopy, underwent some major upgrades and improvements to enhance the user experience. VitiCanopy is now a smart-device and computer application that allows users to measure and interpret objective canopy architecture and its spatial distribution in the vineyard. The case studies presented in this report highlight the role VitiCanopy could play in informing and targeting vineyard management decisions.

Since its recent launch, the new version of VitiCanopy has received 658 downloads on the Apple platform (as of June 25th 2022) with the main number of downloads in Australia (214) followed by the USA, Italy, Chile and China. A similar number has been downloaded on the Android platform.

Key messages highlighted in the case studies are summarised as follows:

- The use of VitiCanopy to monitor vineyard differences in canopy size can help to identify areas of differing performance so that strategies can be taken to increase vineyard productivity and profitability.
- Maps are now created in real time to identify spatial variability in PAI and help direct management decisions. This feature allows users to: i) make site specific management decisions, ii) anticipate yield and quality traits, and iii) direct resources to where they are needed most.
- The history of a site can be created to compare vine performance within and between seasons to help monitor crop conditions, implement disease and water management decisions and forecast yield and quality.
- The combination of VitiCanopy measurements taken during the growing season (plant area index) and at dormancy (pruning mass) could allow for accurate estimations of vineyard above ground biomass production both at the individual vine level or at the whole block scale.
- A prototype for an automated system to collect images from a moving vehicle has been created, tested, and proven to provide reliable results.
- Spectrofluorometric analysis and multivariate data processing have been previously successfully applied to wine chemical traceability to guarantee provenance and even identify a wine blend composition (Ranaweera et al., 2022). Our results successfully classify grape extracts from different vineyards, different areas of performance within a vineyard and even group products from vines subjected to different management. This may be a first step towards a simple and reliable routine method for grape traceability or to help direct the grape stream once they reach a processing facility.

The economic benefits of the project are gained from a better understanding of how management and environment interact to affect fruit quality so that growers can maximise the production of premium and ultra-premium grapes; value can then be added along the production chain to improve profitability of the entire industry. Moreover, by using VitiCanopy, practitioners can refine management practices to ensure the consistent production of high-quality grapes and wine, while minimising

costs. Environmentally, this project provided valuable information on approaches to optimise inputs to ensure that resources (e.g. water, fungicide, fertilizer) are not wasted. The new knowledge could inform a more efficient use of resources through better management decisions and help to achieve targeted grades more regularly. At a social level, a better understanding of how to manage vineyards should reduce conflict between grape producers and end-users. VitiCanopy can be used to improve transparency in quality assessment and improve relations between producers and wine companies.

8. Recommendations

There are a number of researchers and industry users that rely on the use of VitiCanopy to collect data for vineyard management decision making and to assess experimental research trials. A commercialisation plan is in progress and is needed to guarantee continuity and ensure the tool, VitiCanopy is maintained. To help facilitate and support this there is a need for extension to further promote the tool and findings. This could be achieved via the Wine Australia website, Wine Australia newsletter and other marketing/promotion/extension channels Wine Australia have access to. The researchers will keep promoting the tool via webinars, conferences, and scientific and industry publications. VitiCanopy is already incorporated in the viticulture and agriculture courses at the University of Adelaide so that students, the future of the Australian Wine Industry, are already familiar with the tool.

Preliminary studies have been undertaken to assess the potential use of VitiCanopy in other horticultural crops. Initial results suggest that VitiCanopy can be successfully applied to the assessment of canopy architecture in almonds, citrus, cherry, apples and further validation of these findings as well as modifications to suit particular crops are required.

This project has made significant progress towards the implementation of a tractor/quad bike camera system able to acquire images while carrying out other vineyard operations. This could be an opportunity for commercial partners, Agtech solution providers or innovators interested in integrating this into other existing tools or new platforms.

The team also foresees the opportunity for machine learning approaches to be applied to the automatically acquired images, particularly in terms of streamlining the quality control and automation of image analysis.

9. Appendix 1: Communication

Communication and extension of the outcomes of this research are listed below.

Journal Articles

Collins, C., Ritchie, M., James, A., O'Brien, P., Ma, S., De Bei, R., Clarke, A. (2022). Grapevine recovery after fire and a first look at rapid damage assessment with satellite imagery. *OENO One*, 56(2), 265–278. https://doi.org/10.20870/oeno-one.2022.56.2.5444

De Bei, R., Wang, X., Papagiannis, L., & Collins, C. (2022). Assessment of bunch thinning as a management technique for Semillon and Shiraz in a hot Australian climate. *OENO One*, 56(1), 161–174. https://doi.org/10.20870/oeno-one.2022.56.1.4835

Ouyang, J., De Bei, R., & Collins, C. (2021). Assessment of canopy size using UAV-based point cloud analysis to detect the severity and spatial distribution of canopy decline. *OENO One*, *55*(1), 253–266. https://doi.org/10.20870/oeno-one.2021.55.1.3078

O'Brien, P., Collins, C., & De Bei, R. (2021). Leaf removal applied to a sprawling canopy to regulate fruit ripening in Cabernet Sauvignon. *Plants* 10 (5), 1017. http://dx.doi.org/10.3390/plants10051017

Ouyang, J., De Bei, R., Fuentes, S., & Collins, C. (2020). UAV and ground-based imagery analysis detects canopy structure changes after canopy management applications. *OENO One*, *54*(4), 1093–1103. https://doi.org/10.20870/oeno-one.2020.54.4.3647

De Bei, R., Papagiannis, L., Fuentes, S., Gilliham, M., Tyerman, S., Wang, X. & Collins, C. (2020). Shoot thinning of Semillon in a hot climate did not improve yield and berry and wine quality. *OENO One*, *54*(3), 469-484. https://doi.org/10.20870/oeno-one.2020.54.3.2984

Wang, X., Lesefko, S., De Bei, R., Fuentes, S. & Collins, C. (2020). Effects of canopy management practices on grapevine bud fruitfulness. *OENO One*, *54*(2), 313–325. https://doi.org/10.20870/oeno-one.2020.54.2.3016

De Bei R., Fuentes S. & Collins C. (2019). Vineyard variability: can we assess it using smart technologies? IVES Technical Reviews, October 2019. https://doi.org/10.20870/IVES-TR.2019.2544

De Bei, R., Wang, X., Papagiannis, L., Cocco, M., O'Brien, P., Zito, M., ... & Collins, C. (2019). Postveraison leaf removal does not consistently delay ripening in Semillon and Shiraz in a hot Australian climate. *American Journal of Enology and Viticulture*, *70*(4), 398-410. https://doi.org/10.5344/ajev.2019.18103

Wang, X., De Bei, R., Fuentes, S., & Collins, C. (2019). Influence of canopy management practices on canopy architecture and reproductive performance of

Semillon and Shiraz grapevines in a hot climate. *American Journal of Enology and Viticulture*, *70*(4), 360-372. https://doi.org/10.5344/ajev.2019.19007

Peer reviewed papers without impact factor and peer reviewed conference proceedings

De Bei R., Fuentes S., Madgett O., & Colins C. (2022). Assessing vineyard variability using grower friendly digital tools. International Cool Climate Symposium, Brock's University, St. Catharine, Ontario, Canada, 17-21 July 2022

De Bei R., Wang X., Papagiannis L., Cocco M., O'Brien P., Zito M., Ouyang J., Fuentes S., Gilliham M., Tyerman S., & Collins C. (2019). Late leaf removal does not consistently delay ripening in Semillon in Australia. Proceedings of the 20th International symposium GiESCO. Thessaloniki, Greece 2019.

Zito M., Cocco M., De Bei R., & Collins C. (2019). Assessing bunch architecture for grapevine yield forecasting by image analysis. Proceedings of the 20th International symposium GiESCO. Thessaloniki, Greece 2019.

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 29 to June 2, 2017; Sofia – Bulgaria.

Collins C., James A., Ouyang J., Lesefko S., Wang X., De Bei R. and Kidman C. (2017). Early yield prediction through grapevine bud dissection and image analysis. Submitted to the 40th World Congress of Vine and Wine, May 29 to June 2, 2017; Sofia – Bulgaria.

Industry Articles

De Bei R., Wang X., Papagiannis L., Fuentes S., Gilliham M., Tyerman S. and Collins C. (2020). Shoot and bunch thinning: To thin or not to thin? Wine & Viticulture Journal, 35(3), p.36.

De Bei R., Wang X., Zito M. and Collins C. (2020). Agire sulla chioma per gestire peso e volume dei grappoli. L'Informatore Agrario 19/2020.

De Bei R., Wang X., Zito M., Fuentes S., Gilliham M., Tyerman S., Collins C. (2020). Diradare o non diradare, ne vale la pena? Vite e Vino 4/2020.

Conference Presentations

International Cool Climate Symposium, Brock's University, St. Catharine, Ontario, Canada, 17-21 July 2022, Oral presentation as Invited Speaker.

TerClim22, Bordeaux, France, 3-8 July 2022 Oral presentation.

Australian Wine Industry Technical Conference, Adelaide, June 2022. Oral presentation and poster presentation.

21st GiESCO International Meeting (Group of International Experts of Vitivinicultural Systems for Cooperation). Thessaloniki, Greece, 23-28 June 2019 Two Oral presentations, one Invited Speaker

Australian Wine Industry Technical Conference, Adelaide, July 2019. Poster presentation.

42nd World Congress of Vine and Wine. Sofia, Bulgaria 15-19 July 2019. Two Oral presentations.

XII International Terroir Congress. Zaragoza, Spain, 18-22 June 2018. Oral presentation.

20th GiESCO International Meeting (Group of International Experts of Vitivinicultural Systems for Cooperation). Mendoza, Argentina, 5-10 Nov 2017 Oral presentation

Other activities/invitations/outreach

Online Seminar for Agriculture and AgriFood Canada, Summerland Research Centre. Vineyard management, vineyard variability and grape and wine quality. May 5th 2021.

Research selected and featured in “Stories of European-Australian Research” a publication of the European Research Council to showcase stories of success and important research being carried out by European researchers in Australia.

CSIRO ONPrime program. This is a national deep-tech innovation program designed to fast-track great research and technology into real world outcomes. Project title: VitiCanopy. Group members: Dr Roberta De Bei, Dr Dylan Grigg, Mr Francois Duvenage and A/Prof Cassandra Collins.

10. Appendix 2: Intellectual Property

The intellectual property developed in this project is outlined in the above report. The information generated by this project will enter the public domain and will be accessible for future reference.

The intellectual property developed in this project is outlined in the above report and is summarised in the points below.

- The collection of images used for experimentation, algorithm development and validation,
- Development of algorithms used for analysing canopy size, porosity and pruning weight from images,
- Software development that allows for the capture of images, mapping and presentation on a web-platform,
- Hardware design of raspberry pi imaging system that allows for automated image capture,
- Publications and know-how generated during this project through experimentation and the design and validation process.

11. Appendix 3: References

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12. Appendix 4: Staff

A number of staff contributed to this project and are listed below.
Dr Roberta De Bei
A/Prof Cassandra Collins
A/Prof Susan Bastian
A/Prof David Jeffery
A/Prof Sigfredo Fuentes (University of Melbourne)
Mr Lucas De Simoni
Mrs Annette James
Ms Karin Andraschko-Schlosser
Dr Jingyun Ouyang
Dr Lukas Danner
Dr Dylan Grigg
Dr Shashi Goonetilleke
Dr Alice Betteridge
Dr Ruchira Ranaweera
Dr Lira Souza Gonzaga
Mr Patrick O'Brien
Ms Merek Kesser
Mr Lukas Papagiannis
Mr Marco Zito
Dr Massimiliano Cocco

13. Appendix 5

Appendix 5.1 VitiCanopy launch media release

Media Release

Tuesday 25 January 2022

Vines strike a pose for the new VitiCanopy app

The ability to analyse multiple images at once, GPS capability to create maps of the spatial variability of canopy size, and Cloud storage, are just some of the new upgrades to VitiCanopy, the University of Adelaide-developed mobile app that helps grapegrowers manage their vineyards more effectively.

Funded by Wine Australia and the University of Adelaide, VitiCanopy provides users with a quick and simple way to measure grapevine canopy from images uploaded to the app for analysis.

Co-developer, Dr Roberta De Bei from the University of Adelaide's School of Agriculture, Food and Wine said, "Grapevine canopy size is known to play a role in yield, grape quality and the potential productivity of future seasons."

"Monitoring the differences in canopy size within vineyards is a useful way to identify problems that could be related to pests and disease, water status and nutrient status," Dr De Bei said.

"Once grapevine canopy measurements are known, they can be compared against previous seasons to identify optimal traits for grape quality and maximum yield."

The creators of VitiCanopy say the new features make visualising a lot of data even easier, with reports produced not only as CSV files but also in map format, providing visual oversight of canopy size across the entire vineyard.

Co-developer, Associate Professor Cassandra Collins from the University of Adelaide's School of Agriculture, Food and Wine said, "the app has also moved into the Cloud environment, which means images are uploaded directly to the Cloud, saving on phone battery and storage.

"VitiCanopy's upgrade also includes a user-friendly and intuitive website providing additional information on how to get the most value from the app's analysis and reporting tools," Associate Professor Collins said.
Wine Australia General Manager Research, Development and Adoption Dr Liz Waters said the app is a strong addition to the diagnostic toolbox available to growers.

"Measurement of grapevine canopy size is critical to assess growth, vigour and vine water requirements," Dr Waters said.

"VitiCanopy is a valuable tool to help monitor vineyard differences in canopy size, which can help to identify problems early so that strategies and resources can be put in place to maximise vineyard productivity and profitability."

Visit viticanopy.com.au or download the app from the App Store or Google Play.

[Ends]











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About Wine Australia

Wine Australia supports a competitive wine sector by investing in research, development and adoption (RD&A), growing domestic and international markets and protecting the reputation of Australian wine. Wine Australia is an Australian Commonwealth Government statutory authority, established under the *Wine Australia Act 2013*, and funded by grape growers and winemakers through levies and user-pays charges and the Australian Government, which provides matching funding for RD&A investments.

About the University of Adelaide

The University of Adelaide's Waite campus is the largest concentration of agricultural research and teaching expertise in the southern hemisphere. The broad vision of the School of Agriculture, Food and Wine is to drive innovation to secure a sustainable future for agriculture, by creating high-quality, nutritious and climate resilient products. This is done in close partnership with the agriculture, food and wine sectors. In a climate of limited natural resources, higher energy costs, and increasing urbanisation and environmental degradation, the University's work in supporting global food security and agricultural sustainability is critically important.

Appendix 5.2 Comparison between VitiCanopy and similar applications available commercially.

App Name	Operating system	Features	Cost	Pro	Cons	VitiCanopy comparison
EASY LEAF AREA	Android	Analysis of single jpeg or tiff images or batches of images for leaf area. Images must have a red scale of known area in the image in the same plane as the leaves for the program to use as a reference scale.	Free	Easy Simple Ideal for small sample size Research tool	Destructive Requires a reference No batch analysis No mapping Only for single leaves, cannot measure whole canopies	Batch analysis Automatic analysis No user inputs required Mapping
CANOPY COVER FREE	Android	Measures the % canopy cover from the green area in images. It uses sliders to identify the canopy area correctly. Results are geo-located. Results are saved as a text file.	Free	Easy Automatic Non-destructive	Works from the top down, cannot be used for vines/trees. Not geo-referenced	Batch analysis Automatic analysis No user inputs required Mapping
CANOPEO	Android and iOS	Calculates the % canopy cover of green vegetation for any agricultural crop, turf, or grassland based on downward-facing photos taken with your mobile device. Option to add notes associated with each image and upload images to personal account. Canopeo automatically records the geographic coordinates and the current date and time so that you always know when and where each image was taken.	Free	Easy Simple pixel analysis tool Good for research Not suitable for trees/vines	Not suitable for trees/vines One by one analysis Suited to crops other than trees	
POCKETLAI	Android	Calculates Leaf Area Index. It uses the smartphone camera and accelerometer to acquire images from below the canopy while the user is rotating the smartphone along its main axis. When the view angle reaches 57.5◦, the frames are automatically processed to detect sky pixels via two dedicated segmentation strategies, one for clear sky and the other for a cloudy	Not free	Can work on low vines	Not available for download on Google play. To get the app you need to contact the company and obtain a quote.	

		sky. LAI values are stored in a table with information of date, time and GPS coordinates.				
SENTINEL-2 NDVI MAPS	Android	Allows viewing the current NDVI map based on Sentinel-2 satellite data provided by Copernicus. This NDVI map allows farmers to generally know the health of the plants in each region of their crops. The application provides five layers of images: i) Open Street Map, ii) two layers of vegetation index (NDVI and EVI iii) two layers with the true and false colours. Resolution is maximum 15 m. The paid version of the application allows zooming four times higher than the free version. Only the latest image data with a maximum cloud coverage of 20% is displayed.	Free		Low resolution Suitable for ArcGIS users and linked to the GIS mapping/account	Not on google play store, may not be available anymore
ONE SOIL SCOUTING	Android and iOS	It displays NDVI maps of any delineated field. Images are updated every 3–5 days, and a notification system can be enabled to notify the user when a new image becomes available. Current weather and weather forecasts are in the app too.	Free	Low resolution	Free weekly NDVI maps Easy to use	
SMART fLAIr	Android (but does not seem to be available anymore)	Calculates Leaf Area Index (LAI) based on gap fraction analysis and using the smartphone's internal Ambient Light Sensor (ALS). To improve the gap fraction accuracy, the authors enhance the ALS by a diffuser cap combined with an optical band-pass filter.	Cost ?	Needs additional sensors		