Rural R&D for Profit Program

Digital technologies for dynamic management of disease, stress and yield

[RnD4Profit-15-02-018]

Final Report

Wine Australia

June 2016 – August 2020

Alex Sas, R&D Program Manager



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Plain English summary

Digital technologies have the potential to transform Australian agriculture, with one recent study estimating that their adoption would increase the gross value of agricultural production by $20 billion annually, with the cotton and wine sectors accounting for 5% of that improvement. The objective of the project was therefore to develop novel digital technologies and processes for Australian cotton and grape producers so that they could share in these productivity improvements. Eight sub-projects explored suitable technology to support five research goals:

1. Disease management in cotton
2. Yield forecasting in vineyards
3. Measure vineyard canopy, nutrition, microclimate, grape defects and disease
4. Optimise vineyard spraying
5. Tools for spatial data analysis

Diseases are a major constraint to cotton production in Australia, either directly through lost production (estimated at $27-75 million annually), or through the inability to plant fields thought to be at risk. The cotton industry has historically conducted surveys to separately monitor disease severity and spread in New South Wales and Queensland. While this surveillance has provided industry with disease trends, it has not allowed for a holistic systems approach to potentially improve disease management. This project developed a process to capture georeferenced in-field disease survey data across both states and also collated three years of field pathology data and management practices into a new database. Multivariate analyses of the survey data were performed to determine if the previous crop and cotton trash influenced disease incidence and severity. The key finding was that the previous crop had a significant effect on disease in the subsequent cotton crop. This finding has already been communicated to the industry through updates to best practice management guides, grower meetings and workshops. In addition, a new plant tissue assay was developed for the organism that causes Verticillium wilt – *Verticillium dahliae* – that is faster than prior methods. The development of this molecular tool now provides industry with the ability to quickly diagnose the presence of Verticillium and its strain, enabling disease risk to be factored into a decision to grow cotton.

Seventeen new technologies were developed for the wine sector, at various stages of industry readiness. A package of 'precision agriculture tools' (PAT) has already been released. PAT assists with the analysis of spatial data collected for Precision Agriculture. Initial feedback is that while the tools are useful, the platform interface is still too complex to be adopted widely by producers. It is recommended that the remaining technologies be assessed for commercialisation potential with input from the sector. For those systems with lower technology readiness where this assessment is not yet practical, it is recommended to continue research where there is ongoing support.

The technologies developed to estimate yield were rated highly by the Industry Reference Group whose role it was to provide feedback to the project team. An improvement in the accuracy and efficiency of yield estimation has the potential to generate significant productivity gains through the entire wine supply chain. Current methods used to estimate yield are typically inaccurate and time

consuming, with many growers simply replying on an 'educated guess'. A prototype hand-held NIR instrument and calibration set was successfully developed which can predict bud fruitfulness in Chardonnay and Pinot Noir vines, in the vineyard. This information can be used by growers to tailor pruning to maximise their returns. In another project, a data processing pipeline was developed and combined with machine learning to process video captured from Go-Pro cameras to accurately count inflorescences down a vineyard row and thereby provide a yield prediction shortly after budburst. The same method worked reliably for bunch counting but needs further optimisation for vineyards with heavier canopies. Low-power radar was able to detect fruit irrespective of canopy, but its ability to reliably quantify fruit mass still needs to be demonstrated.

An associated sub-project developed technology to provide on-the-go, non-contact measurement of canopy size and structure, whole vineyard nutrition status, and detection of disease. Real-time canopy measurement is potentially of value as canopy size affects water use and fruit quality. A system using LiDAR was developed to define three-dimensional (3D) canopy structure for whole vine rows and another system successfully measured canopy size across a vineyard using consumer drone imagery with photogrammetry or Go-Pro video imagery. All these devices (except the drone) were mounted on vineyard vehicles and used to image commercial vineyards in collaboration with three wine companies. Individual vine nutritional status was able to be estimated for an entire vineyard using hyperspectral imaging and analysis. Measurement of diseased grapes in vineyards was possible but had many challenges, as did the pre-symptomatic detection of disease on leaves. In contrast, hyperspectral imaging was successfully used to measure bunch rot in addition to other defects such as sunburn, berry shrivel and 'matter other than grapes' (MOG) in machine-harvested loads of grapes delivered to a winery. Current methods for the quantification of these defects rely on subjective or semi-quantitative assessment, so the potential of these new tools is of interest to the sector, especially for larger wineries.

A prototype system was developed using acoustic atmospheric tomography and long wave infrared thermography to provide a three-dimensional record of vineyard microclimate at a sub-metre scale. The system was successfully tested in frosty conditions and during days of extreme heat (up to 48°C). The value of the 3D microclimatic information is yet to be quantified by the sector. The goal to optimise vineyard spraying succeeded by developing a kit for sprayers which uses LiDAR and radar to automatically assess canopies and adjust application in response. Chemical savings of 50-90% were achieved in sparse canopies, with a substantial reduction in spray drift. An 'electronic leaf' to measure spray coverage was also developed.

The project achieved its objective to develop innovative digital technologies for the cotton and grape sectors—at least 18 novel devices or processes were produced. While collaboration between the sectors was limited, collaboration within each sector and across research organisations nationally and internationally contributed to this success. Wine Australia has already commenced the assessment of each of the wine sector project outputs for potential commercialisation, and this will include consultation with growers, vineyard contractors and winemakers.

This project was funded by the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program, with co-investment from Wine Australia, Cotton Research and Development Corporation, Horticulture Innovation Australia Limited, LasTek Pty Ltd and the University of South Australia.

Abbreviations and glossary

AAT	atmospheric acoustic tomography
ACCC	Australian Competition & Consumer Commission
AWRI	Australian Wine Research Institute
CRDC	Cotton Research & Development Corporation
FoPEN	foliage penetrating radar
GRDC	Grains Research and Development Corporation
GVP	gross value of production
LAI	leaf area index
LiDAR	light detection and ranging
LWIR	longwave infrared
MDI	mean disease incidence
MOG	matter other than grapes
NIR	near infrared
PA	precision agriculture
PACE	pesticide adjusted for canopy environment
PAVE	pesticide adjusted for vineyard environment
PIRSA	Primary Industries and Regions SA
ppg	propagules per gram
PV	precision viticulture
PWM	pulsed width modulation
RGB	red, green, blue colour model (colour image)
SaaS	software as a service
SARDI	South Australian Research and Development Institute
SODAR	sonic detection and ranging
SWIR	shortwave infrared
TRL	technology readiness level
UAV	unmanned aerial vehicle (drone)
VCG	vegetative compatibility groups (strain)

1 Project rationale and objectives

The development of agricultural machinery and digital technology that can generate objective information about the status of soil, water and crops holds promise of substantial productivity benefits for Australian farmers[1] . A recent study[2] estimated that these benefits could potentially deliver a 25% improvement in the gross value of Australian agriculture. The same study estimated that the biggest gains from the adoption of digital technologies would be through:

- labour savings from automation;
- genetic gains through objective data; and
- closer tailoring of inputs to needs.

The potential boost to wine sector GVP through the adoption of these emerging technologies was estimated at $705 million per annum while the benefit to the cotton industry was nearly $400 million.

The objective of the Rural R&D for Profit program project *Digital technologies for dynamic management of disease, stress and yield* was therefore to develop innovative digital technologies and processes for Australian cotton and grape producers so that they could participate in these productivity improvements.

Eight sub-projects (Table 1) were commissioned by Wine Australia to explore suitable technology to support five research goals. The five goals and associated objectives are:

1. Disease management in cotton
   – To reduce losses in cotton – in particular from disease caused by *Verticillium dahliae* – by developing technology to assess disease risk prior to planting and strategies for disease management.
2. Yield forecasting in vineyards
   – To provide timely yield forecasts more accurately and quicker (and therefore cheaper) than current labour-intensive methods.
3. Measure vineyard canopy, nutrition, microclimate, grape defects and disease
   – To develop and evaluate sensors and associated data processing pipelines to assess key vineyard management parameters (canopy growth, incidence of pre-symptomatic disease, vineyard microclimate, vine nutritional status) non-destructively and on-the-fly, and to assess grape condition on delivery to the winery.
4. Optimise vineyard spraying
   – To develop novel sensors as part of an automated vineyard spraying system to optimise dosing of chemicals applied to each unique canopy, reducing chemical use and spray drift.

[1] Keogh, M and Henry, M (2016). The implications of digital agriculture and big data for Australian agriculture. Research Report, Australian Farming Institute, Sydney Australia

[2] Heath, R (2018). An analysis of the potential of digital agriculture for the Australian economy. Farm Policy Journal, 15(1), Autumn 2018.

5. Tools for spatial data analysis
   - To produce a suite of freeware spatial data analysis tools to enable a non-expert to access the benefits of Precision Viticulture management.

Table 1. The five research themes within the Rural R&D for Profit project *Digital technologies for dynamic management of disease, stress and yield,* and the associated eight sub-projects

Theme		Sub-project	Lead research organisation
1	**Disease management in cotton**	Digital technologies for dynamic disease management CRD 1601NS	CRDC through NSW DPI and Department of Agriculture and Fisheries, Queensland
2	**Yield forecasting in vineyards**	Taking grapevine yield forecasting into the digital age UT 1601	The University of Tasmania
		New non-destructive technologies for simultaneous yield, crop condition and quality estimation CSA 1602	CSIRO
3	**Measure vineyard canopy, nutrition, microclimate, grape defects and disease**	New technologies for dynamic canopy and disease management CSA 1601	CSIRO
		Digital solutions for grape quality measures at the weighbridge AWR 1601	The Australian Wine Research Institute
		Use of Unmanned Air Vehicles for early, real time detection of extreme weather events in vineyards USA 1601	The University of South Australia
4	**Optimise vineyard spraying**	LiDAR and PACE for vineyards UQ 1601	The University of Queensland
5	**Tools for spatial data analysis**	Simple tools for spatial analysis - key enabling technologies for Precision and Digital Viticulture CSA 1603	CSIRO

2 Performance summary

The project activities and outputs – as specified in the Grant Agreement RnD4Profit-15-02-018 – were fully achieved, with two exceptions (Outputs 6e and 7d). Further detail is provided in the summary of the project performance, below.

Activity / Output			Achievement summary	
✓ Output achieved; **P** Output partially achieved			NB: Milestone Report 6 KPIs are **highlighted**	
B1		**Project initiation**		
	1a.	Engage a project manager for the duration of the Activity	The Funding Deed was executed between Wine Australia and the Commonwealth on 22/6/2016. Project initiation outputs included engagement of a project manager and establishment of an Industry Reference Group with agreed terms of reference, as reported in Milestone Report 2.	✓
	1b.	Establish a project steering committee responsible for oversight of the Activity. The project steering committee will agree its terms of reference which will set out its membership, governance arrangements and responsibilities		✓
	1c.	Execute agreements with partner organisations	Dates of contract execution are listed in Appendix 5.5.	✓
	1d.	Advise the yearly breakdown of the cash and in-kind contributions to be provided by partner organisations for the duration of the Activity	The yearly breakdown of the cash and in-kind contributions to be provided by partner organisations across the entire period of the Grant was provided with Milestone Report 1.	✓
B2		**Project planning and management**		
	2a.	Prepare a project plan, setting out the schedule for activities, and the human resources and financial resources required. Prepare a risk management plan as part of the project management plan	Detailed plans for each of the eight sub-projects were developed and provided with Milestone Report 1. The plans included a schedule for activities and target dates for the project term.	✓
	2b.	Prepare a communication and extension plan, setting out the schedule for communication and extension activities, and the human resources and financial resources required	A detailed a communication plan was developed by Wine Australia and presented in Milestone Report 2. The objective of the plan was to encourage awareness of the findings from each sub-project and enhance the credibility of digital technologies in agriculture. The plan identified audiences and stakeholders, communications channels, content and measures of success.	✓
	2c.	Prepare a monitoring and evaluation plan, setting out timeframes for activities to be delivered, and the human resources and financial resources required	A monitoring and evaluation plan was developed and submitted with Milestone Report 2, with an update provide with Milestone Report 3, and here in Sections 2 and 4.	✓
	2d.	Provide a progress report on the evaluation of the project, delivered at the mid-point of the project		✓

Activity / Output			Achievement summary	
B3		**Communication and extension activities**		
	3a.	Identify target audiences and establish appropriate contacts with cotton growers, table and wine grape growers, wine producers, regional associations and extension providers	Extensive grower and industry networks were developed and engaged with, especially for the cotton sub-project. Its activities (disease surveys, assay validation, field trials) demanded frequent and widespread interaction with industry, as witnessed in the extensive communications and extension list in Section 5.1. In contrast, the grape sub-projects were very experimental in nature as they were developing new prototype technology with typically a low technology readiness level (TRL). As a consequence, interaction with industry – apart from the industry project partners – was mostly through media (written publications, radio) or industry conferences and workshops, rather than at field days. The industry partners were intimately involved with the field testing, providing vineyards and grapes for the trials and staff who assisted with the project design and operation. Given that the industry partners were more likely to be adopters and advocates of the new technology, this approach was appropriate.	✓
	3b.	Implement communication and extension plan, and promote project activities and outcomes at regional and national conferences, workshops and seminars for the wine and table grape growers, wine producers and cotton growers	Section 5.1 addresses **KPI 6.2** and lists publications, communications and extension output from the project: 71 Industry Publications and Media pieces; 21 Presentations to Industry; 50 Presentations or Papers at Conferences and Workshops; 17 Papers or Theses Published or in press; and 6 Videos Published Online. The performance targets within Wine Australia's communication plan were nearly all achieved, with a single parameter being 2% under target (Section 4.3).	✓
	3c.	Publish research findings in journals, conference papers, industry publications, RDC publications, newsletters and websites in a form accessible to producers		✓
	3d.	Establish an 'influencer network' to reach a wider audience	The industry members of the Industry Reference Group were the core of the initial 'influencer network'. Due to their commercial interests, these people were the most likely bleeding edge users of the new technologies developed from the project. Wine Australia's *Regional Program* partner network (comprising 11 clusters that cover all the major Australian wine regions) was used to publicise the project to the sector and will be used in the future to evaluate short-listed prototype technology developed by the project.	✓
B4		**Yield prediction in vineyards**		
	4a.	Collect data from vineyards and validate against yields	**KPI 6.3 and 6.4** were achieved. Two sub-projects explored alternative technologies for estimating yield at different times in the season. UT 1601 explored the estimation of yield before budburst so that the data could be used to manage pruning. CSA 1602 evaluated several sensors to estimate yield later in the season, from when the inflorescence was visible till harvest . Inflorescence and bunch count data were collected using non-destructive sensor technology over several seasons and validated against manual counts. Sections 3.2.1 and 3.2.2	✓
	4b.	Collect and analyse bud fruitfulness data		✓
	4c.	Develop and trial a prototype spectral instrument	**KPI 6.5** was achieved. UT 1601 developed a prototype hand-held NIR (spectral) instrument to estimate bud fruitfulness in the field. CSA 1602 evaluated several sensors to estimate yield and developed data processing pipelines. The technologies sit at a range of technological readiness and require further development prior to commercialisation. Sections 3.2.1 and 3.2.2	✓
	4d.	Develop a predictive model for yield estimation	**KPI 6.6** was achieved. UT 1601 and CSA 1602 both delivered non-destructive means of estimating yield. The accuracy of the prediction is explained in Sections 3.2.1 and 3.2.2 and in the respective technical reports available on the Wine Australia website.	✓

Activity / Output			Achievement summary	
B5		**Disease management in cotton**		
	5a.	Conduct a review of suitable digital technologies for collecting geospatial data	A review of suitable digital approaches for collecting and collating geospatial data was undertaken and reported. Pre-requisites for a data collection system were as follows: intuitive interface, secure data sharing to protect anonymity, ability to capture accurate GPS coordinates, compatibility with a larger data-management system, affordability for a large seasonal user base and overall simplicity. The Fulcrum SaaS platform was selected as the most appropriate tool for the capture of georeferenced in-field disease survey data. Section 3.1.1	✓
	5b.	Collect and analyse data and if required conduct trials to support findings	**KPI 6.7** was achieved. Three years of field assessed cotton pathology data and management practices were collected. Multivariate analyses of survey data were performed to test for any effect of previous crop and cotton trash present on early and late season diseases. Key finding was the significant negative impact of previous cropping on disease in the subsequent cotton crop. Section 3.1.2	✓
	5c.	Develop a molecular tool for Australian strains of *Verticillium dahliae*	**KPI 6.8** was achieved. A plant tissue assay was developed that is faster than traditional isolating techniques and is capable of diagnosing *Verticillium dahliae* and providing VCG (strain) in a higher proportion of infected plants. This significantly reduces the turn-around time for diagnostics. This assay was successfully validated by comparing traditional plating assays with the tissue assay on cotton and other crops. The development of this molecular tool now provides industry with the ability to quickly diagnose the presence of *Verticillium* and its VCG, enabling disease risk to be factored into a decision to grow cotton. Section 3.1.4	✓
	5d.	Investigate inoculum threshold for all strains of *Verticillium dahliae* and test on field samples	In a replicated pot experiment, all plants infected with 1ppg from VCG1A, 2A and 4B exhibited external symptoms of Verticillium wilt as did plants infected with 5, 10 and 20 ppg. These results were supported by the field trials which found that inoculum level did not have a significant effect on disease index as high disease indices were recorded with as little as 1 ppg. Section 3.1.4	✓
	5e.	Develop a geospatial database and enter historical disease survey information	**KPI 6.9** was achieved. A geospatial database was designed in Microsoft Excel to collate raw survey data for analysis. Three years (2016-2019) of field assessed cotton pathology data and management practices were collected and multivariate analyses performed. Section 3.1.1	✓
	5f.	Develop improved disease management recommendations	Updates to best practice management of disease were provided to industry regularly through the CottonInfo Cotton Pest Management Guide and through grower meetings and conferences. Key findings communicated included the impact of previous cropping on disease in the subsequent cotton crop. Sections 3.1.2 and 3.1.7	✓
B6		**Disease management in vineyards**		
	6a.	Collect data from vineyards and harvested fruit loads and validate against disease levels	**KPI 6.10** was achieved. Hyperspectral imaging was successfully used to measure bunch rot in machine harvested wine grapes, in addition to other defects such as sunburn in white grapes and berry shrivel in red and white grapes. MOG could also be measured. The presentation of the sample to the camera and lighting was critical to reduce error. Measurement of diseased grapes in vineyards was also possible but had many challenges. Section 3.3.2	✓
	6d.	Conduct simulations to measure contaminants in harvested wine grapes		✓
	6b.	Develop and trial sensors for level of disease in grapes	**KPI 6.11** was achieved. Hyperspectral imagery proved to be an effective tool to measure disease in grapes. Analysis of the hyperspectral data captured from a lab-based linescan camera, demonstrated that eight wavelengths described disease and defects in grapes. This knowledge allowed the testing of a more versatile multispectral 'snapshot' camera. Section 3.3.2	✓

Activity / Output			Achievement summary	
	6c.	Develop a Pesticide Adjusted for the Canopy Environment (PACE) scheme for farmers	**KPI 6.12** was achieved. A modified PACE scheme for vineyards (PAVE) was developed, using the University of Adelaide VitiCanopy app to measure Leaf Area Index – a key parameter for calculating the amount of agrochemical to apply per length of row . In addition to this achievement, a prototype system to automate and optimise spray application was developed. The system uses LiDAR and radar to achieve constant average spray deposit over a dynamic range of canopy densities/growth stages throughout the season. Chemical savings of 70-90% were achieved early in the season with open canopies, with savings of 30% at full canopy maturity. Spray drift is also much reduced. The project also developed an 'electronic leaf' to measure spray coverage. Section 3.4.2	✓
	6e.	Develop prototype technologies and protocols for disease detection	**KPI 6.13** was partially achieved. While it was demonstrated that hyperspectral imaging can be used to measure visible powdery mildew on leaves in potted vines, it was hoped that a method would be developed to detect pre-symptomatic disease not obvious to the naked eye. The initial method tested used detached grapevine leaves, but this created artefacts in the data which necessitated a new approach using potted vines. The data from these later experiments are yet to be analysed and results will be reported as part of a follow-on project between CSIRO and Wine Australia (CSA 1702-3.1). Section 3.3.1	P
	6f.	Deliver workshops for agrochemical manufacturers and regulators for labelling modifications	**KPI 6.14** was achieved. COVID-19 delayed the planned workshop but a virtual event was held instead on 28 May 2020 describing the new technology developed in UQ 1601 and implications for agrochemical labelling. The workshop was coordinated by the National Working Party on Pesticide Applications, and was attended by representatives from the agrochemical industry, wine and cotton sectors, spray equipment manufacturers, and from state and federal departments responsible for agrochemicals. The workshop is likely to lead to data from the project being used to modify agrochemical label restrictions around spray drift management. Section 3.4.1	✓
B7		**Stress management in vineyards**		
	7a.	Collect data from vineyards and validate against grape and vine attributes	**KPI 6.15** was achieved. In-vineyard tests demonstrated that AAT and UAV/LiDAR measurements had correspondence accuracies of around 0.5°C for temperature and 0.3 m/s for each component of wind velocity. This compares very favourably to other inter-instrument atmospheric comparisons, such as LiDAR vs SODAR and is within the measurement errors of the system. Section 3.3.3	✓
	7b.	Develop an Unmanned Aerial Vehicle (UAV) based system that delivers real time monitoring of potentially damaging weather events in vineyards	**KPI 6.16** was achieved. A prototype system was developed to deliver a combination of vineyard canopy, ground and air temperatures, and wind speed observations at the sub-metre scale. The system was successfully tested in frosty conditions, during days of extreme heat (up to 48°C), and for continuous periods of operation throughout a day. The high-resolution tomographic observations allow visualisation of the meteorology within and around a vineyard with respect to both time and space to altitudes of about 130 m. Section 3.3.3	✓
	7c.	Develop a specification and implementation plan	The plan is described in Section 3.3.3 (*Potential for adoption – implementation plan*)	✓
	7d.	Prepare recommendation material and information in a form suitable for delivery to farmers	**KPI 6.17** was partially achieved. While recommendations have been provided through the Implementation Plan, given the relatively immature TRL of the system these will not be promoted to growers until an assessment of the commercialisation potential of the technology is completed.	P

Activity / Output			Achievement summary	
B8		**Enabling technology**		
	8a.	Identify a suitable freeware GIS platform to support spatial analysis, map display and convert various map production/analysis tools	QGIS 2.18 was selected as the freeware GIS package that would be used to underpin the project outputs. Section 3.5.1	✓
	8b.	Refine methods for geostatistical analysis of field experiments in order for analysis to be performed on standard desktop computers	A package of data processing and analytical functions was created using the 'R' software environment. The package is a combination of wrapper functions that include novel algorithmic implementations of multivariate geostatistical methods to understand dissimilarities in the production of a farm by providing their corresponding statistical uncertainty and significances. Section 3.5.2	✓
	8c.	Develop a code to be engineered into a user friendly, open source software tool, which outputs to the GIS freeware	Precision Agriculture Tools (PAT) were produced as a plugin for the freeware GIS package, QGIS. PAT is the front end to pyprecag – an open source Python library of PA analysis tools which contains the processing functions. PAT/pyprecag contains all the tools for spatial data manipulation and analysis that is likely to be needed by adopters of PV/PA. Both 'pyprecag' and the PAT 'front end' were initially released in January 2019. Section 3.5.3	✓

3 Achievements and industry relevance

3.1 Disease management in cotton [CRD 1601]

This sub-project was led by the CRDC and undertaken by NSW DPI and Department of Agriculture and Fisheries, Queensland. It demonstrated the applicability of a strategic and geospatial approach to surveillance to develop new knowledge and inform research direction for an improved soil-based biological suppression of disease. It also developed new assays to identify *Verticillium* and measure its risk to cropping. All the RnD4P-funded project outputs were achieved.

Analysis of field assessed cotton pathology data, management practices, soil biology and environmental data provided insights to improve management recommendations to industry (e.g. crop rotation crop, solarisation) as well as provided insights into research needs. A laboratory-based pathogen suppression potential assay was developed which provides a quantitative measure of a cotton soils' ability to support or inhibit soil-borne fungal pathogens such as *Verticillium dahliae*. A plant tissue molecular assay was also developed that is faster than traditional isolating techniques.

3.1.1 Collection of geospatial disease survey data

A review of suitable digital approaches for collecting and collating geospatial data was undertaken and reported. Pre-requisites for a data collection system were as follows: intuitive interface, secure data sharing to protect anonymity, ability to capture accurate GPS coordinates, compatibility with a larger data-management system, affordability for a large seasonal user base and overall simplicity.

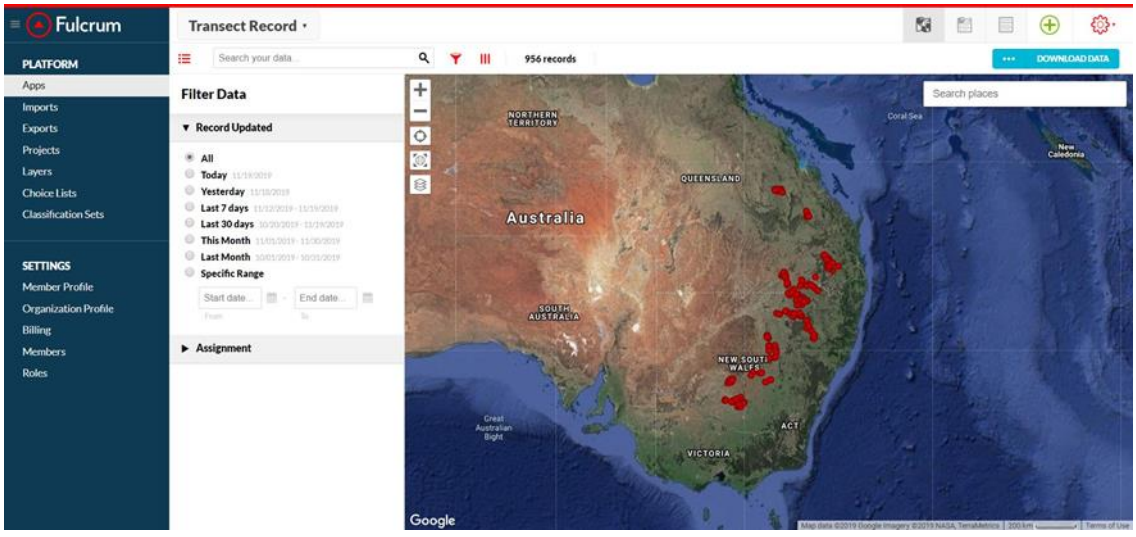


Figure 1. *Fulcrum* platform dashboard displaying captured geospatial disease survey records

The Fulcrum SaaS platform was selected as the most appropriate tool for the capture of georeferenced in-field disease survey data. The Fulcrum desktop interface allows the visualisation of monitoring field activities across the cotton production regions of New South Wales and Queensland (Figure 1).

3.1.2 Statistical associations identified in historical datasets

A geospatial database was developed and three years of field assessed cotton pathology data and management practices were collected. Multivariate analyses of survey data were performed to test for any effect of previous crop and cotton trash present on early and late season diseases. Further correlation network analyses were performed on the data to identify relationships between diseases and yield and diseases themselves in the whole data set and in each state.

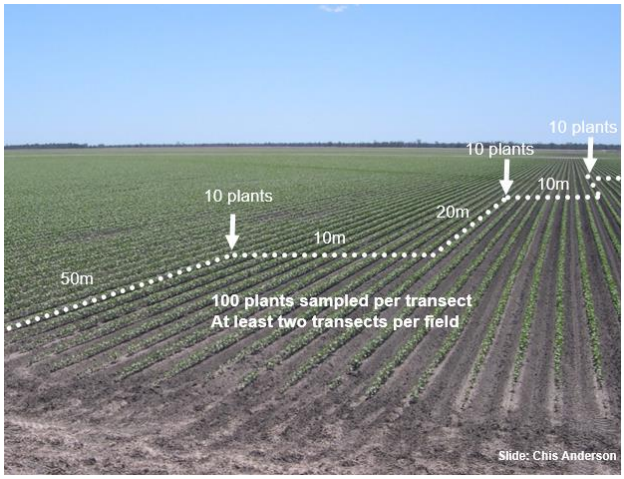


Figure 2. Schematic of stratified walk to conduct disease survey of a field

Key findings include the impact of previous cropping on disease in the subsequent cotton crop. For example, Verticillium wilt was significantly higher following winter cereal crops than cotton. Seed rot was significantly lower following a fallow or winter cereals, boll rot was significantly higher following summer grains, and tight-lock was significantly lower following fallow and winter cereals, than cotton. Tight-lock (Figure 3) had the strongest negative relationship with yield in the data set, providing statistical support of anecdotal findings. Detection of cotton bunchy top and mealy bugs highlights the need to ensure that ratoon or volunteer cotton and weed hosts are eliminated on farm, particularly over winter. The amount of cotton trash present in the field did not have any significantly detectable effect on disease in the analyses performed on these data.

Given the impact of previous crop on disease incidence, an estimation of crop residues other than cotton may provide insight to how other crops influence disease, such as maintaining inoculum levels through asymptomatic colonisation or providing a suitable carbon source for saprophytic growth. Hence, these findings provide direction for research to investigate cropping rotations that potentially will decrease/increase disease incidence of important diseases of cotton. The groundwork achieved in this project has provided the foundation knowledge and critical directions to improve the collection and storage of data, and to build on the analyses already conducted.



Figure 3. Normal cotton (left) compared to tight-lock cotton

Updates to best practice management of disease were provided to industry regularly through the CottonInfo Cotton Pest Management Guide and other industry publications, and through grower meetings and conferences as listed in Section 5.1.

3.1.3 Disease suppression potential of soils from different regions

Composition and abundance of microbial communities were analysed for soils collected from different regions with different cropping histories and varying disease incidences (Figure 4). Results from the long-term experiments indicate that: (i) the diversity and abundance of soil fungal communities varied significantly by crop management history and, (ii) fungal communities in suppressive cotton soils were characterized by higher diversity and higher connectedness. The high level of organization along with higher diversity in the soil fungal community in the suppressive soils would provide the cotton plant with a stable microbial reservoir across varied seasonal environmental conditions.

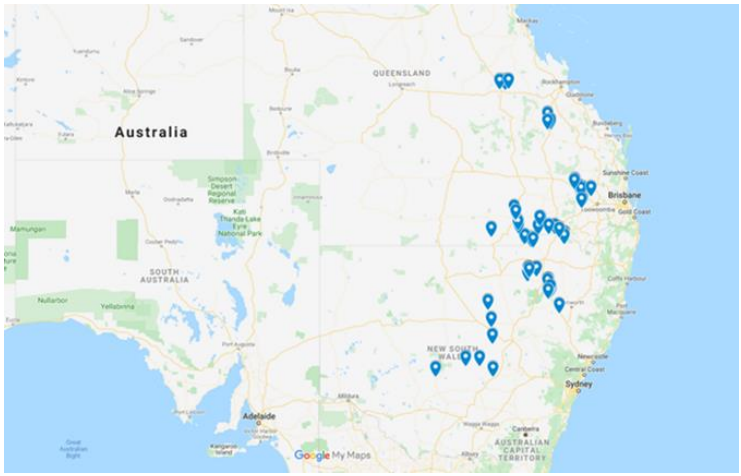


Figure 4. Locations in Queensland and New South Wales where soil was collected for microbiological analyses. Samples were collected during disease surveys and from experimental trial sites

This project has provided additional insights into long term disease implications of systems, as well as short term. Field trials found that a bare fallow and corn rotation both yielded significantly better than cotton and sorghum, producing at least 1.6 bales/ha more cotton. Changes in the microbial diversity and activity in the short-term rotation experiment clearly indicated the significant and important contribution of soil microbiome (bacteria and fungi) for

the suppression of Verticillium wilt disease in cotton. The influence of rotation crops such as sorghum and corn could be attributed to: (i) increased microbial catabolic diversity and activity (ii) higher diversity of bacteria and fungi, (iii) increased abundances of specific groups of microorganisms involved in antibiosis, antifungal (cell-wall degradation) and plant growth promoting capabilities, and (iv) lower pathogen levels. These changes would have contributed to the suppression of the pathogen, disease incidence and impact. Whereas the fallow treatment caused a significant decline in the total microbial activity and catabolic diversity, genetic diversity of bacteria and fungi resulting in lower pathogen suppression capacity. Although the lower pathogen levels would help in the reduction of disease incidence, long-term adoption of fallow would not benefit in maintaining or improving the overall soil biological health. The traditional continuous cotton system seems to promote the growth of pathogenic fungi such as *V. dahliae* and result in lower microbial diversity and abundances of beneficial microorganisms.

A laboratory-based pathogen suppression potential assay was developed which provides a quantitative measure of a cotton soils ability to support or inhibit soil-borne fungal pathogens such as *V. dahliae*.

Results from this study clearly indicate the presence of a genetically diverse fungal community in cotton soils and distinct variation in the community composition and diversity between fields in different cotton regions.

3.1.4 Verticillium wilt

Development of new assays to identify *Verticillium* and measure its risk to cropping

The aim of this research was to develop tools to inform grower decision making with regards to Verticillium wilt. Using *V. dahliae* cultures in the long-term culture collection and those obtained throughout this project enabled the team to assign presumptive Vegetative Compatibility Groups (VCGs) without the use of Nit Mutants and further investigate the genetic diversity between Australian isolates. Molecular studies indicated the Australian defoliating cotton isolates are distinct from the defoliating isolates in the USA. Analysis of the USA VCG1A isolates revealed they are genetically different to the Australian VCG1A. Molecular testing has also demonstrated the presence of both pathogenic and non-pathogenic VCG1A isolates. Australian VCG1A does not always cause severe crop damage as reported overseas, while VCG2A can cause more severe damage compared to international isolates. This project has also identified that the Australian VCG2A has two distinct molecular groups which correlates with their pathogenicity (non-defoliating and defoliating) in cotton.

Isolates were also used in many laboratory and pot experiments. These were particularly useful for inoculating soil with a known inoculum to determine the minimum number of propagules required to cause disease for each VCG. Soil isolation techniques were optimised for estimating inoculum levels as well as a protocol for soil sampling in cotton fields. This work provides guidance on where to sample, how deep to sample, how many samples are required. It also outlines the methods for soil preparation and isolation techniques such as the amount of soil to be isolated per replicate and what semi-selective media to use.

Once an effective method for estimating inoculum levels was established using the dry plating technique, work was undertaken to determine the minimum inoculum level required to cause disease in fields. Extensive plots trials in commercial cotton fields were used to establish a disease risk matrix and thresholds for minimum disease incidence. Two observations of the collected data stood out. First, a large sample size of pre-plant inoculum levels showed there was an upward trend - as the ppg increased, so too did the minimum disease incidence. Second, there was considerable variation within any inoculum level. For example, in plots with 2 ppg, the disease incidence ranged from 10 - 100%.

The effect of long-term rotation following cotton with non-hosts such as durum wheat and sorghum on inoculum levels was evaluated over time. The inoculum levels significantly decreased following these crops but increased again following the planting of cotton. The value in rotation is when inoculum levels are low before the incidence levels cause yield loss. Care must also be taken when selecting alternative crops to plant in cotton fields. Biofumigant blends containing mustard and Ethiopian cabbage were confirmed hosts to *V. dahliae* as was safflower. Growers should seek advice on what crops are potential hosts for *Verticillium* prior to planting.

The published LAMP assay was evaluated using nine Australian *Verticillium* isolates from different VCGs, three USA VCG1A isolates and *Verticillium theobromae* as a specificity control. The LAMP assay failed to work, even after multiple optimisation efforts and consultation with the published authors and was not able to differentiate between Australian defoliating and non-defoliating pathotypes.

A plant tissue assay was developed that is faster than traditional isolating techniques and is capable of diagnosing *V. dahliae* and providing VCG in a higher proportion of infected plants (Figure 5). This significantly reduces the turn-around time for diagnostics. This assay was successfully validated by comparing traditional plating assays with the tissue assay on cotton and other crops. The development of a *V. dahliae* specific inoculum quantification assay was extremely challenging and semi-successful. The molecular soil assay can detect *V. dahliae* and the sensitivity of detection was 10-30 ppg in naturally infected soil. This is not sensitive enough when one propagule per gram of soil is enough to cause disease. The VCG of soil inoculum can be determined using a combination of the dry plating soil assay and sequencing.

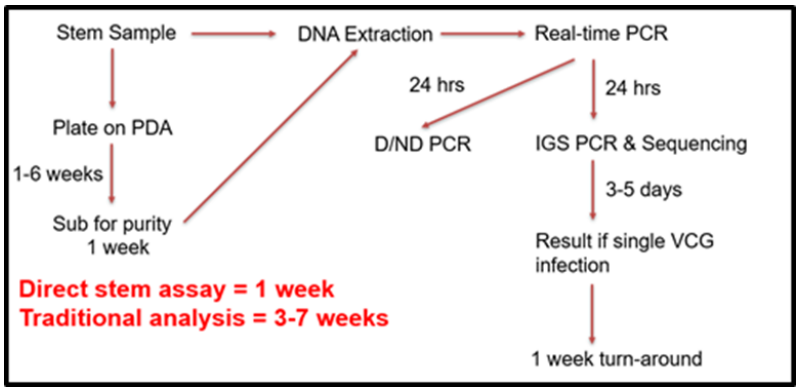


Figure 5. Flowchart comparing workflow and turn-around time for the newly developed plant tissue (direct stem) assay for *V. dahliae* with traditional methods. Utilising the direct stem assay, identification of *V. dahliae* can be achieved much quicker

Integrated management of Verticillium wilt

The management of Verticillium wilt requires an integrated approach that ultimately reduces soil inoculum levels without deleterious effects on overall soil biological health. The field trials conducted in this research have shown that rotation can reduce disease but needs to be longer than one year out of cotton where Verticillium levels are high. Two years of rotation to either non-hosts (sorghum and corn) or a bare fallow significantly reduced Verticillium levels compared to growing three years of continuous cotton. One year of rotation (corn, sorghum or fallow) on the other hand was not long enough to significantly lower disease levels. The assessment of microbial changes in the soil under the different rotations sequences suggest that management of this disease through cropping to other non-host crops that may also promote disease suppressive microorganisms may be a better option than fallow as they reduce disease incidence but also maintain overall soil biological health. A decline in overall microbial populations in the long term could potentially make soils more conducive to soil borne diseases.

V. dahliae has one of the widest host ranges of any fungal pathogen, including over 400 susceptible crop and weed hosts. It may cause classic characteristic symptoms but also can develop asymptomatic, endophytic infections. The susceptibility of some rotation crops commonly grown in the Australian cotton farming system has been largely unknown to date. Our studies have shown that grain sorghum is a non-host (previous study) and that faba bean (previous study) and cultivars of chickpea, mungbean, wheat and barley are all susceptible symptomatic hosts with some differential cultivar and strain reactions observed in some of these crops. While the susceptibility of these crops has not been proven under natural field conditions there is clearly the potential for infection to occur and close monitoring of field plants of these alternative hosts should be carefully monitored and assessed when grown in fields known to have a history of Verticillium.

To conclude, these analyses of laboratory and field-based research, have provided a wealth of knowledge to address systems questions on disease management. Research to understand management strategies that promote microbial diversity, increase specific groups of beneficial microorganisms, and reduce pathogen capability to cause disease, is required.

3.1.5 Impact on productivity and profitability

Diseases are a major constraint to sustainable production in Australia. Cotton disease impacts on profitability directly through crop losses estimated in 2014/15 at $27-75 million, as well as indirectly, through inability to plant some affected fields to cotton due to risk of significant yield losses of up to 40%.

Historically there has been a limited research focus to reduce the impact of boll rots as the impact was not well understood and believed to be only an occasional issue in Central Queensland (CQ). This project has provided the industry with new insights, given that the analyses of survey data highlighted that tight-lock had the greatest impact on yield.

Environmental conditions are the key factors in determining infection rates of boll rots. Boll rots are favoured by wet and humid conditions, especially from a thick rank canopy and high moisture

from rains and dews. Rainfall on exposed soil that splashes soil up onto low bolls enables infection for some boll rots. Low mature bolls and lodged plants are at high risk of infection.

A type of boll rot referred to as tight-lock was identified in this project as having the strongest negative relationship with yield. The main economic effect is that the boll's lint is not harvestable by mechanical cotton pickers. This disease is endemic to the south-eastern US and can cause severe yield losses up to 70% in some fields. When conditions are conducive for tight-lock development, cotton crops in CQ can be significantly affected with potential yield loss. The relationship between previous crop and tight-lock in cotton requires further investigation as a potential management strategy.

As determined on the Darling Downs in 2018/19 and in the Macintyre in the 2017/18 season, losses due to boll rots are not restricted to CQ. On the Darling Downs, at time of surveying 11% of bolls were tight-locked and 2% with seed rot and boll rot. At harvest, at least 0.5bales/ha yield loss in one field was attributed to boll rot on lower lodged branches due to rain. This equates to an estimate of $22,500 loss due to boll rot.

This project determined that crop rotation is key to reducing lost production from Verticillium wilt. For example, two successive years of corn (a non-host for *V. dahliae*) increased the subsequent cotton yield by 1.9 bales/ha. At $500/bale this equates to an additional $950/ha compared to continuous cotton. An economic study would need to be conducted to understand the full impact of crop rotation on the farm profitability, however the initial findings are very promising. Integral to the management of Verticillim wilt and associated productivity improvements was the development of the new, rapid assay plant assay to identify *V. dahliae* and, importantly, the strain.

3.1.6 Lessons learnt

This project demonstrated benefits in collaborating internationally to fast-track improvements in scientific methodology.

3.1.7 Collaboration and industry interaction

The cotton industry has historically conducted disease surveys separately in New South Wales and Queensland to monitor disease severity and spread. While this surveillance has provided industry with disease trends, improving disease management has relied on traditional R&D trials to inform management advice. This sub-project developed new digital approaches to capture disease survey data independent of state borders, and analyse it, in order to develop a holistic systems approach to the management of cotton disease.

To ensure the goal a national disease survey was achieved, quarterly meetings of the Cotton Pathology Survey Project team were convened, involving representatives from Department of Agriculture and Fisheries Queensland, NSW DPI and CottonInfo. These multi-agency meetings reviewed the progress of early season surveys and addressed any concerns participants may have had regarding the new process.

The involvement of CottonInfo on surveys has resulted in a successful collaboration in which CottonInfo now have a better understanding of cotton diseases and state pathology teams have a better understanding of regional issues directly resulting in quick and effective dissemination of research findings back to the cotton community. This has been through regional newsletters, field day presentations (CottonInfo and Pathologists), research updates at annual general meetings and Crop Consultants Australia (CCA) meetings, CottonInfo E News, industry articles and CottonInfo presentations at Cotton Seed Distributors (CSD) roadshows. A summary of the industry interaction is provided in Section 5.1.

Contacts developed in the wine industry through the project Industry Reference Group were built upon and used to inform project methods and as a soundboard for ideas.

At the international level, the project team worked with researchers and students from Texas A&M University, and our collaborators in Spain generated nit mutants used to identify eight *V. dahliae* isolates. This project demonstrated benefits in collaborating internationally to improve methodology approaches.

3.2 Yield forecasting in vineyards

Current methods used to estimate yield are typically woefully inaccurate at the vineyard block level. Most growers are not provided with any incentive to invest the time needed to produce a statistically relevant estimate. In many cases the estimate is simply an 'educated guess'. However, access to accurate estimates of the potential crop from prior to budburst through to harvest is of interest to the sector at all levels. If growers had confidence in the potential fruitfulness of the buds prior to budburst, pruning could be adjusted accordingly. Winery supply chain management relies on the accuracy of grape supply forecasts, and grape pricing is often influenced by the suggestion that supply of a variety from a region may be 'up or down' on last season.

The development of technology to improve yield estimation therefore has the potential to generate significant productivity gains for the sector. This challenge was tackled from two angles: yield estimation pre- and post-budburst. A team from the University of Tasmania [sub-project UT 1601] explored hand-held technology to non-destructively measure the fruitfulness of buds, prior to budburst, while a multi-disciplinary group from CSIRO [sub-project CSA 1602] tested various sensors to predict yield at block level once the inflorescence or bunch was visible.

3.2.1 Pre-budburst yield estimation [UT 1601]

This sub-project was conducted by researchers from the Tasmanian Institute of Agriculture at the University of Tasmania. It achieved its objective to demonstrate the feasibility of prediction of bud fruitfulness (potential yield) prior to pruning through the use of a portable hand-held device.

Knowledge of bud fruitfulness at pruning has the potential to inform better pruning decisions and in turn allow growers to prune vines according to their yield targets. However, industry lacks the ability to make a reliable, early-season prediction of yield. Yield prediction prior to budburst (at pruning) currently relies on staff to remove buds from the vines and dissect them microscopically to determine the number of inflorescences (Figure 6), which requires skill and is time consuming.

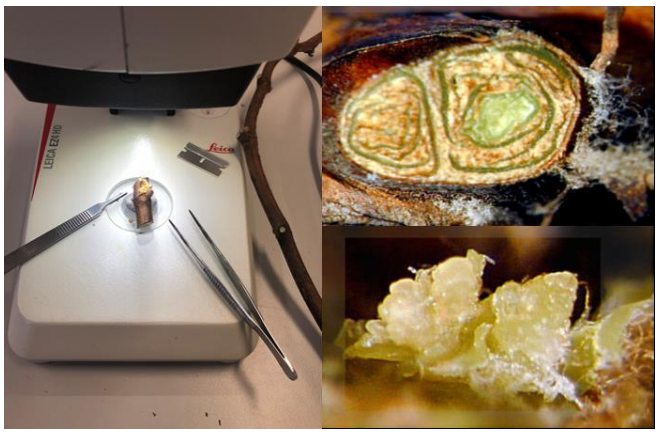


Figure 6. Longitudinal bud dissection under light microscope, exposing two inflorescences

Due to the destructive nature of this technique, the fruitfulness measures obtained can only ever be an indication of the actual fruitfulness of the buds being retained at pruning. This fact, combined with the error related to sample size limitations, has resulted in a slow uptake of bud dissection by industry. There has also been limited uptake of remotely sensed imagery for yield prediction, due to a variety of factors including cost and reliability.

Near Infrared Spectroscopy (NIRS) can be a powerful analytical technique for the rapid analysis of various compositional parameters in wine grapes, must and grapevine tissues. This study investigated the feasibility of using NIRS technology to non-destructively predict grapevine bud fruitfulness. Discriminant Analysis models to categorise buds were prepared using Principle Component Analysis reduced spectra and were compared against microscopic bud dissection data and actual fruitfulness measured in the field at flowering.

Accuracy of prediction

Accurate predictions were obtained for the bud fruitfulness of both Pinot Noir and Chardonnay varieties over 4 consecutive seasons, utilising three different instruments. As indicated by good prediction accuracy values, portable NIRS technology has the potential to predict grapevine bud fruitfulness. In the final year, the Bruker MPA instrument employed in the laboratory demonstrated an accuracy of 97% when predicting the fruitfulness of Pinot Noir and Chardonnay buds. When used to directly scan buds in the vineyard, the ARCoptics Rocket portable instrument (Figure 8) demonstrated an accuracy of 100% for predicting bud fruitfulness of Pinot Noir buds in 2018 and an accuracy of 80% in 2019 when predicting fruitfulness of Pinot Noir and Chardonnay. In 2018 when there were sufficient unfruitful buds to create a category of their own and when calibrations were prepared using ‘yes’ or ‘no’ for presence of inflorescences the prediction rate was 80% correct. This high accuracy for predicting unfruitful buds would be particularly valuable for industry.

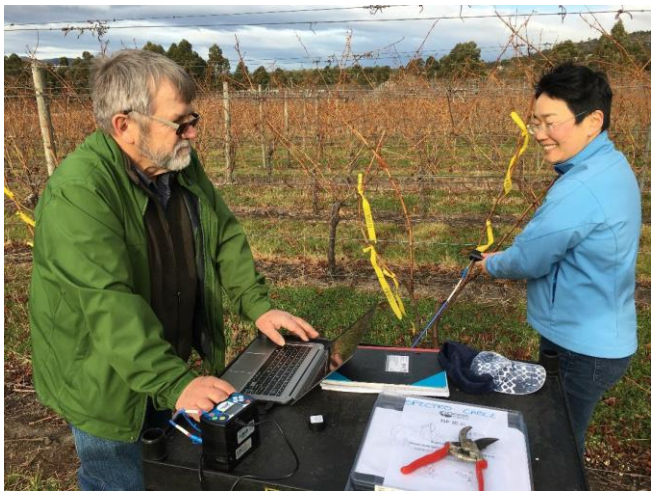


Figure 7. In the first year of scanning in the field, buds were scanned using the Ocean Optics Jaz and required two people to collect spectra

Overall, the challenges with the technique include orientation of the probe, confusion due to compound buds, and confusion created by the shoot apex contributing to the spectral signal.

Software platform

Software developed to use alongside the technology has demonstrated proof of concept that the tools can be employed in the vineyard to scan a representative number of buds and predict the level of fruitfulness to inform pruning decisions on a block level. The software can be found at https://digiviti.indicium.cloud/ A video clip to assist with demonstrating the ease of application of the research for industry was also produced https://www.youtube.com/watch?v=https://www.youtube.com/watch?v=fAa1MnR26yY



Figure 8. ARCoptics Rocket Portable NIR being used to scan buds in the field. It is a single-person operation

3.2.2 Post-budburst yield estimation [CSA 1602]

This sub-project was conducted by a multi-disciplinary team from CSIRO. It achieved its objectives of developing and testing non-destructive technologies for predicting and estimating yield following inflorescence emergence. The work presented here has demonstrated the viability of each of the approaches tested. The potential of these technologies for commercialisation in partnership with the wine industry should be explored.

The project has clearly demonstrated the viability of using colour digital video and machine learning to count inflorescences at scale in the vineyard and thereby provide a yield prediction shortly after budburst. The same method works reliably for bunch counting on green or red grapes, but needs further optimisation for vineyards with heavier canopies. Low-power radar was able to detect fruit irrespective of canopy, but its ability to reliably quantify fruit mass still needs to be demonstrated.

Two basic approaches were evaluated to estimate the amount of fruit in the vineyard. Firstly, digital video imaging was used in an attempt to image as much of the fruit as possible and, secondly, foliage penetrating radar was used to try estimate the mass of the fruit. In both cases, new data analytics needed to be developed and a data processing pipeline produced.

Digital imaging had the advantage that it needed low cost equipment and the basic tools for the data processing were available, but relied on the fruit being visible from the outside of the canopy, albeit multiple camera angles could be used. Further, calibrations were required to convert the fruit visualised to mass. Foliage penetrating radar (FoPEN) had the potential to directly measure fruit mass through the canopy, but required new hardware, new data processing tools and was an unproven method for this purpose.



Figure 9. Left: An array of Go-Pro consumer video cameras mounted onto a vineyard vehicle and used to capture video of inflorescences and bunches to estimate yield. The number of cameras mounted and used for a given run varied. Right: Low-power radar system (white panel at driver's right shoulder) in use in the vineyard.

As described above, the yield component with the largest inter-annual variation is bunch number and, in the absence of bunch mass data, could be used with knowledge of historical yield components to make a yield prediction. Consequently, the major effort of the digital imaging work was to achieve an accurate estimate of bunch number.

Inflorescence counting

Over 800 individual video frames, from three different vineyard blocks, taken under various sky conditions and view angles were hand labelled for the location of inflorescences. A subset of these were publicly released under a Creative Commons license https://doi.org/10.25919/5de4546aeacce.

Image labelling and optimisation of the detector is continuing, to improve the range of vineyards and image collection conditions for which it is effective, but at the time of writing recall was over 85% and precision over 80%.

Bunch counting

The same methodology was used to estimate bunch number later in the season. The work concentrated on two time-points, pre-veraison, whilst the berries were still green and, therefore, more difficult to differentiate from the canopy, and pre-harvest, when the fruit were fully coloured and the bunches at their largest. At both time-points the images from sprawl or loose vertically shoot positioned (VSP) vineyards exhibited significant occlusion of bunches. Self-shading also sometimes made identifying bunches in the images difficult.

To assist with these difficulties, a classification system was added to the manual labelling, with “full”, “partial” and “hidden” classes. The full class representing exposed bunches, partial representing bunches where only a few berries were visible and hidden representing potentially perceived fruit where it was uncertain whether fruit were there, primarily in dark shaded areas of the image.

The precision and recall of the two detectors trained were lower than for the inflorescence detector, likely due to the smaller number of input images and more difficult task due to varying occlusion and the use of classes, but of a similar magnitude.

Moving from digital ground truths to field estimates

The results above compare the number of objects detected by a human in a video frame with those detected by the machine learned detector. However, although still images can be used to make spot in-field estimates, the aim of the work and the reason for videoing entire rows was to count at scale, whole rows or whole vineyards. In the videos, each inflorescence was seen in many frames from slightly different angles and a process needed to be developed to account for this. These multiple views were in fact beneficial as it gave multiple opportunities for an inflorescence to be seen and counted, even where it might be occluded from one viewpoint. Two methods were trialled to account for this: tracking and mosaicking.

The initial tracking algorithm was improved by adding a machine learning step which reduced count error from about 20% to approximately 5% for inflorescences (Table 2). A still from a demonstration video, with inflorescences being counted, is provided in Figure 10.

Table 2. Inflorescences detected by machine-learning enhanced tracking-detector pipeline compared to human field counts for sample rows from two vineyards

Rows	Human counts	Sensor method	Error
1	2,628	2,742	4.3%
2	2,516	2,390	-5.0%
3	2,241	2,109	-5.9%
4	2,337	2,288	-2.1%
5	5,917	5,598	-5,3%

The development of the tracking algorithm was undertaken using the inflorescence videos and detector, but it was also applied to the videos for bunch counting. The error rates were higher in bunches than for the inflorescences, but the tracking still needs to be further tuned for use with bunches.

The mosaicking approach worked by taking only a small portion of each video frame and producing a mosaic where each part of the row only appeared once. This was conducted as a proof of concept with a very limited number of labelled ground truth images and was successful, albeit with reduced precision and recall compared to the results above. It is likely that a larger effort to label images and optimise the detector would improve this.



Figure 10. Frame from video taken at E-L 14 growth stage with detected inflorescences and their count overlaid. Note the success of the machine-learning enhanced count despite the complex background as a result of the background vegetation.

In summary, the combination of the detector and tracking algorithm developed through this research offers a real opportunity to estimate inflorescence and bunch number in commercial vineyards at scale, with multiple rows or whole blocks able to be quickly imaged. The processing is computationally intensive, but could be implemented on recent consumer devices based on GPUs.

Bunch mass with foliage penetrating radar (FoPEN)

An experimental system was developed to test whether radar could be used to discern berries from foliage. The success of this proof-of-concept lead to several field tests during the 2017/18 and 2018/19 seasons with different radar sensors (Figure 9). Most of these tests involved scanning part rows with different arrays and array positions on the vehicle, then removing sections of leaves and/or fruit. A software tool was developed to visualise the complex signal as the radar sensor moved down a row. At the time of writing that data has not been fully analysed, but shows promise in the detection of obscured bunches within the canopy. It remains to be seen whether FoPEN can be used to quantify the mass of fruit present.

3.2.3 Impact on productivity and profitability

Access to accurate estimates of the potential crop from the period prior to budburst through to harvest is of interest to the sector at all levels. If growers had confidence in the potential fruitfulness of the buds prior to budburst, pruning could be adjusted accordingly. Winery supply chain management relies on the accuracy of grape supply forecasts, and grape pricing is often influenced by the suggestion that supply of a variety from a region may be 'up or down' on last season. According to the recent ACCC market study of the wine grape sector[3]:

> ***"Seasonal deviations from expected harvest yields can impact the level of market supply and the amount of inventory held by winemakers. This, in turn, influences grape prices."***

At present, yield estimation is a subjective assessment with very small sampling sizes compared to vineyard size. This commonly results in errors at the block level of up to 30%, resulting in an under or over supply to the winery. Knowing the yield accurately ahead of harvest allows a winery to better plan intake and adjust for over or under supply of a variety. The cost of yield estimation post budburst was previously estimated to be $16/ha, but increases in wage rates and the high error rates mask the true cost. It has been suggested that a reduction in the yield estimate error from 33% to 20% would amount to a saving of $85 million per year[4]. Further improvements would magnify the savings.

Sub-projects UT 1601 and CSA 1602 have developed technologies capable of improving yield estimation for the sector, however they are at TRL of 2 - 5 (Table 3) and require further development prior to potential commercialisation. Industry will assist in prioritising the technology created within

[3] Wine grape market study. Final report (2019) Australian Consumer and Competition Commission https://www.accc.gov.au/system/files/1612RPT_Wine%20Grape%20Growers%20Final%20Report_D03.pdf

[4] Clingeleffer, P.; Dunn, G.; Krstic, M.; Martin, S. (2001) Crop development, crop estimation and crop control to secure quality and production of major wine grape varieties: a national approach. Final report to Wine Australia

CSA 1602 for further development. The success of UT 1601 opens the possibility for the development of a low-cost, custom-built device based on LEDs to measure bud fruitfulness. It is anticipated that the results of this project can inform a final investigation aimed at commercialisation and the custom manufacture of device available to industry at an affordable cost.

Table 3. Technology readiness level[5] (TRL) of the developed yield estimation tools

Sub-project	Technology	TRL
UT 1601	Bud fruitfulness from hand-held NIR scan	5-6
CSA 1602	Yield estimation from video capture of inflorescences	4-5
	Yield estimation from video capture of bunches	4
	Yield estimation from 2.5/3D RGB information	3
	Direct estimation of yield using radar	2-3

3.2.4 Lessons learnt

Execution of the agreement for CSA 1602 took longer than planned which delayed the start-up of the project and meant that much of the first growing season was missed.

This project brought together previously disparate groups within CSIRO and a number of wine companies with sites across South Australia. While this has been a highly successful endeavour, the time required to ensure that all parties had a common understanding was more than expected and a greater allowance in the project planning for this may have eased the project start-up.

Whilst CSIRO is uniquely placed in Australia to bring together diverse teams from different research areas, it was still necessary to bring mechatronics and coding expertise into the domain knowledge team at CSIRO Agriculture & Food as part of the technical support. This was only partially anticipated and probably delayed the optimal team structure being established.

3.2.5 Collaboration and industry interaction

The CSA 1602 project team has maintained a dialogue with the industry partners (Accolade Wines, Rymill, Wingara Wine Group), the Industry Reference Group (including members from a number of wine companies) and presented work at key industry events, such as the Australian Wine Industry Technical Conference and Exhibition. The team are also in active discussions with Wine Australia about pathways towards commercialisation of the most suitable technologies.

The CSIRO project team collaborated with a number of industry partners (see above) and undertook informal discussions with the TeleVitis team at the University of Rioja, who are developing related technologies for the Spanish wine industry, about future interaction, particularly in the area of hyperspectral imaging of vineyards. These collaborations are aimed at supplementing Australian skills

[5] Technology Readiness Levels (TRLs) are a numerical classification of the status of the development of a technology, with range in ranking from 1 (least developed) to 9 (actual system proven in operational environment).

and know-how with relevant overseas experience to provide additional resources and thereby improve the efficiency of developing tools for Australian growers.

Although not formally listed in the original funding application, a discussion with Accolade Wines to undertake work described in this report at their McLaren Vale vineyards pre-dated the project. Further collaboration with commercial wine companies and grape growers was critical for field testing of equipment and methodologies in a commercial setting. In addition to the collaboration with Accolade, the project leads arranged to work with Wingara Wine Group and Rymill from the Coonawarra region. The Woodside vineyard managed by Adam Loveys provided access to some highly managed vines of alternative varieties, but was unfortunately lost in the 2019/20 season bushfires, prior to the end of the project.

It is important also to note that the project facilitated high levels of collaboration within CSIRO, with three different groups based in three different states coming together to generate novel hardware and data processing pipelines that would have been difficult to undertake within CSIRO Agriculture and Food alone.

The collaboration with Accolade will continue through a CSIRO-Wine Australia project to undertake further development of selected technologies from this project and assessment for commercialisation potential. It is anticipated that the collaborations with Wingara Wine Group (through their Katnook Estate winery) and Rymill will also continue. The results of the University of Tasmania project will also inform an assessment of the commercialisation potential of a hand-held bud fruitfulness detector for grapegrowers.

The University of Tasmania team worked closely with Tolpuddle Vineyard who provided access to the field site for the life of the project and with viticulturists Carlos Souris and Wendy Borg. They also partnered with a local software development company (Indicium Dynamics) to create a software platform for use with the NIR technology. The software platform was designed to demonstrate to growers how the tool works, and then with a log-in, provide an interface for entering vineyard details, capturing data, and reporting a bud fruitfulness prediction for each block analysed. Mark Whitty's research group from the University of New South Wales collaborated by calculating flower number in inflorescences using their in-house technology.

List of collaborators

Taking grapevine yield forecasting into the digital age [UT 1601]

- Lead research organisation: The University of Tasmania
- Collaborators: Tolpuddle Vineyard, access to vineyards; Indicium Dynamics, software design; LasTek, NIR instrument advice; Carlos Souris and Wendy Borg, product design

New non-destructive technologies for simultaneous yield, crop condition and quantity estimation [CSA 1602]

- Lead research organisation: CSIRO
- Collaborators: Accolade Wines, Rymill, Wingara Wine Group, Adam Loveys: access to vineyards and support with field trials; University of Rioja

3.3 Measure vineyard canopy, nutrition, microclimate, grape defects and disease

The objective of this area of research was to develop and evaluate sensors and associated data processing pipelines to assess key vineyard management parameters (canopy growth, incidence of pre-symptomatic disease, vineyard microclimate, vine nutritional status) non-destructively and on-the-fly, and to assess grape condition on delivery to the winery.

The unique aspect of this work is the assessment of these parameters on a whole-vineyard scale, non-destructively, and using sensors which are fitted to a vineyard vehicle, drone or aeroplane. For example, the current method for determining the nutritional status of a vineyard block is to sample *c.* 30 leaves and have them analysed. The technology described below shows potential to predict the status of key nutrients in each vine across the vineyard, using imagery obtained from a hyperspectral sensor fitted to an aeroplane.

3.3.1 New technologies for dynamic canopy and disease management [CSA 1601]

This sub-project was led by CSIRO. It was established to test and develop technologies to provide non-contact measurements of canopy size and structure, vine nutrition, canopy function and pre-symptomatic detection of disease.

LiDAR, stereo-imaging, photogrammetry (structure-from-motion) from consumer drone and photogrammetry from consumer action-cams were all used to collect 3D data on vine canopies and structure. In addition, consumer action-cams were also used to estimate canopy size from continuous video. All these devices (except the drone) were mounted on commercial vineyard vehicles and used to image commercial vineyards in collaboration with several wine companies. Data-processing pipelines were developed in all cases to produce grower-relevant data from the sensor outputs.

Hyperspectral imaging of the same vineyards from fixed wing aircraft was undertaken by Fraunhofer IFF with Airborne Research Australia, using a bespoke imaging system built by Fraunhofer. Additionally, a lab-based hyperspectral imaging system was used to develop detailed calibrations of vine nutrition against leaf images. A laboratory hyperspectral system, mounted in a glasshouse, was used to image grapevines with various stages of powdery mildew infection and calibrations against disease status developed.

This project encompassed a significant amount of work by a large, geographically dispersed, team across a broad range of technologies and industry targets for digital viticulture. The reporting of project achievements below is necessarily a brief summary of that work. The project achieved its objectives of developing and testing technologies for 3D imaging of vineyard canopy structure, of developing and testing hyperspectral imaging methods for assessing vine nutrient status, and of testing hyperspectral methods for pre-symptomatic disease detection. The project utilised three sets of paired vineyards with different fruit qualities (as assessed by the wine style targeted by the

grower) in order to assess the potential for altering canopy management to improve fruit value, although that potential outcome is not directly addressed in this report. With the exception of pre-symptomatic disease detection, the research demonstrated the viability of each of the approaches tested and it is recommended that the potential of these technologies for commercialisation is assessed in partnership with the wine industry.

Technologies to assess and contrast canopy structure

Canopy management is an important tool in viticulture as it affects vine carbon acquisition and fruit quality. Due to its three-dimensional nature there are few existing tools or methods to assess canopy structure and these are impractical for grower use. The project used and developed a variety of hardware to make 3D measurements of vineyard canopies, including static LiDAR, hand-held LiDAR, trawling LiDAR mounted on the GRover vine phenotyping platform, vehicle mounted spinning LiDAR, vehicle mounted consumer action video cameras and consumer UAV video imaging.

LiDAR

Seven different LiDAR devices were tested, including three devices designed and built by CSIRO Data61. These were iterations of the AgScan3D+ (a spinning LiDAR) system and included one based on a Hokuyu UTM-30LX sensor, the second on an ASI Forecast LiDAR, whereas the third was based on a Velodyne Puck LiDAR. These ASI Forecast system was used for the majority of the project. They were vehicle mounted (Figure 11) and easily able to scan a small vineyard block in around 30 minutes.



Figure 11. The ASI Forecast-based spinning LiDAR mounted to the forward-facing edge of the tractor roof, being tested on an industry collaborator's vineyard in McLaren Vale, South Australia

The light absorbing area of the canopy is the major determinant of vine production and water use for a given environment and thus it was decided that single-sided leaf area per volume of 3D space would be the most flexible parameter to determine from the AgScan3D+ data, as it could be

used for canopy density and area (or LAI) determinations. A mathematically determined relationship was developed between leaf area in 3D space and the proportion of laser returns to rays passed through, and tested with simulated data. The output from this was a 3D dataset, with an estimate of leaf area per volume of 3D space (m^2m^{-3}). The data could be represented by a point-cloud with one point per 12 cm cube and the point value being the leaf area density (Figure 12).

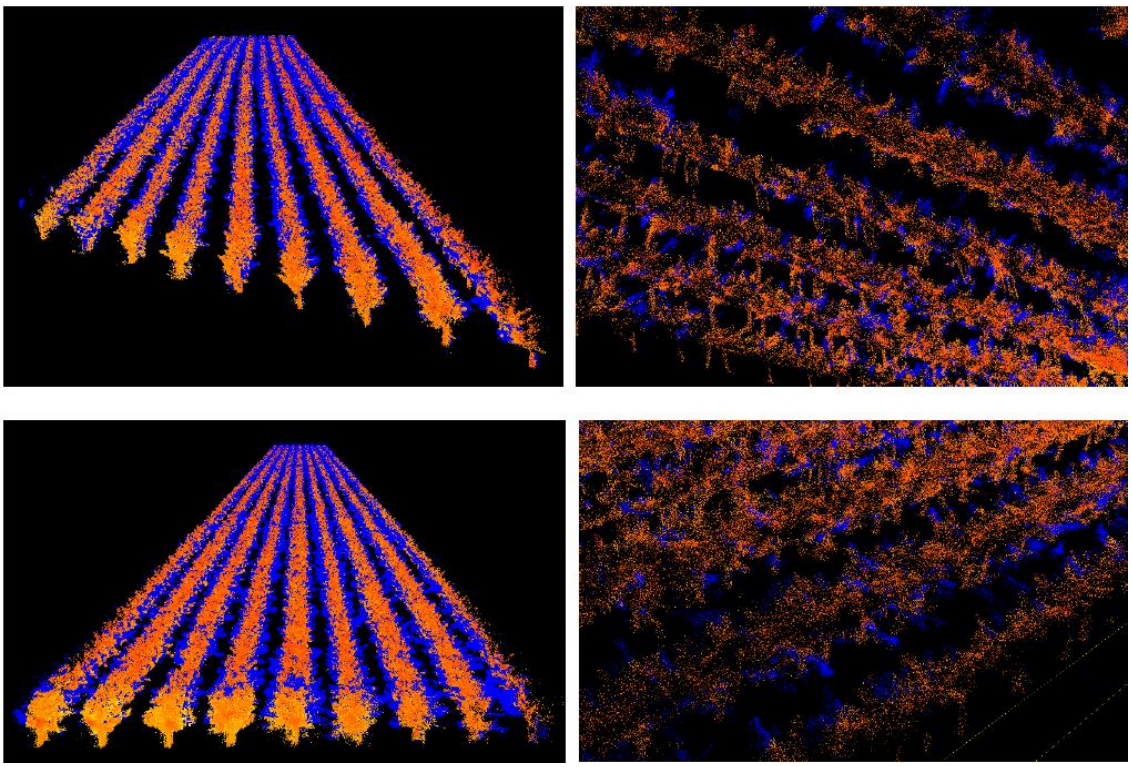


Figure 12. Representation of canopy density as a coloured point-cloud with colour (from blue to red) representing density. Several rows of vineyard block (left two panels), view from underneath the vineyard with ground removed (top right) and view from above (bottom right)

Go-Pro video cameras

In contrast to the instrument development required for LiDAR use, the second approach was to use off-the-shelf 'action cams' to record video and then a range of computational analyses to infer canopy information from the videos. Standard Go-Pro cameras (various models, Hero5 – Hero 7) were mounted either looking almost directly up through the canopy or at various angles facing the canopy (Figure 9). Imaging was undertaken at all sites and at various times during the 2017/18 to 2019/20 growing seasons.

A data pipeline was developed to extract metadata and corresponding video frame, exclude neighbouring vine rows and categorise pixels either sky, leaf, post, wood or grapes. The gap fraction of the resulting image can then be estimated by excluding non-leaf elements, producing a LAI of the canopy only – effectively a density estimate (Figure 13).

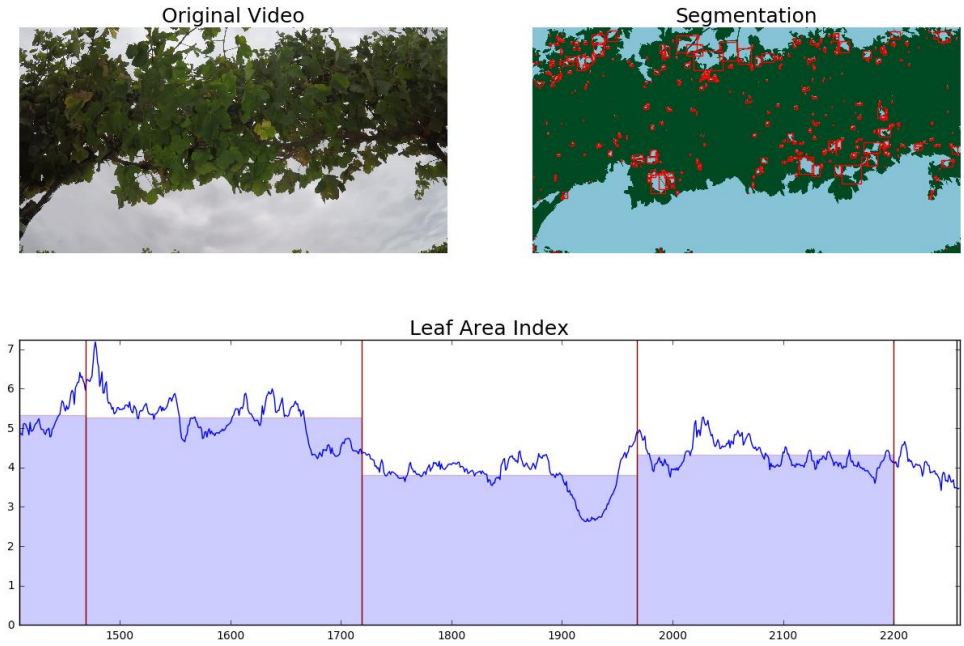


Figure 13. Video still, colour segmented image and trace of LAI estimation from gap fraction. The trace represents LAI estimates assembled from sequential Go-Pro video frames taken down a vine row

Drones

A significant advantage to using a drone over other techniques for looking at canopy size is the ability to rapidly get data on a large scale, e.g. a 4 ha vineyard block can be flown in under 20 minutes from an altitude of 30 m. Disadvantages include the short flight time due to battery limitations with most drones and regulatory compliance – the same issue likely to limit uptake of the sensor technology described in Section 3.3.3. To maximise the potential uptake of a drone-based technique to assess the canopy, a standard consumer drone (Phantom 4+, DJI) with a built in RGB video camera was used. The drone was flown at various times during the 2017/18 to 2019/20 growing seasons. Even with this equipment, the pixel size was more than small enough to produce accurate canopy measures, being <1 cm.

The research developed a pipeline to generate a spatial map of canopy cover from drone imagery. Instead of using commercially available software to generate the RGB point-cloud, the team opted to use the freely available open-source 'OpenDroneMap' tool to maximise the potential for a comprehensive package to be developed with minimal encumbrances. The pipeline produces data that can be mapped as the user prefers and be adapted to other purposes, such as estimating 'wire-fill'.

Assessing vine and vineyard nutrition status

The project took two approaches to assessing nutrient status. Firstly, a ground-based approach with the aim of using proximal hyperspectral imaging in the field and, secondly, aerial hyperspectral imaging with a fixed wing manned aircraft.

Ground-based imaging

The ground-based approach was used controlled laboratory conditions to build detailed spectral calibrations against key nutrients. Hyperspectral scans of 200 leaves were paired with nutrient analysis of the samples and used to build calibrations for 13 nutrients, with nitrogen being best predicted. The data suggest that with an expanded calibration set it may be possible to develop a useful prediction for K, Mg, P and Zn.

Aerial imaging

Two sets of flights were undertaken as part of the collaboration with Fraunhofer IFF (Germany), one in the 2017/18 growing season and one in 2018/19. The flight missions were conducted by engineers from Fraunhofer and Airborne Research Australia (Flinders University). The Fraunhofer hyperspectral imaging system was fitted to the wing of an ECO Dimona aeroplane. The system produced resolutions of about 40 cm per pixel, enough to separate canopy from the vineyard floor cover crop, and 400 wavebands from visible to shortwave infrared (SWIR). However, as the aerial imagery was easily able to cover multiple hectare vineyard blocks it created an unexpected difficulty in sampling statistically relevant ground truth data to build a calibration.

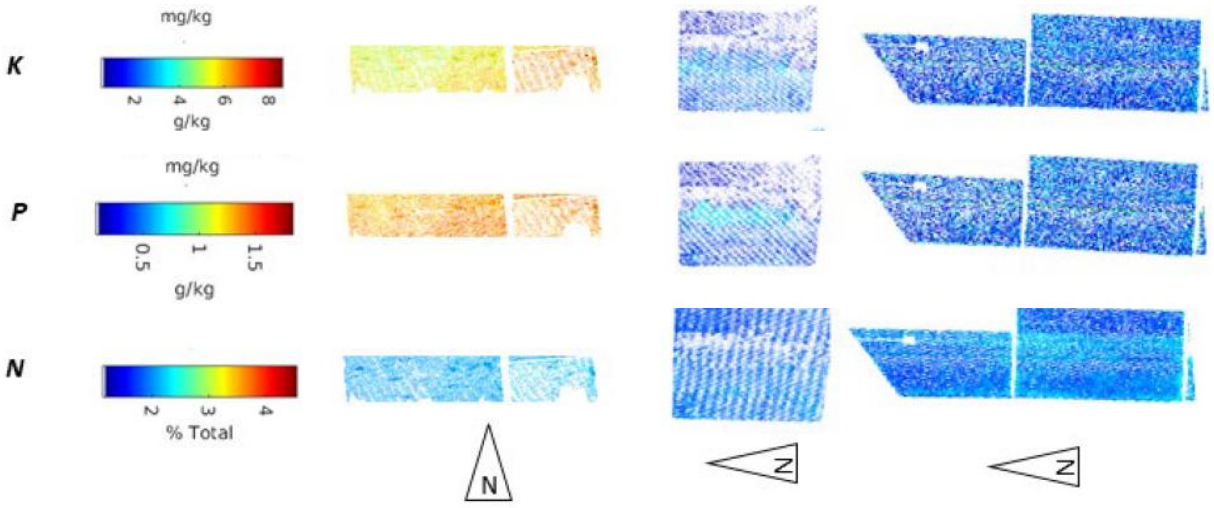


Figure 14. Visualisation of whole block N, P and K data for paired Accolade Wines, McLaren Vale blocks (left), Katnook Estate, Coonawarra (centre) and paired Rymill, Coonawarra blocks (right)

This part of the project demonstrated the potential to use aerial hyperspectral imaging for assessment of vine nutrient status at scale (Figure 14). Significant further sampling would be required prior to a commercial rollout of a service based on this type of instrument. However, once calibrations across a broader range of vineyards are generated it is likely that service providers using fixed winged aircraft should be able to use NIR/SWIR instrumentation to provide spatial data on vine nutrient status, thereby assisting growers to optimise fertiliser application.

Viability of early disease detection with hyperspectral imaging

Powdery mildew was targeted as it is the most prevalent fungal disease affecting vineyards in Australian viticulture. To build a library of spectra from pre-symptomatic leaves required inoculating leaves with fungal spores and then regularly scanning them to find leaves and/or areas

of leaf which succumbed to the disease. Initially, this was done using individual leaves isolated in Petri dishes. The leaves were scanned in situ daily, with the dish lids removed, using the lab based hyperspectral camera system described above.

The single leaf assay was subsequently replaced with whole vines in a glasshouse environment. This was due to the concern that data analysis may be unable to differentiate the accelerated senescence of the infected leaf from senescence of a non-infected leaf and thus that results would only be applicable where a known inoculation had occurred (Figure 15).

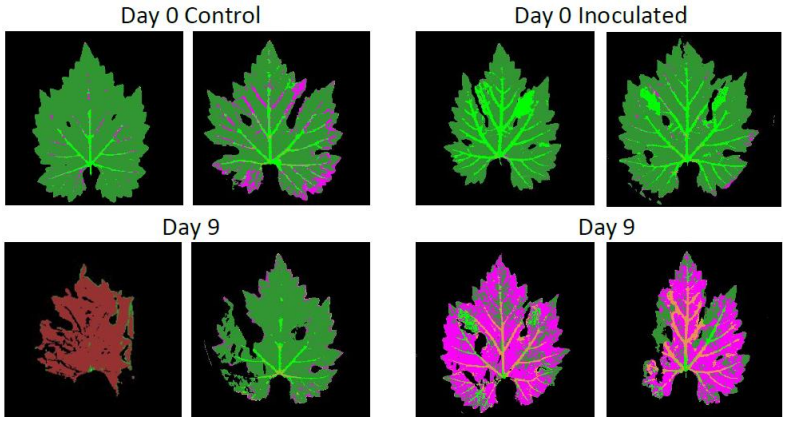


Figure 15. Classification of hyperspectral image pixels as leaf (dark green), vein (light green), senesced tissue (brown) or infected tissue (pink). Leaves were non-inoculated (left) or inoculated (right) and the same leaf was imaged immediately after inoculation (top) or nine days after (bottom)

The new method used potted vines in a glasshouse located in two separate chambers. In one group, the leaves were inoculated with powdery mildew; the other group was the uninoculated control. In order to scan the vines in the glasshouse a Headwall hyperspectral camera was built into a larger field instrument with halogen lighting and mounted on a 2 m linear stage. The vines were then each scanned from three angles, 90° apart. A variety of statistical and machine learning approaches were assessed for their ability to indicate the sites of mildew infection. The data from these later experiments are yet to be analysed and results will be reported as part of a follow-on project between CSIRO and Wine Australia (CSA 1702-3.1).

3.3.2 Digital solutions for grape quality measures at the weighbridge [AWR 1601]

This sub-project was conducted by a team from the Australian Wine Research Institute. It achieved its primary objective to develop technology for rapid assessment of grape quality on delivery to the winery, in particular the detection of *Botrytis*-infected grapes and the presence of matter other than grapes (MOG) in mechanically harvested loads. A secondary objective was to determine whether these methods could also be applied in vineyards for non-destructive *Botrytis* assessment of grapes on the vine.

Infection of wine-grapes with *Botrytis cinerea* typically causes rot which may substantially reduce both quality and yield and can promote growth of other spoilage organisms. Current methods for the quantification of *Botrytis* infection rely on subjective or semi-quantitative assessment, and the task is challenging even for skilled assessors. If bunch rot is present in the load but not observed, the value of the resultant wine may be reduced by 50%. MOG is often present in the mechanically harvested load when it arrives at the weighbridge. It can consist of items such as leaves, petioles, canes, grapevine wood, insects and vine trellis material. Excessive MOG can cause taints and other quality problems and large foreign objects can cause damage to processing equipment. MOG is also assessed visually.

The development of a process to objectively measure Botrytis bunch rot and MOG will provide greater transparency of the assessment process and help prevent the production of poor quality wine. Hyperspectral imaging has recently been shown to have potential for this purpose.

Selection of sensors

A hyperspectral camera collects information from a large number of wavelengths, and this information is stored as a spectrum in each pixel of a digital image. The initial focus was to develop a proof of concept and establish the critical wavelengths for the identification of disease-affected grapes. This research was laboratory-focused and used a Specim FX10 hyperspectral camera (a linescan 'pushbroom' type camera where either the camera or the sample needed to be moved in order to collect an image). The linescan camera covered the 400-1000 nm wavelength range and could discriminate clean and infected red and white grapes, for both laboratory infections and field samples (Figure 16).

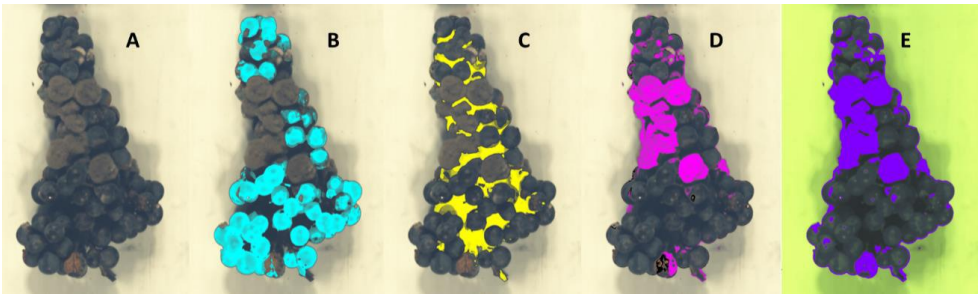


Figure 16. RGB image of a *Botrytis*-infected Merlot bunch (A); false colour overlay of hyperspectral analysis (400-1000 nm) showing uninfected berries (B), shadowed internal spaces (C) and infected berries (D). False colour overlay of multispectral analysis (550, 650, 850 nm) highlighting infected berries (E).

The calibrations were not dependent on growing region, grape variety and *Botrytis* strain. Hyperspectral imaging could also discriminate *Botrytis* infection from sour rot (mixed fungal and bacterial infection of grapes). Hyperspectral imaging could also identify sunburn in white grapes (Figure 17) and shrivel in red and white grapes.

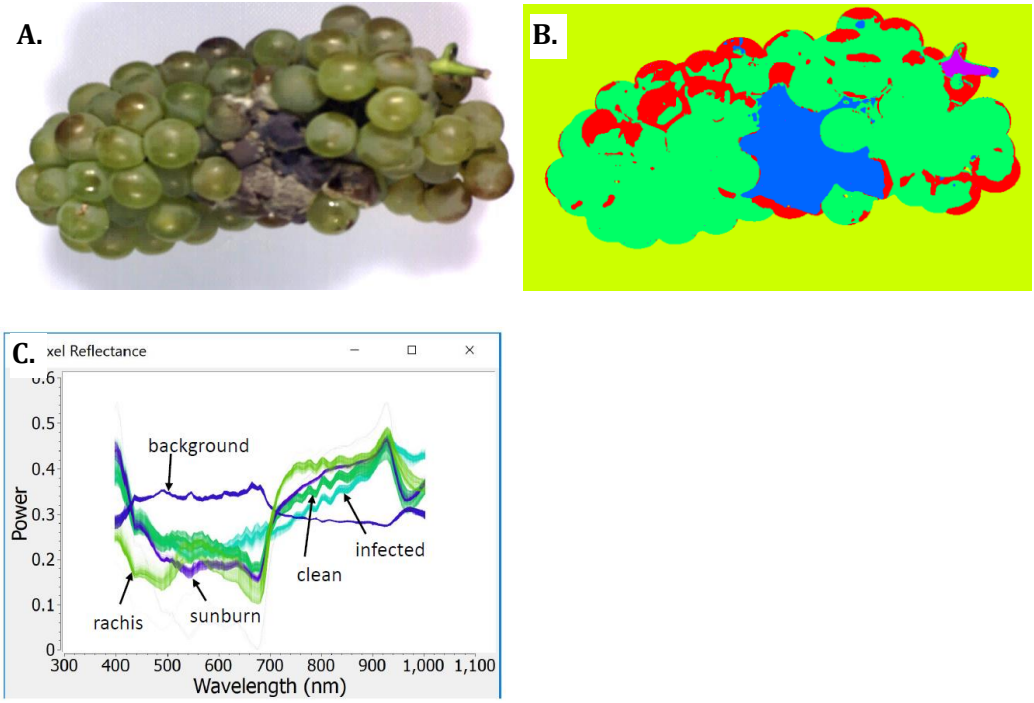


Figure 17. Standard RGB image (A) and false colour overlay of hyperspectral analysis (B) of grapes classified as either clean, infected or sunburnt and bunch rachis (stem). Spectral libraries for the categories (C). Key wavelengths (selected as regions of difference) were 560, 760, 950, 1000 nm

The spectra of materials to be classified were distinct and had broad peaks. This enabled the selection of a small number of wavelengths for use in a multispectral camera – an Ocean Optics SpectroCam. The multispectral camera worked in snapshot mode (the camera or the sample did not need to be moved to collect the image) and produced smaller and less computationally intensive images. It was therefore better suited to be deployed at the winery than the hyperspectral linescan camera. The multispectral camera created eight separate single band images, centred on wavelengths selected from the hyperspectral imaging (444, 531, 680, 717, 790, 860, 918, 972 nm). Two types of lighting were trialled; when halogen lighting was used images could be recorded using all wavelengths, while LED lighting produced insufficient output in NIR wavelengths so only the first four bands could be used. When the samples were displayed on a board both the LED and halogen lighting were sufficient to allow *Botrytis*-infected fruit and MOG to be distinguished. However, for bulk samples, where there was more variable shadowing within the image, only the halogen lighting was suitable.

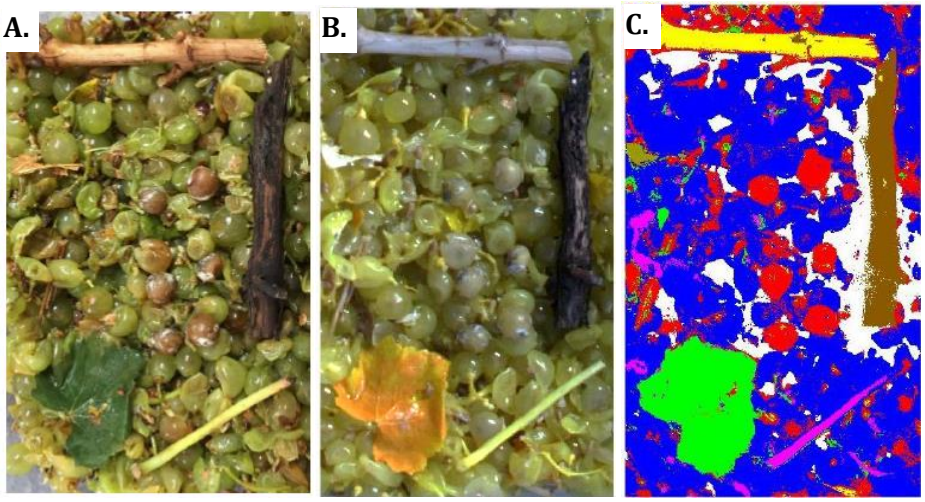
Validation at the weighbridge

Simulations were conducted both in the laboratory and at a winery intake testing station (the weighbridge). Both hyperspectral and multispectral imaging could discriminate the components

that often form mater other than grapes (MOG) in mechanically harvested grape loads (i.e. canes, wood, petioles, leaves, and insects.

It was not practical to collect images from the top of loads of grapes prior to their unloading at the winery as the sample needs to be presented on a flat plane and in a well-lit environment to minimise the influence of shadows. Instead, large samples (20 kg) were collected from the loads using a pre-existing sampling system, and displayed on trays for imaging. Tests under field conditions at a winey intake testing station indicated that imaging could be performed with halogen lighting under varied ambient lighting conditions but imaging in full sun required constant changes to camera exposure settings and daylight cast long shadows as the day progressed which made the images difficult to analyse.

The proportion of the image attributed to clean and disease-infected grapes was able to be determined using both the hyperspectral and multispectral systems (Figure 18). There was a close correlation between the proportion of the image that was classified as disease-infected and the number and weight of infected berries in a sample.



D.

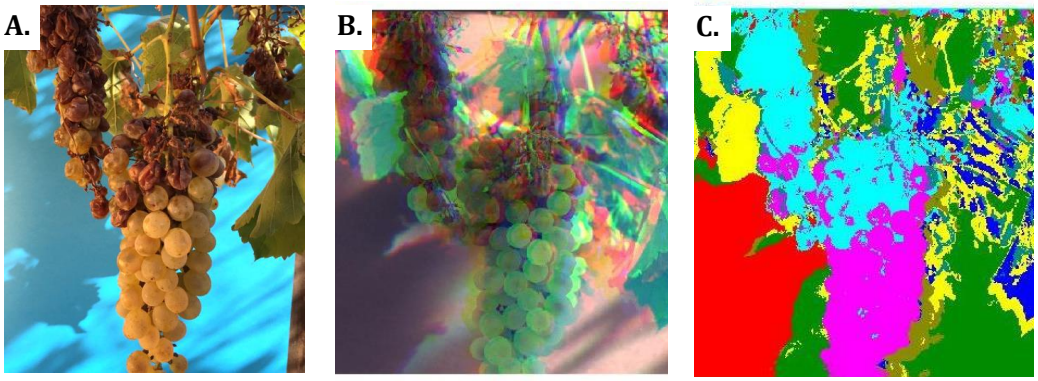
Class Summary	Pixel Count	Percent
Unclassified	0	0.00
shadow	55691	11.08
dead leaf	1652	0.33
wood	28151	5.60
infected	82302	16.38
clean	262020	52.14
cane	17562	3.49
petiole	11192	2.23
leaf	43946	8.75

Figure 18. Hyperspectral imaging with SpectroCam using halogen lighting and all eight filters. Standard RGB image of mechanically harvested Colombard (A); SpectroCam image (false RGB) (B); Spectral classification including a spectral library for dark shadows. When no spectral library for dark shadows was included some shadows were classified as infected grapes. When a spectral library for dark shadows was included, some grapes in shadow area were not classified, some wood in light shadow was classified as infected, some wood was classified as shadow, edge effects on objects remained. Some natural infection in the sample was identified.

Assessment of *Botrytis* in the vineyard

The multispectral camera was also tested in the vineyard by taking images of infected grapes on the vine (Figure 19). Multispectral imaging could discriminate infected grapes, clean grapes and grapevine tissue but the system was not practical as the camera filter wheel needed a stable voltage to synchronise well, so a generator was needed. Each wavelength requires manual exposure control, making shifting ambient light from the sun a problem. Sample movement within the canopy was also an issue as the camera takes separate images of the same scene for each filter.

The *RotBot* app was also tested in the vineyard. While *RotBot* can discriminate clean and *Botrytis*-infected white grapes, it has its limitations. Firstly, the image must be taken against a blue background. In addition, for correct classification, grapes must only be visible in the image: bunch rachis, petioles, immature canes were classified as clean grapes; lignified canes, grapevine bark, dried petioles, dried leaves, sunburnt or shrivelled grapes and powdery mildew berry scars were classified as infected grapes.



D.

ROI Summary	Pixel Count
dark background	123563
light background	40813
leaf top	17596
leaf bottom	22275
infected	8269
clean	10071
cane	1696
stem	1162

Figure 19. Multispectral imaging in the vineyard with SpectroCam. Images were taken with a blue background, and a combination of natural and halogen lighting. RGB image (B); SpectroCam false RGB image (A); False colour image of spectral classification (C); pixel count summary shows 46% of the bunch surface is infected.

3.3.3 Use of UAVs for early, real time detection of extreme weather events in vineyards [USA 1601]

This research was conducted by a team from the University of South Australia. The objective was to develop technology to provide measurement of whole vineyard microclimate at a sub-metre scale. This knowledge would inform management decisions to protect the crop against damage from weather-related stress. One of the project outputs (*7d: Prepare recommendation material and information in a form suitable for delivery to farmers*) was only partially achieved. While recommendations have been provided through the Implementation Plan (below), given that the system is not 'grower-ready' these will not be promoted until an assessment of the commercialisation potential of the technology is completed.

The research used a technique known as atmospheric acoustic tomography (AAT) coupled with long wave infrared (LWIR) thermography to characterise the vineyard microclimate. The AAT system investigated was based on a commercially available unmanned aerial vehicle (UAV) fitted with sensors that measure the sound of the UAV as it flies autonomously over the vineyard. A two-dimensional array of microphones deployed throughout the vineyard also measure the sound generated by the UAV as it flies. Each microphone measurement of sound is time-matched to that measured onboard the aircraft and, from the correspondence relationships, subtle variations in sound speed for the signals propagating between the UAV and each ground sensor computed. A depiction of the concept in 2D is shown in Figure 20. Measurements for a 10 ha block take approximately 10-15 minutes.

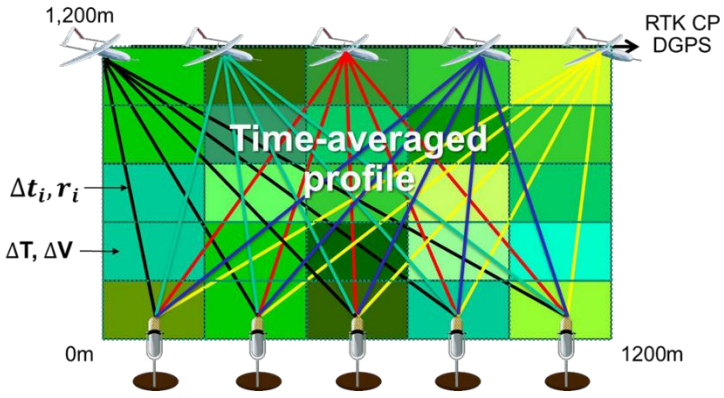


Figure 20. Graphical depiction of acoustic atmospheric tomography. As the UAV overflies an array microphones on the ground, the propagation delay, Δt_i, for the i^{th} ray (of length r_i) may be computed from the correspondence of the sound fields measured synchronously by them and a microphone onboard the UAV. The intersection of the rays allows 'elements' of the atmosphere to have their temperature (T) and wind velocities (V) computed.

Validation of technique

To assess the accuracy of the AAT, the results obtained through tomographic inversion were compared to a ZephIR LiDAR. Over a period of 5 days, field trials were conducted near Rowland Flat in South Australia. The days were hot (max > 40°C) with moderate winds (5 – 10 m/s). The UAV was repeatedly flown at an altitude of up to 120 m above a 300 m x 300 m array of 49 microphones. A DJI Phantom IV UAV carrying two iMet-XQ sensors was also repeatedly flown

around the perimeter of the microphone array between an altitude of 20 m and 120 m. Position (based on SPS GPS), thermodynamic temperature, pressure, and relative humidity were recorded at 1Hz.

The AAT and UAV/LiDAR measurements had correspondence accuracies of around 0.5°C for temperature and 0.3 m/s for each component of wind velocity (Figure 21), respectively. This compares very favourably to other inter-instrument atmospheric comparisons, such as LiDAR *vs* SODAR and is within the measurement errors of the system. Optimisation of the procedures used in the AAT and a more detailed analysis of this data is ongoing.

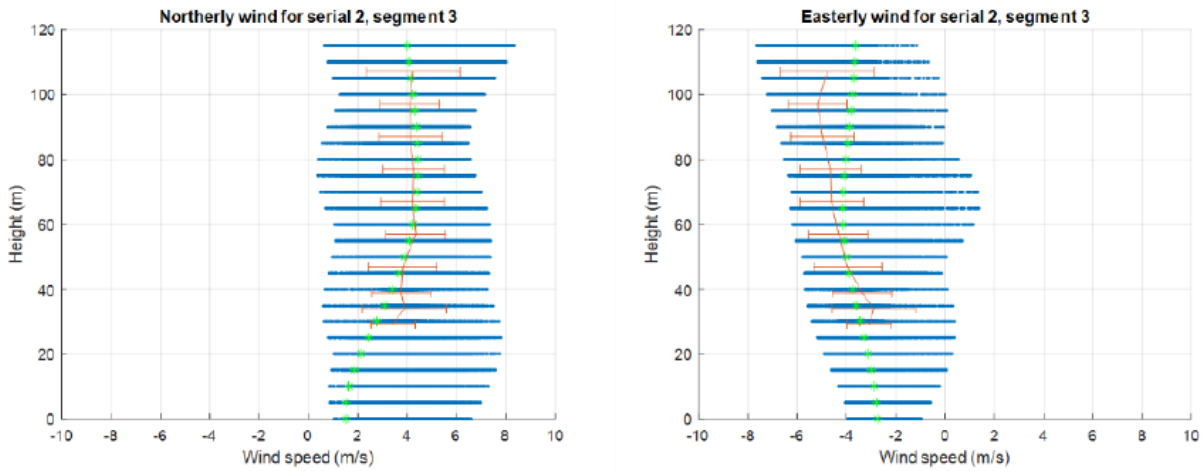


Figure 21. Comparison between horizontal wind speed components observed by LiDAR (red) and UAV-based AAT (green)

A technique known as 'structure from motion' – in which 2D imagery is stereoscopically transformed into 3D views of the world – was used to generate 3D heat maps of the vineyard (Figure 22), and these 3D heat maps were fused with the 3D meteorological information. The result is visualisation of vineyard micro-climates at unprecedented levels of accuracy and resolution, which allows a greatly improved potential understanding of the of the plant-atmosphere thermal dynamics.

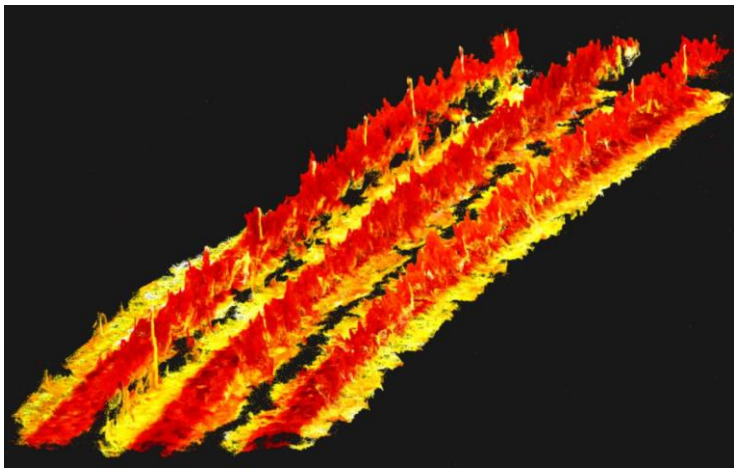


Figure 22. 3D temperature map of vines taken in spring using the UAV-borne thermal imaging sensor

In-vineyard microclimate measurements – extreme heat

Measurements were conducted on days for which maximum air temperatures exceeded 40°C. Trials were conducted over a 10 ha vineyard at Rowland Flat, South Australia. The spatial resolution of the thermal camera provided a ground sampling distance of about 10 cm. The figures below show orthographic projections of thermal maps of surface temperature obtained using the LWIR payload and 3D temperature and wind velocity profiles. There was significant variation in microclimate across the vineyard. Note that surface temperatures of the (non-plant) material in the vineyard routinely exceeded 60°C (Figure 23) on a day where the maximum temperature was nominally 42°C. At the hottest part of the day vine temperatures reached 40°C.

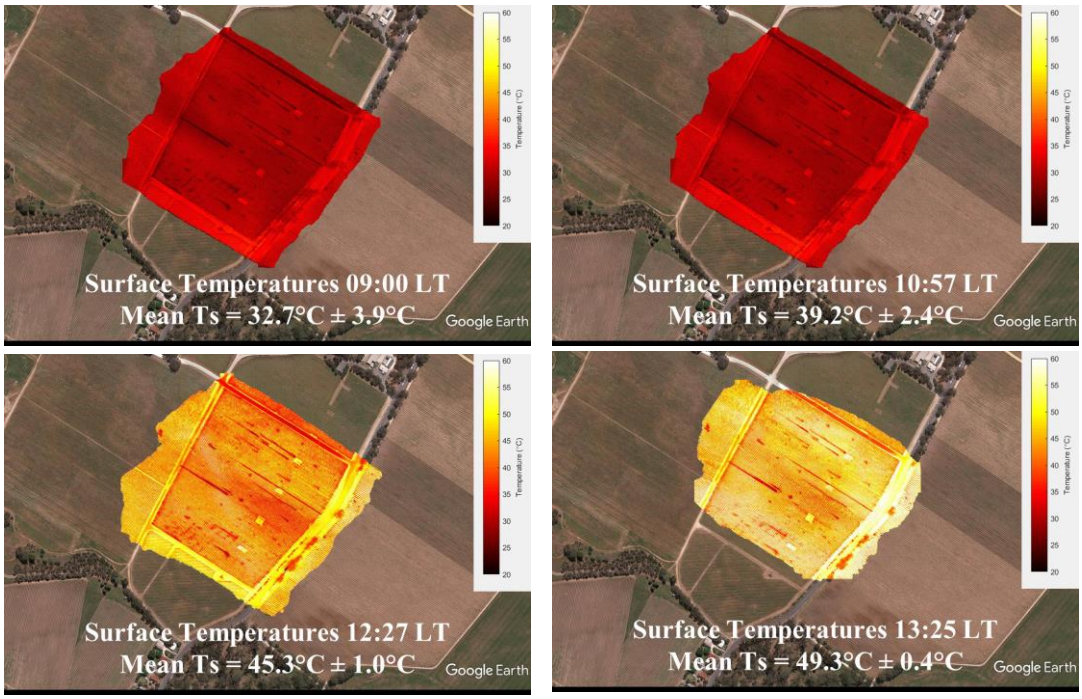


Figure 23. Surface temperature maps for four time periods on the same day for a Rowland Flat vineyard. The nominal maximum temperature was 42°C but parts of the vineyard reached close to 60°C.

In-vineyard microclimate measurements – frost

There are two types of frost event: advection frost and radiation frost. Advection frost events are very rare in wine-growing regions of Australia and occur when cold air moves into a region and replaces the warmer air present prior to the change in weather. Such events are associated with moderate to strong winds, no temperature inversion and low humidity. During these events temperatures often fall below 0°C and remain there for prolonged periods.

Radiation frosts are much more common occurrences, particularly nocturnal ones. Characterised by clear skies, low wind speeds and temperature inversions, radiation frosts occur because heat is lost in the form of radiant energy, i.e. more heat is radiated away from a vineyard than is received by it, so the temperature drops. Air temperature cools faster near the radiating surfaces (the ground and vines), causing a temperature inversion to occur, i.e. temperature increases with height above ground.

Energy is gained by downward radiation from the sky, by conduction of heat upward through the soil, and by convection of warmer air to colder plants. Wind is a factor because it increases the amount of energy transferred from the air to the vines; and a wind of about 2m/s produces enough convective heat transfer to balance the heat losses. This is the goal behind frost fan protection.

Two frost events were monitored in a vineyard in Coonawarra. During the first event, air temperatures fell to around 0°C but frost did not form on the ground or on the vines. During the second event, air temperatures fell to about the same level, but frost did form on the ground. As the vines were close to budburst during the second event the vineyard managers operated the frost fans to protect the plants from damage. The data for the second event is shown in Figure 24.

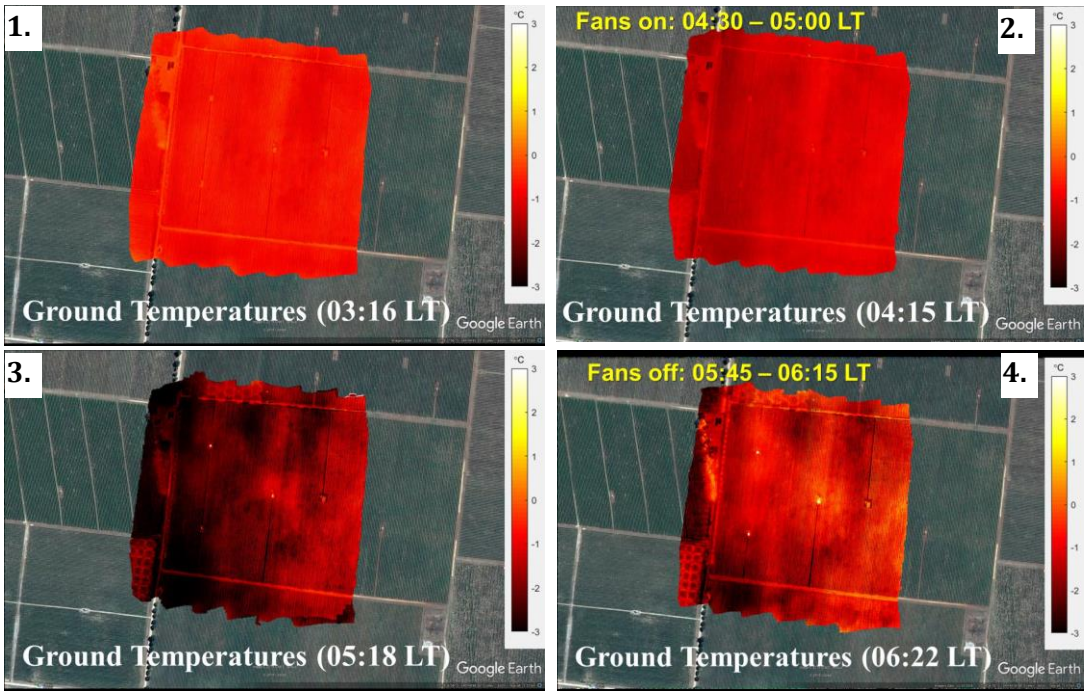


Figure 24. Surface temperatures measured during a frost event in a vineyard in Coonawarra. The local time at which the flights took place is shown on each image and the temperatures are colour-coded in accordance with the bar to the right.

The frost fans can be seen in image in Figure 24 as the three groups of slightly lighter (hotter) pixels towards the centre of the vineyard. They are particularly prominent in images three and four in the sequence, which were taken while the diesel generators driving them were operating. It is apparent, particularly from images three and four, that the fans have provided beneficial impact to the surface temperatures of the vineyard, but that their effectiveness in this regard varies as a function of distance from the fan.

The atmospheric data from the first event indicated that a stronger inversion was forming, however stronger wind conditions around 100 m (Figure 25) which may well have prevented the formation of frost crystals on the ground surfaces by mixing warmer air from higher in the atmosphere with colder air closer to the ground. Examination of such events would not be possible without the technology developed under the program or the establishment and

maintenance of masts, which are both very costly and would interfere with meteorological conditions.

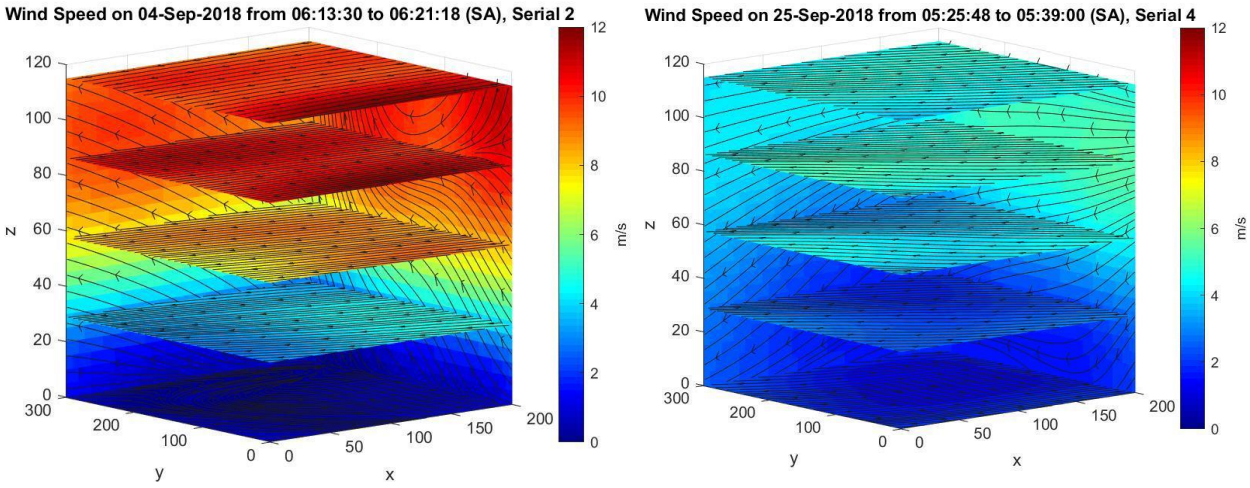


Figure 25. 3D wind speed profiles measured during two frost events in Coonawarra. Arrows indicate wind direction. Higher wind velocities at 100 m on 4 September (left) may have prevented on-ground ice formation which occurred on 25 September (right)

Research summary

The project demonstrated a prototype system to deliver a combination of vine, foliage, ground, and air temperatures, and wind speed observations at the sub-metre scale. The system was successfully tested in frosty conditions, during days of extreme heat (up to 48°C), and for continuous periods of operation throughout a day. The high-resolution tomographic observations allow visualisation of the meteorology within and around a vineyard with respect to both time and space to altitudes of about 130 m.

The system will allow users to accurately estimate and visualise microclimates across vineyard blocks in 3D, potentially permitting computation of plant stress factors like evapotranspiration and crop water stress index. As the technology is still in its infancy, the full value of the microclimatic information it offers is still being assessed.

Potential for adoption (implementation plan)

Based on the experience gained during the project, there are two possible concepts of operations, one more commercially viable than the other.

The less commercially viable option centres on measurement, visualisation, and delivery of microclimatic conditions for a vineyard in near real time. The key impediments to realising this challenge commercially, however, are linked more to Australian Federal UAV regulations and automation of the flying processes than to any technological deficiency of immaturity per se. For example, current air safety regulations apply to UAVs based on their weight, and any drone (plus its payload) weighing more than 2kg must be operated under a Remote Operations Certificate (ReOC) by a licenced operator. Consequently, a drone operator with a ReOC must be employed to operate the system as and when it is required to fly. The commercial rates for such personnel vary, but competent operators cost around $1,500 per day. Also, unless retained under a suitable

commercial arrangement, the operator would likely be required at short notice based on local meteorological measurements and/or predictions. This would impose considerable operational overheads (and hence cost). Furthermore, if multi-UAV techniques are not used, the ground sensor component must be deployed; and this takes time, approximately one day per 10 ha. Whilst not skilled work (the deployment needs are like those of an irrigation system), two people are generally required to test sensors. Alternatively, the ground component could be pre-deployed and left in situ for extended periods. This requires the equipment to be weatherproofed and imposes further (modest) cost.

The more commercially viable option for a concept of operations centres around measurement of events over a growing cycle, potentially over several cycles. This can be accomplished either through an extended deployment, which would require weatherproofing of the ground sensors, or a pre-planned deployment of the system throughout one or more years. The advantage of this approach is that for frost events the technology could be used to assess need for frost fans, optimise the location of frost fans, determine the impact of frost protection strategies, generate spatial maps of frost measured over time, and determine the propensity for atmospheric inversions in certain regions. Similarly, for heat stress events, the system could potentially be used to calculate evapotranspiration and crop water stress index (both as a function of space/geography and time), the spatial variation of plant vigour, and how much irrigation is needed within a vineyard and where.

To substantially reduce costs, it would be possible for the entire acoustic tomography system to be replaced with a single sonic anemometer (or several on a tower or distributed spatially). This would cost about $5,000 per anemometer and a similar amount for a 10 m tower. Approximations can then be made with respect to average vertical wind profiles based on Monin-Obukhov Similarity Theory (MOST). Atmospheric buoyancy criteria that permit sensible heat flux to be calculated can also be computed. However, any extrapolations drawn from such point observations would be vastly inferior to those based on AAT and shown in this report.

UniSA has previously worked with a company (Midspar) to miniaturise an acoustic tracking device that could be used in place of the ground sensor data acquisition system. The cost of this system is, however, around $20,000 per unit, as opposed to about $5,000, not including the power supply and solar panels (noting each Midspar unit can sample 12 microphones as opposed to 7 for the UniSA systems). Moreover, the sensitivity of the Midspar system allows detection and tracking of the sound fields generated by the UAVs at much greater range (3km for petrol-driven UAVs).

Based on the analysis of AAT from this project, it is likely that the minimum practical ground sensor separation is about 50 m, which is 49 sensors and 7 UniSA ground stations per 10 ha vineyard. Other drone systems could be employed, including fixed wing systems, to cover larger areas than this project attempted, but the cost of any such system would scale accordingly.

Payload miniaturisation is also a possibility for the thermographic drone, but the need for a sensor with high thermal accuracy pushes the cost of such a system up to around $20,000. Less expensive thermographic systems are certainly available (circa $5,000) but they have very low thermal and spatial resolution and would not deliver the capability demonstrated in this report.

3.3.4 Impact on productivity and profitability

The three sub-projects (CSA 1601, AWR 1601, USA 1601) have each tested or developed sensor technologies to either describe the canopy and vineyard environment in fine scale 3D, or measure disease or defects in harvested grapes or on the grapevine. While promising, this technology has not yet reached a level of maturity (Table 4) that would allow non-specialist users to deploy and operate it in the field. All will require further development prior to potential commercialisation.

The potential to objectively measure disease in the vineyard, or disease and defects in loads of grapes delivered to the winery is of immediate practical relevance to the wine industry. The presence of disease or defects may result in a reduction in the price paid by a winery for grapes, and as stated previously, the assessment of these parameters is at best semi-quantitative.

A recommendation from the recent ACCC report[6] into market practices in the sector was that:

> ***". . .winemakers should use well-documented and objective testing and sampling methods for quality assessments in the vineyard and at the winery."***

From a grower's perspective, an objective system to measure disease in grapes and MOG will provide greater transparency of the assessment process and more confidence than the current visual system. There is strong potential to further develop the hyperspectral disease/MOG detection research (AWR 1601) into a turnkey application for industry use. The implementation of a hyperspectral system at the grape receival point as described in this report would allow effective screening of fruit for *Botrytis* and MOG at intake. It would allow the winery to identify and avoid or better manage disease-affected loads during processing and therefore prevent the production of *Botrytis*-affected wine, which can be virtually unsaleable.

Canopy and disease management are both major vineyard costs and this project has focussed on providing tools to better inform decision making. A decade-old report[7] estimated that the economic impact of three main grapevine diseases – powdery mildew, downy mildew and various bunch rots (including *Botrytis*) – to Australian growers was $180 million per year, through lost yield and increased costs. Ineffective canopy management can lead to greater disease in adverse seasons (e.g. high rainfall near harvest), but more importantly represents a lost opportunity to improve fruit composition. For example, choosing a different canopy structure can lead to improved compositional parameters and a more preferred wine[8].

It is possible that in the not too distant future, growers will be able to access automated imaging of the vineyard that generates a three-dimensional model of the vine, highlighting the differences

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[6] Wine grape market study. Final report (2019) Australian Consumer and Competition Commission. Retrieved from https://www.accc.gov.au/system/files/1612RPT_Wine%20Grape%20Growers%20Final%20Report_D03.pdf

[7] Assessment of economic cost of endemic pests & diseases on the Australian grape & wine industry. Final report (2010) GWRDC project GWR 08/04. Prepared by Scholefield Robinson Horticultural Services Pty Ltd and EconSearch Pty Ltd

[8] Edwards, E. J., Smith, J., Walker, A., Barril, C., Boettcher, A., & Foster, D. (2017). Targeted manipulation of vine balance: does vine balance directly affect fruit composition? In K. Beames, E. Robinson, P. Dry, & D. Johnson (Eds.), Proceedings - Sixteenth Australian Wine Industry Technical Conference (pp. 96–100). Retrieved from https://awitc.com.au/proceedings/16AWITC.pdf

to the desired canopy structure and how to improve fruit composition through canopy management. That same imaging may provide whole of vineyard data vine microclimate, vine nutrition or early warning of mildew infection. Such a system could also provide a record over time and predictions of future growth and development through a 'Digital-Twin'[9] , allowing proactive management.

Developing a Digital-Twin and the decision-making tools that rely on it requires a significant investment of development effort, that, critically, must be built on a solid knowledge base. The rationale of both CSA 1601 and USA 1601 was to provide that base and to undertake the initial development of the hardware and algorithmic tools required.

Table 4. Technology readiness level (TRL) of the sensor tools developed from sub-projects CSA 1601, AWR 1601 and USA 1601

Sub-project	Technology	TRL
CSA 1601	Canopy size and structure:	
	% cover from drone imagery	4-5
	LAI from under-vine 'action-cam' imaging	4-5
	Size and structure from LiDAR	5
	Size and structure from multi-'action-cam' photogrammetry	2-3
	Hyperspectral imaging to determine vine nutrition (elemental composition)	4
	Pre-symptomatic disease detection with hyperspectral camera	2
AWR 1601	Disease and MOG detection with hyperspectral camera	4-5
USA 1601	Microclimate characterisation using AAT and LWIR	4-5

3.3.5 Lessons learnt

The project agreements took more than six months to execute, delaying some activities in the first season. This placed pressure on the project teams, especially during the first year of the project as much of the work is seasonally dependant. A more streamlined contracting process would be beneficial.

For CSA 1601, the project brought together previously disparate groups within CSIRO, staff from Fraunhofer IFF in Magdeburg, Germany and a number of wine companies with sites across South Australia. Whilst the collaboration was a highly successful endeavour, the time required to ensure that all parties had a common understanding was more than expected and a greater allowance in the project planning for this may have eased the project start-up.

[9] Digital twin for the future of orchard production systems. Moghadam, P., Lowe, T., and Edwards, E. J. (2020). Poster presentation at TropAg 2019, Brisbane. Abstract published in Multidisciplinary Digital Publishing Institute Proceedings, 36(1):92

3.3.6 Collaboration and industry interaction

The three project teams developed strong relationships with their wine industry collaborators, many of which are ongoing. Given the exploratory nature of this RnD4Profit-funded research, interaction with the wider industry was limited to conference presentations, workshops and media (Section 5.1). With this phase of the research concluded, the next steps will be to assess the suitability of each of the technologies developed for commercialisation and this will involve broad consultation with the sector.

The wine sector partners helped shape the direction of the research. Accolade Wines was actively involved both with developing the project brief for AWR 1601 and provided access to grape samples and winery facilities (especially the weighbridge stations). During the course of the project the AWRI investigated other methods of assessing disease at the weighbridge on behalf of Accolade Wines and this relationship is likely to continue. The software and hardware vendors were critical to the success of the project. Adept Turnkey supplied the hyperspectral camera and provided advice on its implementation, especially lighting. Given that adequate lighting is critical to correct interpretation of the image, their input was invaluable. Lastek supplied the multispectral camera and provided advice on its set-up and use. The hardware and software providers are now ideally placed to collaborate with wine companies to implement a solution.

The CSIRO-led sub-project (CSA 1601) included a contracted collaboration with the Fraunhofer Institute for Factory Operation and Automation (IFF) in Magdeburg, Germany, which ran over two years. The original collaboration was built on to a small extent with discussions over how to bring together ground-based hyperspectral calibrations and aerial-based measurements. This led to the test of the concept to measure whole-vineyard vine nutrient status described in Section 3.3.1. CSIRO Agriculture and Food and Fraunhofer IFF have agreed to look for future opportunities to build on the collaboration, including joint publications. Fraunhofer IFF undertook their flights in collaboration with Airborne Research Australia and Dr Everard Edwards (CSIRO; Chief Investigator for CSA 1601) was directly involved in those collaborative discussions. It is likely that this relationship would continue if future work was required by CSIRO Agriculture and Food.

Discussions with Accolade Wines were the genesis of CSA 1601, and included an invitation to undertake the project work at their McLaren Vale vineyards in South Australia. The collaboration with Accolade will continue through the CSIRO-Wine Australia project CSA1702-3.1, which will undertake further development of the technologies described in this report and commercialisation suitability assessment. Further collaboration with wine companies and grape growers was critical for field testing of equipment and methodologies in a commercial setting. In addition to the collaboration with Accolade Wines, Wingara Wine Group and Rymill provided access to paired vineyards in the Coonawarra (South Australia) region, and assistance with the experiment. More recently, discussions have occurred with Platfarm to test using this platform to display and share the imagery acquired from the project data pipelines. Not all collaborations were with larger wineries or businesses: Adam Loveys provided access to some highly managed vines of alternative varieties in a Woodside (South Australia) vineyard. This project has also aided collaboration within CSIRO, with three different groups based in three different states coming together to generate novel hardware and data processing pipelines that would have been difficult to undertake within CSIRO Agriculture and Food alone.

List of collaborators

New technologies for dynamic canopy and disease management [CSA 1601]

- Lead research organisation: CSIRO
- Collaborators: Accolade Wines; Fraunhofer Institute for Factory Operation and Automation (IFF) (Magdeburg, Germany); Airborne Research Australia; Wingara Wine Group; Rymill; Adam Loveys

Digital solutions for grape quality measures at the weighbridge [AWR 1601]

- Lead research organisation: The Australian Wine Research Institute
- Collaborators: Accolade Wines, vineyard samples, access to weighbridge station and advice on project application; PIRSA and SARDI, *Botrytis* cultures; Adept Turnkey, Hyperspectral camera and lighting advice; Lastek, Multispectral camera advice; ESRI, ENVI image analysis software advice; CSIRO Data61, Scyven software advice; Plant and Food Research NZ, RotBot app advice

Use of Unmanned Air Vehicles for early, real time detection of extreme weather events in vineyards [USA 1601]

- Lead research organisation: The University of South Australia
- Collaborators: SARDI, Treasury Wine Estates, Pernod Ricard Winemakers, US National Center for Atmospheric Research, Barton Vale Technologies

3.4 Optimise vineyard spraying [UQ 1601]

This sub-project was conducted by a team from the University of Queensland. It achieved its objective to improve the accuracy of spray placement and dosing in dynamic grapevine environments and to inform regulators of the opportunities to use this technology to manage spray drift risk.

It is well established that most drift from vineyard spraying comes from spray over the top of the canopy. Drift is highest when gaps in the canopy are largest, so controlling the equipment to avoid spraying through gaps is a key drift reduction strategy. Having the means to automatically turn nozzles off when there is no foliage adjacent to them – and on when there is – provides a significant opportunity to avoid spray drift and reduce chemical used, creating benefits to the environment, community and grower.

Precision, variable rate and targeted spraying require accurate assessment of the canopy which changes throughout the season and within and between each vine plant and row. To assess these site-specific characteristics assessments can be made visually or using digital tools such as sensors. The research investigated sensors – including LiDAR and radar – to assess crop density and target location; a freely available app (VitiCanopy) to provide an improved estimate of dose through a PAVE calculation; drones to automate spraying; and a novel electronic 'leaf' to verify spray deposition.

3.4.1 Sensors to automatically adjust spray and dose

A LiDAR was mounted on a multi-ducted air-assisted sprayer and used to map out the 3-D grapevine canopy in real time while the tractor and sprayer drove along each vine row (Figure 26). Radar was used to measure the sprayer speed to feed into a computer-controlled spray system whereby the time to turn each nozzle on and off was delayed based on the driving speed. Application rates were adjusted for the canopy and set by changing the duty cycle of a Pulsed Width Modulation system which included a solenoid for each nozzle. For example, a section of vineyard with double the canopy foliage density as detected by the LiDAR would receive double the spray rate from the solenoid causing the nozzle to be spraying for double the time period.



Figure 26. Silvan Oktopus Sprayer with LiDAR Spray Control System (left). The LiDAR is mounted to the forward-facing side of the tank (right)

The prototype LiDAR system developed through the project allowed sprayers to be converted to offer performance similar to current best practice for dose management and drift avoidance, i.e. recapture/ recycling spraying. The greatest savings in chemical (50-90%) was achieved for the sparsest canopies with the lowest LAI values (<0.5). Such canopies could represent dormant vines, or early-season growth, or simply vineyards with poor uniformity of vine growth and size. As the leaves grew and the canopy filled the gaps to provide LAI values around 1, savings of 50-80% chemical was achieved. At high densities (LAI values around 2), savings around 40-60% were achieved and with full foliage and fruit on the vines (LAI around 3), fewer gaps meant that the chemical savings was down to 10-50%. A range of values is expected because many other factors affect spray coverage and chemical use rates, for example: vine health, canopy structure and uniformity, meteorological conditions, sprayer setup and driving speed. Assuming the worst case, it is reasonable to expect chemical savings of at least 50% for sparse canopies, reducing to 40% for early season foliage to 10% in the late season.

Documented reductions in spray drift can be used to argue for a reduction to operational restrictions imposed on the use of certain agrochemicals. Dr Hewitt presented the results this research to a workshop attended by representatives from the agrochemical industry, wine and cotton sectors, spray equipment manufacturers, and from state and federal departments responsible for agrochemicals. The workshop was coordinated by the National Working Party on Pesticide Applications is likely to lead to data from the project being used to modify agrochemical label restrictions around spray drift management.

3.4.2 PAVE to manually calculate dose per row

Labels on agrochemical products used in vineyards commonly prescribe the dose as an amount of product to be applied per unit ground area, for example kg/ha. This method of dose expression is quite acceptable in broadacre situations where a boom sprayer is targeting small weeds and basically operating in a two-dimensional environment but for tree and vine crops where the target is more three-dimensional the standard way of expressing dose rates on pesticide labels has some shortcomings. The Pesticide dose rate Adjustment to the Crop Environment (PACE) scheme was pioneered by Peter Walklate (a member of the project team) and Jerry Cross in the United Kingdom to provide a more realistic method of dose expression.

Although a LiDAR sprayer will automatically achieve what the PACE scheme is designed to do, not all vineyard operators can justify the capital investment in these types of machines. The research evaluated alternatives to LiDAR that would allow smaller-scale vineyard operators to utilise a PACE-type scheme. An estimate of canopy density is essential for the PACE calculation. Leaf Area Index (LAI) was validated as a suitable proxy for density and was a measured using the VitiCanopy app developed by The University of Adelaide with support from Wine Australia. This led to the creation of a modified version of PACE called PAVE (Pesticide Adjusted for the Vineyard Environment):

Product dose required per 100m of vine row = *Target Deposition Rate (µL/cm^2) × LAI × Row Spacing (m) ÷ Spray Efficiency (0 - 1)*

3.4.3 Drones

A UAV (XAircraft P20; Figure 27) was successfully used to spray grapevine canopy and mid-rows with low spray drift deposition risk, but only when the swath was appropriately offset based on the wind conditions in the vineyard. By spinning the rotary atomiser at high rotation rates, the droplet size was finer than the coarser sizes obtained at lower rotation rates.

For vine canopy applications, the optimum flight height was determined to be 1 m above the canopy. Flying at 1 m/s, 200 L/ha was effectively applied to the vineyard with a crosswind speed of 9-13 km/h. The data show that when spraying from above the canopy the deposition rates tend to be highest at the top and outside of the canopy. To penetrate further into the canopy a finer spray is needed which is more prone to displacement in the wind. This study showed that to minimise drift when aerial spraying with drones the wind speed should be as low as possible and ideally in the range below 10 km/h, however caution should be taken at speeds below 2-3 km/h as surface temperature inversions are more likely.



Figure 27. XAircraft P20 drone spraying a vineyard with mature canopy

3.4.4 Electronic 'leaf'

The project also developed a novel electronic leaf system (Figure 28) to measure spray coverage. It is possible to transmit the measurements to a remote computer to validate spray application or to the spray control system in real time during spray applications. This was an integral part of the aspirational vision for the longer-term project outputs for grower benefit because any successful spray operation requires a way to measure the success of placing the spray where it is required and some canopy regions such as the inside can be harder to reach.



Figure 28. Left to right - mylar card, water sensitive paper and electronic leaf in grapevine canopy to measure spray coverage

3.4.5 Impact on productivity and profitability

The systems developed and evaluated in this project will offer economic, productivity and environmental/social benefits to growers. When spraying is optimised, less chemical is used, crops are better protected and more productive, improving grower profitability. In addition, impact to the environment and humans from off-target spray drift is reduced.

Some of the technology developed from the project is at a relatively high TRL (Table 5). The development of the LiDAR+PWM sprayer system was fast-tracked by collaboration with international groups investigating similar technology, and it was this collaboration which undoubtedly led to the recent commercialisation of a US-designed and built version (refer to section 3.4.7). The estimated retail price of this US-built system is used for the costing described below.

Table 5. Technology readiness level (TRL) of the spraying technology developed

Sub-project	Technology	TRL
UQ 1601	LiDAR + PWM kit to automatically adjust spray and dose	6
	PAVE to calculate dose required per row	6
	Electronic 'leaf' to measure spray deposition	3-4

The LiDAR system has clear advantages for both new sprayer investments and for conversion of existing sprayers. The payback time for investment in the LiDAR-equipped sprayer system is as follows:

- Assuming an average 30% chemical savings results in a range of savings over 5 years from $1,500/ha (wine grapes) to $3,000/ha (table grapes), providing a simple pay-back period of 2.5 - 5 years for a 100 ha, or only half that time if only the LiDAR conversion kit is required.
- $60,000 - $80,000 estimated cost to purchase commercial LiDAR bolt-on kit to convert an existing two-sided sprayer, plus $70,000 to purchase new sprayer (if required). Total maximum cost $150,000.

Additional factors

- The actual chemical costs will vary among growers probably in a range of $200-$2,000/ha.
- This example was based on conservative estimate of mean 30% savings in chemical but this could be doubled or tripled for some canopies/ scenarios.
- Additional savings can be realised with larger, multiple row units.

A challenge for many growers is the control of Eutypa and Botryosphaeria dieback where 100% spray coverage is required on woody canopy surfaces to significant control. The amount of chemical wasted if a sprayer is turned on the whole time while driving down rows for such an application will exceed 90% compared to applications targeting only those woody materials. The LiDAR sprayer could accurately detect these surfaces and then activate the spray only onto them, saving >90% chemical while achieving 100% coverage (Figure 29).



Figure 29. The LiDAR-equipped sprayer used 90% less fungicide to treat this vineyard for trunk diseases while delivering the required spray coverage. The purple rectangles fixed to the vine are water-sensitive papers which change from yellow to purple on contact with water

3.4.6 Lessons learnt

An unexpected and significant learning was the incorrect assumption that all growers would want to reduce the amount of agrochemical applied to the vineyard. The workshops revealed that some growers with high value table or wine grapes regard any chemical reduction as an unacceptable risk to production. The workshops also suggested that actual savings in chemical use rates from recapture/recycling and LiDAR equipped sensor sprayers may be even higher than achieved in this research as growers are currently over-applying sprays without being aware. Fine-tuning of rates to the required level may therefore deliver a large reduction in chemical use. The deposition sensors studied in this research will therefore be of high value for verifying existing spray rates.

Interaction with growers during the project also confirmed that an understanding of basic spray equipment set-up is as important to improve spray performance as is the adoption the new sensor technology. Meaningful improvements to spray performance can still be achieved through simple adjustments to spray angles, nozzle types and operating pressures.

3.4.7 Collaboration and industry interaction

This project involved extensive collaborations across stakeholder groups within and beyond Australia. Some of the relationships were already in place prior to this project but all are likely to continue as collaborative efforts to minimise risk from agrochemical application grow.

Silvan, an Australian manufacturer of sprayer equipment provided an Oktopus sprayer and staff to support testing of the LiDAR spray unit. This involvement exposed at least one major Australian sprayer manufacturer to the potential of the sensor technology. FMR, a South Australia/New Zealand-based manufacturer of agriculture and sprayer equipment – including the recapture/ recycle R-series unit tested in these studies – also provided equipment and staff to support the field studies. This relationship ensured that equipment developed within the project would be applicable to Australian uses and needs. The project team also consulted with other sprayer and nozzle manufacturer companies, including Croplands and Teejet.

The team investigated the development of LiDAR sensor conversion kits for existing sprayers with Vuetech, a Brisbane-based company agricultural technology company.

Collaboration with the international academic community on this project was extensive:

- Study exchanges were conducted with two United States Department of Agriculture Agricultural Research Service (USDA-ARS) groups. The lead scientists were Drs Heping Zhu (Ohio – LiDAR sensor systems) and Chenghai Yang (Texas – PIX4D imaging). Given the shared research interests and similar goals (though for different crops) and the long history of collaboration, it was logical to work together on aspects of the research to avoid re-inventing things in both countries. These groups are keen to continue to work together and this will bring ongoing, long-term benefit to Australian agriculture for crop spraying progress.
- Dr Jordi Llorens from the Universitat Politècnica de Catalunya joined the University of Queensland project team for several months.
- Drs Peter Walklate and Jerry Cross (East Malling Research and Peter Walklate Associates) in the UK previously developed a dosing system for apple spraying called Pesticide Adjusted for the Crop Environment (PACE), on which the PAVE vineyard dosing system is based.

The National Working Party on Pesticide Application (NWPPA; https://nwppa.net.au/) includes all major stakeholder groups in Australia for pesticide application. The NWPPA were informed of the research throughout the life of the project, with regular updates provided at their meetings. The NWPPA acted as the conduit to inform the Australian Pesticides and Veterinary Medicines Authority and state agrochemical regulators of the research findings.

The Industry Reference Group informed the direction of the research. The project team was pleased to work with grape growers (Campbell, Vinland Estates; Ballandean Estate Wines; S&J Sergi; Sam Puglisi Table Grapes; Treasury Wine Estates) who showed a strong interest in the research and supported the studies not only by providing access to vineyard sites and machinery but also by assisting with some of the research. In addition to this interaction, Andrew Hewitt and Chris O'Donnell held numerous grower workshops in several states and presented at the triennial wine

industry conferences (refer to Section 5.1 for a complete list of workshops, conferences and publications).

Near the conclusion of the project, a commercial, US-built LiDAR-based sprayer conversion kit was made available to the project team for evaluation in Australian vineyards. Delivery is expected in August 2020 and plans have been developed to assess the technology in the 2020/21 growing season in vineyards located in Queensland and South Australia, and extend the results to the sector through Wine Australia's *Regional Program*.

3.5 Tools for spatial data analysis [CSA 1603]

This research was conducted by a team from CSIRO. All specified project outputs were delivered.

Precision Agriculture (PA) is a management strategy that takes account of temporal and spatial variability to improve sustainability of agricultural production[10]. Precision Viticulture (PV) is the application of PA in grape production.

Recent surveys in both the wine and grains sectors suggest that adoption of PV/PA will be improved by simplifying the processes involved in the management and analysis of the captured spatial data, and by reducing the cost-barrier to these platforms. This project sought to address this opportunity by producing a suite of open source tools, accessible through a freeware platform, which may enable a non-expert to implement the core data analysis tasks which PV/PA require.

The project had three aims:

1. To identify a suitable freeware GIS platform to support spatial analysis, map display and the various map production/analysis tools used in our previous research;
2. Refine methods for geostatistical analysis of field experiments in order for analysis to be performed on standard desktop computers; and
3. Develop a user-friendly, open source software tool.

These three outputs would deliver a set of accessible freeware Precision Agriculture tools ('PAT') that facilitate low-cost adoption of PA and PV.

3.5.1 Freeware GIS platform

A list of 14 freeware GIS candidates was created ensuring that the platform:

- was a general purpose desktop GIS software application;
- supported both raster and vector data for editing and analysis;
- enabled customisation through scripts and/or plugins; and
- supported multiple operating systems (e.g. Windows, Mac).

Three shortlisted candidates were then assessed by a GIS professional with no prior experience in the platforms. QGIS 2.18 was ultimately selected as the freeware GIS package that would be used to underpin the project outputs. The technical report for this project provides further detail underpinning this decision. Consistent with the selection of QGIS 2.18, it was decided that programming of the analysis tools would be done using Python 2.7.

[10] https://ispag.org/about/definition

3.5.2 Create tools to simplify geostatistical analysis

A package of data processing and analytical functions was created using the 'R' software environment. The package is a combination of wrapper functions that include novel algorithmic implementations of multivariate geostatistical methods to understand dissimilarities in the production of a farm by providing their corresponding statistical uncertainty and significances. The models implemented in the package are:

- global cokriging
- local cokriging based on a radius expanding algorithm
- local cokriging based on cross-validations with either:
    - an adaptive neighbourhood radius, or
    - adaptive neighbourhood points; and
- Subsampling methods using:
    - bootstrapping, and
    - k-means clustering.

These tools were implemented via the PAT library 'front end' – see below

3.5.3 PAT – Precision Agriculture Tools

PAT was produced as a plugin for QGIS and is the front end to pyprecag – an open source Python library of PA analysis tools which contains the processing steps. Collectively, PAT and pyprecag are the substantive outputs from this project. PAT/pyprecag contains all the tools for spatial data manipulation and analysis that is likely to be needed by adopters of PV/PA.

Both 'pyprecag' and the PAT 'front end' were released in January 2019 as per the agreed project schedule; a second release was made in late June 2019 with enhancements to PAT which enable greater automation of some steps. Following the initial release (v0.1.0) there were two minor updates and two new feature releases such that the current version is now v0.3.0. As at 30 June 2019, there had been 1,086 downloads of v0.1.2 via QGIS.

Instructions for setting up QGIS for PAT are accessible from https://github.com/CSIRO-Precision-Agriculture/PAT_QGIS_Plugin#precision-agriculture-tools-pat-plugin-for-qgis. Users are encouraged to install PAT from the QGIS Plugin repository having downloaded QGIS. Enquiries regarding PAT can be directed to PAT@csiro.au.

3.5.4 Lessons learnt

The project team concede that they were naive when commencing this project to assume that the release and maintenance of software is easy. Part way through the project both QGIS and Python upgraded the versions of their software. This meant that while the project could successfully deliver the PAT tool, there was a risk it would quickly become redundant because of version incompatibility.

Fortunately, CSIRO funded the work needed to upgrade PAT to work with the new versions of QGIS (version 3) and Python (version 3) once CSA 1603 had concluded.

It is now obvious that the deadlines to release PAT would not have been met without the additional input from the CSIRO eResearch team. In summary, the project was under-resourced in terms of both time and staff.

3.5.5 Collaboration and industry interaction

A project advisory panel was established to guide the utility and useability of the software being developed. This panel comprised Mr Colin Hinze (Bird in Hand Winery, Adelaide Hills – now with Pinion consultancy), Mr Hans Loder (Vineyard Manager, Penley Estate, Coonawarra) and Dr Kathy Evans (University of Tasmania/Tasmanian Institute of Agriculture). Their freely offered input on the PAT tools, which the team trained them in, was much appreciated and enabled some tool finessing to make them easier for users to understand. Both Mr Hinze and Mr Loder are long term collaborators with CSIRO in PV. In contrast, Dr Evans had no prior experience with GIS. Accordingly, the panel had a mixed skill set with respect to their approach to PAT and their feedback was valuable. One benefit to accrue through the link to Dr Evans was the adoption of PAT by a PhD student co-supervised by her and the Project Supervisor.

Finally, the project benefitted from an additional collaboration internally within CSIRO. The 'eResearch' initiative operated by CSIRO's Information Management and Technology business unit provided specialist assistance with aspects of Python coding and software packaging and with the release of PAT.

The project team has raised awareness of PAT through conferences and industry events, and through articles in the SPAA newsletter and other media (refer to Section 5.1). Challenges still exist with the perception among producers of PV and PA as being too technical. To address this Wine Australia has worked with GRDC and SPAA to include the use of PAT in a series of PA case-studies being developed for grain producers. Further investment needs to be made in the development of training packages to realise the full value of PAT.

3.5.6 Impact on productivity and profitability

PAT makes no direct contribution to the productivity of primary production. However, since it is a key tool for the facilitation of adoption of PA/PV, it potentially makes an important contribution to enterprise profitability through enhanced resource use efficiency and in the case of the wine sector, selective harvesting[11]. For example, the targeted application of gypsum to a sugarcane field variably affected by soil salinity and sodicity led to a saving in the costs of applying gypsum of $330/ha[12]. All

[11] Bramley RGV, Trengove, S. 2013. Precision Agriculture in Australia: present status and recent developments. Engenharia Agricola 33, 575-588

[12] Bramley RGV, Jensen TA, Webster AJ, Robson AJ. 2018. Precision Agriculture and sugarcane production – A case study from the Burdekin region of Australia. Chapter 9 in Rott PC (Ed) Achieving sustainable cultivation of sugarcane. Volume 1: Cultivation Techniques, quality and sustainability. Burleigh Dodds Science Publishing, Cambridge, England. pp.185-202

of the spatial data analysis which underpinned this example may be performed in PAT. The 'PA in Practice' manuals produced by the Society for Precision Agriculture Australia (SPAA) and accessible at https://spaa.com.au/resources/ provide several examples of the profitable use of PA by grain producers, while examples of the potential profit enhancement available to grapegrowers and winemakers through the adoption of selective harvesting were also demonstrated[13] [14]; again the spatial analysis underpinning these examples can be completed in PAT.

The primary driver for the production of PAT was the assumption that the main barriers to adoption of PA/PV was the perceived difficulty of data analysis and the cost of the GIS system. Now that PAT has been released, users can, with limited knowledge, and with no cost other than in terms of their time (including time needed for familiarisation with GIS), perform the various spatial analysis steps irrespective of the cropping system that they work in. PAT therefore has the potential to significantly benefit primary producers.

[13] Bramley RGV, Proffitt APB, Hinze CJ, Pearse B, Hamilton RP. 2005. Generating benefits from Precision Viticulture through selective harvesting. In: Stafford JV. (Ed) Proceedings of the 5th European Conference on Precision Agriculture. Wageningen Academic Publishers, The Netherlands. 891-898.

[14] Bramley RGV, Ouzman J, Thornton C. 2011. Selective harvesting is a feasible and profitable strategy even when grape and wine production is geared towards large fermentation volumes. Australian Journal of Grape and Wine Research 17, 298-305.

4 Evaluation

This section addresses the Final Report metrics described in the *Monitoring and Evaluation Plan* submitted with Milestone Report 3.

4.1 Digital technologies developed

➢ *What new digital tools are available as a result of the project?*

A list of the digital technologies produced, and their TRL, is provided below:

Sub-project	Technology	TRL
CRD 1601	Rapid molecular assay to diagnose *Verticillium* and its VCG	released
UT 1601	Bud fruitfulness using hand-held NIR	5-6
CSA 1602	Yield estimation from video capture of inflorescences	4-5
	Yield estimation from video capture of bunches	4
	Yield estimation from 2.5/3D RGB information	3
	Direct estimation of yield using radar	2-3
CSA 1601	Canopy size and structure:	
	% cover from drone imagery	4-5
	LAI from under-vine 'action-cam' imaging	4-5
	Size and structure from LiDAR	5
	Size and structure from multi-'action-cam' photogrammetry	2-3
	Hyperspectral imaging to determine vine nutrition (elemental composition)	4
	Pre-symptomatic disease detection with hyperspectral camera	2
AWR 1601	Disease and MOG detection using hyperspectral camera	4-5
USA 1601	Microclimate characterisation using AAT and LWIR	4-5
UQ 1601	LiDAR + PWM kit to automatically adjust spray and dose	6
	PAVE to calculate dose required per row	6
	Electronic 'leaf' to measure spray deposition	3-4
CSA 1603	Precision Agriculture Tools (PAT) for spatial data analysis	released

4.2 Industry impact

- *How well did the project deliver new opportunities or approaches for vineyard/cotton field management? What is the likelihood of adoption of the outcomes and the digital technologies trialled during the project i.e. which appeared to be the most promising/likely to be adopted? Are the technologies developed through the project fit-for-purpose and suitable for broad use in the viticultural and/or cotton industries?*

Sub-project CRD 1601 delivered a significant improvement in knowledge regarding the holistic management of disease in cotton, on a national scale. It demonstrated the applicability of a strategic and geospatial approach to disease surveillance which led to new recommendations for crop rotation and soil solarisation to reduce disease risk. These recommendations have already been passed to producers and others in the industry but the impact on practice change is yet to be evaluated. In addition, the project developed new assays needed to identify *Verticillium* and measure its risk to cropping.

The impact of the wine sector sub-projects was evaluated by a small but diverse industry panel at a virtual workshop held after the research had concluded. The 6-person panel comprised:

- Vineyard contractor
- Wine company (large corporate) viticulturists x 2
- Grapegrower with multiple large vineyards in warm, 'irrigated' regions
- Grapegrower with multiple large vineyards in cooler regions
- Grapegrower with small, boutique, vineyards in cooler regions

Their assessment of each sub-project is presented in Table 6. There was unanimous support for the yield estimation technology (UT 1601 and CSA 1602), which is not surprising given the obvious usefulness of the data across the supply chain, and the ability for participants to immediately visualise how the devices might be applied in the vineyard. As the technology became more experimental (e.g. CSA 1601) this visualisation became more hypothetical, with some participants strongly supporting the projects, and some undecided. Only the output from one project failed to receive any indication that it would be adopted by the sector in its current form. CSA 1603 – *Simple tools for spatial analysis – key enabling technologies for precision and digital viticulture* – was regarded as being too complex in its current form to be widely adopted by growers. The panel believed that spatial analysis is useful but the tools need to be presented in a far simpler package assuming that growers are the target audience.

Wine Australia has commenced the assessment of each of the wine sector project outputs for potential commercialisation, and this will include consultation with a much larger number of producers, contractors and winemakers. Given the relatively low TRL of most of the devices and process produced (Section 4.1), they will require further development and therefore investment before being available to the sector. The panel made a strong recommendation that any product development should consider multiple solutions within a single device or platform to reduce the complexity for the grower.

Table 6: Likely adoption of delivered project technologies by the sector

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
UT 1601: Taking grapevine yield forecasting into the digital age				
1	**Yes**	Highly desirable, but may get superseded by other projects targeting crop assessment. Would target taking geospatially referenced samples of bud fruitfulness and then adapt pruning to underpin and secure crop loads. Spatial awareness would allow a variable application of what is traditionally a broader brush whole of block approach. Rating 8/10	It would replace need for the 3rd party dissection work that we have found traditionally expensive and of low reliability	
2	**Yes**	To determine bud numbers more quickly to gauge pruning decisions and early prediction of yield. This would need to be layered with bunch counts later in the season	A better understanding of yield potential early in the season	
3	**Yes**	I expect it will allow a larger number of buds to be assessed plus allow different areas within a patch to be assessed separately giving a more accurate reading of fruitfulness to allow more informed pruning decisions.	More accurate early yield potential (High/Med/Low) providing more informed pruning decisions as well as fruit intake planning decisions especially for annual purchased fruit contracts. In low cropping year moving early to secure fruit can result in cheaper fruit.	
4	**Yes**	Innovative tool. Speed & volume of information would be valuable especially for a service provider for a region. Not really a tool for the individual grower.	Obvious pruning/ bud number planning to target vineyard potential yield.	The path to commercialisation has been thought out - good!!
5	**Yes**	Potentially purchase the NIR equipment to use ourselves.	Consistency of data collection, more confidence in the accuracy of the data, reduced cost associated with bud dissection process, improved turn-around time to get results (days vs weeks), greater number of blocks that can be assessed.	
6	**Yes**	Our business employs multiple people each season to assess bud fertility before making pruning decisions. The difficulty we find is variability in results from different technicians, and for the most part in a double cordon, commercial grade crop we are really just looking for an absence of necrosis to guide height and width decisions. This tool could be used to rapidly assess broad areas non-destructively and provide consistent results. The traffic light function is perfectly suited to large scale warm climate producers, maybe less so for small detailed parcels requiring more direct information.	Labour savings, consistency in results, great reporting and communication tool to farm managers and contractors	

[15] Participant ID of the viticulture Industry Reference Group member

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
CSA 1602: New non-destructive technologies for simultaneous yield, crop condition and quality estimation				
1	**Yes**	Rating 8/10. Large spread of technology within this project with many potential applications. A simple replacement for manual inflorescence counts, which would allow larger sample numbers (accuracy) and compete commercially with the cost of manual assessments. In the immediate short term, the image capture is a simple way to spatially record vine specific images year on year and would be very appealing in itself without ANY interpretation of the data (the grower could make their own interpretation of the image and benchmark with past seasons).	IF BULLET PROOF and robust it could reduce environmental footprint required to manage pests and disease. Might benefit from producing an electronic signature to the application rates for customers but also as a check (when compared to NDVI or LiDAR biomass) so that a grower can have confidence that the actual applied target volume matches objective.	
2	**Yes**	More accurate yield estimation	To add the ability to capture during every pass within a vineyard (by tractor, ATV etc) and layer data from other analysis	
3	**Yes**	If not cost prohibitive could be used in conjunction with UT 1601 to ground-truth bud fruitfulness data.	Could remove the error from multiple staff carrying out inflorescence/bunch counts. Allow a greater sample area to be counted than currently done.	
4	**Yes**	Very useful. More accurate predictions and to client information. Better dealing with the fruit customer, logistics planning at harvest.	Cashflow predictions	Can be affordable on mass regional scale. Commercialization potential high. Can be potential cost saver to industry (capacity planning).
5	**Yes**	Field based disease assessment is what excites me around this project		
6	**Yes**	This work is exciting. Our current yield assessments involve overlaying historical data with in-field, destructive assessments. Our labour expense last year on yield assessment totalled $50k. Potentially we could use tractor mounted units to use existing passes (herbicide/fungicide) and reference the collected data against historical for each block hoping to reduce the labour component completely and avoid the destruction of 100+ tonnes in potential yield from destructive sampling across the season.	Labour savings, potentially increased accuracy of estimates, reduction in destructive samples.	

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
CSA 1601: New technologies for dynamic canopy and disease management				
1	**Yes**	Rating 9/10. An emerging priority. I like the applicability of a sensor suite being able to be incorporated into existing operations (i.e. mounting on tractors). The LiDAR could be used as "eyes and ears" to help growers drive other hardware platforms, variable fertilisers or DIIMotion fertigation to standard fungicide sprays.	The LiDAR data could potentially act as the base data set to drive automated vine interactions by future technology.	
2	**Yes**	To review canopy size and function and compare this across years	Better assessment of issues prior to them occurring and a historical record that does not rely on memory and is less subjective.	
3	No		No obvious benefit to my operation, but larger wineries/ vineyard operators may benefit if mounted to machinery currently operating in their vineyards to provide information on nutrient/vigour issues that can be managed on a broad scale. Smaller operations and to some extent larger, would get a better result from people actually being in the vineyard monitoring. Nothing better than a vineyard manager being in the vineyard and not the office.	
4	**Yes**	Very useful. Can be mounted to machinery when passing through vineyard. Ideal for vineyard planning & targeting resources.	Has potential to replace fly over methods to produce NDVI maps. GIS positioning for field tablet use.	Create partnership circle - vineyard data collectors (machinery passes) -service company to collate data & distribute back to grower in useful planning form for vineyard operations.
5	**Yes**	Vine nutrition component of this project excites me	Consistency of data collection, more confidence in the accuracy of the data, reduced cost associated with nutrition process, improved turn-around time to get results (days *vs* weeks), greater number of blocks that can be assessed.	
6	**Yes**	This would be an extremely useful tool to utilize tractor and ATV passes to assess nutritional deficiencies and disease outbreaks. Due to the large scale of our farms (900+ hectares) operators are rarely trained well in nutrient and disease identification, this would assist in ground truthing and decision making. The canopy spatial mapping is probably of less interest as there are many spatial tools on the market to assess high/low vigour areas.	Reduction in yield loss due to disease, rapid and detailed assessment of nutritional requirements. Utilize existing vehicle movements for assessment and data collection.	

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
AWR 1601: Digital solutions for grape quality measures at the weighbridge				
1	**Yes**	Cautious support. Rating 7/10 for weighbridge disease model; 9/10 for objective MOG assessments. As a grower would need to gain confidence in the MOG rating and then accept that as feedback from customers		Am concerned about unintended consequences of using this at the weighbridge to determine rejection thresholds after crop is off the vine. This debate/dispute assessment between grower and winery is best resolved in the vineyard - ultimately need a solution to use in the vineyard.
2	**Yes**	Yes for the MOG component only. To determine accurate MOG levels in fruit delivered beyond visual weighbridge assessment of weighing.	A less disputable assessment of MOG at the weighbridge/crusher.	
3	No			Potential for larger wineries to provide an accurate quantitative measure of MOG reading avoiding variation between weighbridge attendants; similarly for diseased/damaged fruit. If it could be adapted to the discharge arm of a harvester it could be used by harvest operators to change harvester settings to reduce MOG in real time, avoiding winery penalties.
4	**Yes**	Innovative tool, but needs work. Winery-based tech	Improved vineyard harvesting techniques . Proof based harvesting.	Commercialisation of this tech should be easy once developed. Would have potential for wide wine industry take-up. May need involvement/partnership with a commercial development company.
5	No			May only be useful for MOG assessment, would prefer in-vineyard assessment rather than at the weighbridge
6	**Yes**	As a weighbridge tool to assess MOG and have rapid communication with growers and harvest contractors without any bias or opinion. The Botrytis detection function would assist in both discussion with growers regarding infection levels but more importantly in difficult seasons to stream fruit based on infection levels into the winery.	Improved wine quality in difficult seasons, rapid and unbiased assessment of MOG.	

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
USA 1601: Use of Unmanned Air Vehicles for early, real time detection of extreme weather events in vineyards				
1	No	NO. Rating 3/10. Ultimately growers won't need to use this process to understand frost risk/movement as historical vine damage gives a much more objective overview of the risk pattern. Similarly, with the heat, vines will show the damage pattern. Until we have a mechanism to differentially water then there is limited value in determining this patten. Also, only defence against heat impact to date is pre-watering (not real time application). Why go to the trouble of extrapolating temperature variation via tomography when you could use inexpensive temperature sensors located in the field at the actual canopy interface?		If perhaps this tech could be used in real time by a full-sized helicopter to help mitigate frost risk I could see some value. Might be able to build a dataset from existing vineyards in a region and perhaps adapt to green field sites to assess suitability although once again incident variability could render the risk mitigation offering relatively poor.
2	No			The technology has a place but the cost to implement is a barrier and relevance to other industry priorities is low.
3	**Yes**	Use to map frost prone areas of existing vineyards for accurate identification of risk areas and guidance for installation of the appropriate frost control measures (fan *vs* water). Map potential new property areas to assess frost risk.	Allow installation of frost control measures in the correct areas on existing sites resulting in crop potential being achieved. Avoid purchasing a property with high frost risk, or knowing the frost risk prior to purchase allowing economics of that risk to be accounted for in budgeting for a new development.	
4	No			Needs further development to become practical and easy to use. Great for a start up to potentially take further.
5	**Yes**	I think this may be useful during frost events to help with targeting where on-ground assessments would need to occur.	Quicker turn around on where to target on foot assessments.	

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)	What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
USA 1601: Use of Unmanned Air Vehicles for early, real time detection of extreme weather events in vineyards			
6	No		I see this work as an interesting assessment but something that will really just tell you what you already know. In vineyard systems inter-block evapotranspiration is impossible to manage due to irrigation system configuration. The frost assessment would be a handy tool when developing on a frost prone site but wouldn't provide any useful information after a system was commissioned.

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
UQ 1601:	**LiDAR and PACE for vineyards**			
1	**Yes**	Rating 9/10. Yes, but are likely to move to recycled sprayers as well. Would like to see this incorporated into recycled sprayer AS WELL as variable application rate.		
2	**Yes**	To ensure that dilute rates are appropriate for the canopy size	Reduced risk with agrochemical residues and an opportunity to reduce the risk of calibration error and resistance to certain active constituents.	
3	No			LiDAR solenoid on/off system will benefit some operators that want to reduce chemical use and drift without upgrading to a recycle system. Electronic leaves have potential for real time coverage information to alert managers/ operators of issues with spray coverage.
4	**Yes**	Very useful. Potential cost savings (bit will need to validate for my business). This technology will eventually become common place - it's the way our industry must move.	Reduced chemical use and environmental chemical loading. High score for sustainability systems.	Still relatively expensive and needs commercial vineyard testing to prove reliability.
5	**Yes**	The electronic leaf wetness sensors is the exciting part of this project	Being able to assess the coverage efficacy of our spray carts (which is not done that often), especially for the earlier (dormancy) sprays.	
6	**Yes**	The main benefit I see for our business is the electronic leaf sensor as an update from water sensitive paper in the field. This would be used to assess calibration on our own spray equipment and could be a very useful tool for the management of third party growers where the certainty of application can be difficult to measure. I don't see the benefit of the "on off" LiDAR function and I am assuming most of the 60% chemical saving would come from the recycle sprayer rather than the canopy mapping software. Our new Interlink sprayers are $100k per unit around the same price as the FMR recycle sprayers so if a chemical saving is required that is the option we would go with.	The electronic leaf sensor would add assurance in application for third party growers and assist with company vineyard application and coverage assessments. The LiDAR canopy assessment and sprayer function isn't of any interest.	

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
CSA 1603: Simple tools for spatial analysis – key enabling technologies for precision and digital viticulture				
1	No	No. Rating 4/10. Frankly, if a high level of training is needed the system either needs to be redesigned or is not for growers. Concerns also regarding the longevity of the software upgrade issues. I think this is conceptually vulnerable (hopefully) to being another function on Google Earth soon, at least for NDVI data. Hopefully Moore's Law kicks in and Google offers it for free. This tech has been around for some time with limited uptake by industry due to (my opinion) the challenge to show payback OR ability for industry to quantify and adapt to payback (i.e. differential harvest and lack of robust grading systems) . People/ companies simply don't have the time or resources to invest in this type of knowledge gain unless there is a significant ROI. Most major companies have shredded their technical departments/ resources as the industry tightened and I suspect that this has a lot to do with payback/ value propositions.		Only via 3rd party suppliers offering simple hands-off options for growers. Unlikely growers or companies individually can afford to invest the time and energy to learn this software and then find payback on that time within the current uses of PA.
2	**Yes**	Potentially very useful but format needs to be simplified. I'd use it to review spatial data	To make better decisions based on spatial data and do this remotely to make better use of time used travelling to vineyard sites. It's a tool to monitor change but also layer other data upon to develop knowledge to mitigate risk.	Precision Ag is valuable but it needs to be simplified to allow consumption by the majority of growers/users.
3	No			I can see it as a useful tool for large scale vineyards in its current form, however for it to be useful for smaller companies or growers it needs to be simple to use and also requires either training or simple instructions.

ID[15]	Is this technology (or parts of it) a 'must have'? If you answered 'yes', how would you use the technology in your business? (Yes / No, plus supporting comments)		What benefits could it bring to your business?	If you don't see a use for the technology in your business, can you see it being of value to other grape growers/ sectors? If so, how?
CSA 1603: Simple tools for spatial analysis – key enabling technologies for precision and digital viticulture				
4	**Yes**	Great tool, but format needs to be simplified to make it useful. I'd use it for differential management, on-going year-to-year comparisons, vineyard mapping planning, soil mapping	Targeted spending and materials use. Understanding spending. Can this product be picked up by an AgTech start-up or other group to commercialise so on-going service backup can be supplied?	Not in its current form. Format more research based not easy to navigate, very noisy. Super complicated
5	No			Potentially useful for consultants to offer as a service to growers.
6	No			I feel this work has been done for decades with little improvement or application for industry. There are many cost-effective mapping and analysis tools available on the market. Our business has been a product available through a national ag service provider to map canopy density and variability for the past 12 months. This application costs $1/ha and provides all the tools required to a grower in an extremely simple to use format. I don't see industry uptake or any benefit to the average grape grower in continuing in this space.

4.3 Media and communication

The performance targets within Wine Australia's media and communication plan were nearly all achieved, with "key message delivery – media" just falling short of its 50% target (Table 7).

Table 7. The five research themes within the Rural R&D for Profit project *Digital technologies for dynamic management of disease, stress and yield,* and the associated eight sub-projects

Measurement	What	How	Target	Status
Articles generated	The number of articles produced per project for Wine Australia News and stakeholder publications		**2 per project**	Achieved – 2 articles per project. Cotton project information published in cotton industry-specific publications (listed in Section 5.1)
Audience impact - newsletters	Stakeholder interaction with Wine Australia newsletters	Based on MailChimp industry benchmark	**3%**	Achieved – 3.2%
Key message delivery - media	Measurement based on the delivery of a set of predetermined messages in generated media coverage	Coverage evaluated on a scale of 0-3: 0= No key messages communicated 1 = One key message communicated 2 = Two key messages communicated 3 = Three key messages communicated	**50%**	Under target at 48%. However, 88% of articles included at least one message. In addition, as the projects progressed it became clear that specific project findings were of more relevancy to stakeholders than the initial broad messages identified at the commencement of the plan. Therefore, more emphasis was placed on messages specific to the individual projects.
Funding acknowledgement	The percentage of total articles that mention Wine Australia and DAWE correctly in either written, visual or verbal form	Each piece of coverage is simply marked as including this or not	**60%**	Achieved – 86%.
Sentiment	The percentage of coverage that is positive or neutral for the projects	Each piece of coverage is marked positive, negative or neutral	**70%**	Achieved – 100% of coverage was either positive or neutral.

5 Appendix - additional project information

5.1 Media, publications and presentations

Industry publications and media

- "Improving Australia's winegrape profitability through digital technologies" 14/06/2016; Daily Wine News. https://winetitles.com.au/improving-australias-winegrape-profitability-through-digital-technologies/
- "Wine and cotton industries receive $3m boost to develop new yield and disease monitoring systems 14/06/2016; Published by ABC. http://www.abc.net.au/news/2016-06-14/wine-and-cotton-industries-receive-3m-boost-for-research/7509156
- "Improving Australia's winegrape profitability through digital technologies" 14/06/2016; Published by Get Farming. http://getfarming.com.au/2016/06/14/improving-australias-winegrape-profitability-through-digital-technologies/
- "Grape and cotton growers get funding to help yield and disease prevention" 14/06/2016; Published by Wellington Times. http://www.wellingtontimes.com.au/story/3968373/grapeandcottongrowersgetfundingtohelpyieldanddiseaseprevention/
- "Wine tax: Nationals leader Barnaby Joyce on the case" 15/06/2016; Published by Central Western Daily. http://www.centralwesterndaily.com.au/story/3968936/winetaxnationalsleaderbarnabyjoyceonthecase/
- "Wine tax: Nationals leader on the case" 15/06/2016; Published by Central Western Daily
- "Improving wine grade profitability" 15/06/2016; Published by Tumbarumba Times
- "Digitally improving wine" 16/06/2016; Published by The Islander
- "Improving profitability through digital technologies" 1/07/2016; Published by Australian and New Zealand Grapegrower and Winemaker
- "Digital technologies to support the grape and wine community" 31/07/2017; Published by Wine and Viticulture Journal
- Radio: 26 hits across ABC Radio network 14/06/2016; Published by ABC Radio
- Radio: Broadcast Southern Cross 15/06/2016; Published by Southern Cross GTS/BKN
- "Surveying for disease – an update on early season disease survey results" CottonInfo e-news, 24 April 2017
- "Spotted anything unusual?" CottonInfo e-news, 6 November 2017

- "Solarisation under the microscope at Garah" Spotlight, Autumn 2018 https://www.cottoninfo.com.au/sites/default/files/documents/Autumn18_Sc.pdf
- "Longer rotations are required to reduce Verticillium where disease levels are high" Linda Scheikowski, Linda Smith, Gupta Vadakattu, Tim Shuey and Dinesh Kafle. Australian CottonGrower Dec 2018 p 14-18 https://www.cottongrower.com.au/images/articles/7683ed7e57fa7f89f444d2f2593a51df.pdf
- Regional Disease Update 2016 – 2017 for the CRDC Pest Management Guide
- Regional Disease Update 2017 – 2018 for the CRDC Pest Management Guide
- Regional Disease Update 2018 – 2019 for the CRDC Pest Management Guide
- Regional disease survey summary for the 2017/18 CSD Trial Results USB Booklet
- Regional disease survey summary for the 2018/19 CSD Trial Results USB Booklet
- "Fact Sheet - Vert Update: The latest in vert research." Holman, S., K. Kirkby, L. Smith and H. Hatnett 2016 https://www.cottoninfo.com.au/sites/default/files/documents/Vert%20update%20%28long%29%20-%20August%202016%20v3.pdf
- "Breaking the Verticillium Cycle" Spotlight Magazine – Winter 2017, page 11 https://www.crdc.com.au/sites/default/files/pdf/Winter17_sc_0.pdf
- "Diagnosis for Decision Making" Spotlight Magazine – Autumn 2018, page 30 https://www.crdc.com.au/sites/default/files/pdf/Autumn18_Sc.pdf
- "All the dirt on Vert" Spotlight Magazine – Spring 2019, page 22 https://www.crdc.com.au/sites/default/files/pdf/CRDC%20Spotlight%20Spring%202019.pdf
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- "Embrace vineyard variability, says precision viticulture expert" 9/11/2018; Published by Wine Australia RD&E News. https://www.wineaustralia.com/news/articles/embrace-vineyard-variability
- "Free GIS 'toolkit' released" Knights S. (2018) Precision Ag News 15 (3), 12-1
- "CSIRO's precision agriculture tools (PAT) now available" 13/02/2019. Waite Research Precinct News. https://www.thewaite.org/csiros-precision-agriculture-tools-pat-now-available/

Presentations to industry

- Crop protection update meetings in Emerald, Qld (18 October 2016), and Theodore, Qld (20 October 2016)
- CRDC Board tour in Narrabri with Namoi growers to highlight collaborative project between DAF and CottonInfo. 16 August 2016
- Presentation to CRDC Board on nematode research program, Theodore, Qld. 7 February 2017
- Presentation on seed treatments and managing seedling diseases to Emerald. Qld, and Theodore, Qld, growers during CSD roadshows. 7 - 8 June 2017
- Presentation to Goondiwindi growers at local meeting organised by Sally Dickinson providing an end of season review. 19 June 2017
- Presentation to growers and consultants in the Macintyre Valley (Goondiwindi) at a Verticillium information session (Linda Smith: season update; Linda Scheikowski: results from the 'Getta Getta' trial) 9 August 2017
- Presentation made at Auscott and Wee Waa to growers concerning Verticillium (Linda Smith: Verticillium wilt update; Linda Scheikowski: Verticillium – 'Getta Getta' rotation trial) 30 August 2017

- Discussion with Hillston cotton growers and consultants concerning black root rot. Field visits followed with further grower and consultant discussions. 14 November 2017
- Research updates presented at the Macintyre Valley End of Season Review in Goondiwindi. Season survey update (Linda Smith); Verticillium wilt research update (Linda Scheikowski). 13 June 2018
- Research updates presented at the CCA meeting in Narrabri. Disease survey update (Linda Scheikowski); Verticillium wilt research update (Linda Scheikowski). 21 June 2018
- Disease survey update and research summary presented at the MCGA meeting in Mungindi. 14 November 2018
- Research update on the use of corn in rotation with cotton to manage Verticillium wilt. Wee Waa. Linda Smith and Linda Scheikowski. 6 June 2019
- Disease update at the CCA workshop, Jondaryan, Qld. Linda Smith. 15 August 2019
- Disease update by Due Le at the CCA workshops in Griffith (22 August 2019) and Moree (29 August 2019)
- Verticillium update at 'Strathguyle', Garah, NSW and farm walk. Verticillium wilt research (Linda Smith) and overview of a solarisation trial to manage Verticillium wilt. 24 January 2018
- CottonInfo 'Cotton diseases 101', organized by Sharna Holman, presented to new local agronomists at Emerald, Qld. 9 October 2018
- "Taking grapevine yield forecasting into the digital age: assessing bud fruitfulness non-destructively" Jones J, Close D, Dambergs B, Rodemann T; Wine Tasmania 'Cut cut cut' pruning workshop. 23-24 June 2019
- "Assessing bud fruitfulness non-destructively" Jones J, Close D, Dambergs B, Rodemann T; AVSO Intelligent Systems Profitable Winegrowing, Mildura, Vic. 02-03 August 2017
- "Monitoring grapevine pathology with hyperspectral imaging" Bob Dambergs, Australian Society of Viticulture and Oenology Frontline Pest and Disease Management for Healthy Vineyards seminar, Mildura Victoria, 25-26 July 2018 https://www.asvo.com.au/videomonitoring-grapevine-pathology-hyperspectral-imaging
- "Digital Spraying" Andrew Hewitt, Australian Society of Viticulture and Oenology Frontline Pest and Disease Management for Healthy Vineyards seminar, Mildura Victoria, 25-26 July 2018 https://www.asvo.com.au/videodigital-spraying
- Presentation/equipment demonstration by Andrew Hewitt and Chris O'Donnell at wine grower workshops in:
    - New South Wales (Griffith, Leeton and Yanco; August 2017)
    - Tasmania (Hobart and Launceston; January 2018)
    - Queensland (at the Stanthorpe 'vineyard walks' in 2017, 2018, 2019, 2020)

Presentations or papers at conferences and workshops

- Linda Smith, National Disease Surveys Update; Quick diagnostic kit for *Verticillium dahliae* based on LAMP technology; Reniform nematode – an update. FUSCOM Goondiwindi NSW, 7-9 August 2017.
- Linda Scheikowski, Verticillium – Getta Getta trial. FUSCOM Goondiwindi NSW, 7-9 August 2017.
- Gupta, V.V.S.R., Smith, L. and Scheikowski, L., (2017) How different are soil fungal communities in different cotton growing regions. FUSCOM Goondiwindi NSW, 7-9 August 2017.
- Smith, L. (2017). Plant Disease Epidemiology: The challenges to managing economically important pathogens in Australian cotton. Cotton Research Conference Abstract Book, 3rd Australian Cotton Research Conference, CSIRO Discovery Centre, Canberra, 5-7 September 2017: 17.
- Scheikiowski, L. Smith, L. and Shuey, T. (2017). Vericillium wilt – rotation crops. Cotton Research Conference Abstract Book, 3rd Australian Cotton Research Conference, CSIRO Discovery Centre, Canberra, 5-7 September 2017: 54.
- Gupta, V.V.S.R., Smith, L., Scheikowski, L., Hunter, G. and Greenfield, P. (2017) Region-based differences in the diversity and abundance of fungal communities in cotton soils. 3rd Australian Cotton Research Conference, CSIRO Discovery Centre, Canberra, 5-7 September 2017.
- Smith, L.J., Scheikowski, L.J. and Cobon, J. (2017). Can reniform nematode (Rotylenchulus reniformis) in Australian cotton be managed by crop rotation? Science Protecting Plant Health Conference Handbook, Brisbane Convention & Exhibition Centre, Brisbane 26-28 September 2017: 69.
- Gupta, V.V.S.R., Penton, C.R. and Tiedje, J.M. (2017) Small worlds-big functions: soil fungal networks and plant health. Oral presentation 2nd Global Soil Biodiversity Conference, held during 15-19 October in Nanjing, China.
- Gupta, V.V.S.R. (2019) Australian Cotton Soil microbiome, Invited oral presentation at the International Agricultural Microbiomes RCN workshop (National Science Foundation USA funded) held during on Nov 25th in Melbourne, Australia
- New approaches to disease surveys: Linda Smith. Australian Cotton Conference, Gold Coast 7 - 9 August 2018
- Two year rotation lowers incidence of Verticillium wilt: Linda Scheikowski. Australian Cotton Conference, Gold Coast 7 - 9 August 2018
- Gupta, V.V.S.R. (2018) Microbes do bounce back in Cotton soils. Australian Cotton Conference, Gold Coast 7 - 9 August 2018
- 2017/18 National Disease Surveys- An Update: Linda Smith and Aphrika Gregson. FUSCOM Griffith NSW, 28 – 29 August 2018
- Verticillium Wilt Update: Linda Scheikowski. FUSCOM Griffith NSW, 28 – 29 August 2018

- Genetic characterization of black root rot pathogen on cotton in NSW: Duy Le. FUSCOM Griffith NSW, 28 – 29 August 2018
- Alternaria leaf spot – an emerging disease and pathogen in cotton?; Duy Le. FUSCOM Griffith NSW, 28 – 29 August 2018
- Cotton disease diagnostics – season 2017/18 update: Aphrika Gregson. FUSCOM Griffith NSW, 28 – 29 August 2018
- Fusarium species collected from seedling and mature cotton in NSW: Duy Le. FUSCOM Griffith NSW, 28 – 29 August 2018
- Two year crop rotation lowers incidence of Verticillium wilt in cotton. Linda Scheikowski, Linda Smith, Tim Shuey and Dinesh Kafle. Australasian Soil-borne Diseases Symposium, Adelaide, 4 – 7 September 2018
- Genetic characterisation of black root rot pathogen of cotton in NSW Australia. Duy Le and Aphrika Gregson. Australasian Soil-borne Diseases Symposium, Adelaide, 4 – 7 September 2018
- Gupta, V.V.S.R., Kirkby, K., Smith, L and Penton, C.R. (2018) Disease suppression: soil fungal community diversity and interactions. In: Proceedings of 10th ASDS meeting, Gupta VVSR et al. (eds.). pp. 171-172, Adelaide.
- Gupta, V.V.S.R., Kroker, S.K., Hicks, M., Nidumolu, B. and Weir, D. (2018) Effect of adding compost on microbial activity and composition in Australian cotton soil. In: Proceedings of 10th ASDS meeting, Gupta VVSR et al. (eds.). pp. 161-162, Adelaide
- Duy Le: Alternaria leaf spot of cotton: a re-emerging disease associated with a new pathogen. AACS Cotton Research Conference, Armidale NSW, 28 – 30 October 2019
- Aphrika Gregson Colletotrichum truncatum, a new causal agent associated with cotton boll rot in Australia. AACS Cotton Research Conference, Armidale NSW, 28 – 30 October 2019
- Dinesh Kafle et al. Understanding the ecology of reniform nematodes in Australian cotton. AACS Cotton Research Conference, Armidale NSW, 28 – 30 October 2019
- Linda Scheikowski et al. Host or non-host: study on Verticillium dahliae. AACS Cotton Research Conference, Armidale NSW, 28 – 30 October 2019
- Linda Smith et al. Prevalence and distribution of cotton diseases in 2018/19 season. AACS Cotton Research Conference, Armidale NSW, 28 – 30 October 2019
- Gupta VVSR et al. Harnessing beneficial microbiomes in cotton systems. AACS Cotton Research Conference, Armidale NSW, 28 – 30 October 2019
- Le DP, Gregson A, Ravichander P, Aitken E, Scheikowski L, Smith L, 2019. Fusarium wilt of cotton: surveillance, detection and management. Fusarium Workshop, the 22nd APPS, Melbourne, Australia November 2019 (oral presentation)
- Le DP, Gregson A, Jackson R, Smith L, 2019. Cotton diseases: the big four in NSW. The 22nd APPS, Melbourne, Australia November 2019 (oral presentation)

- Jones J, Close D, Dambergs B, Rodemann T, 2019, 'Taking grapevine yield forecasting into the digital age: assessing bud fruitfulness non-destructively', 17th Australian Wine Industry Technical Conference, Digital Technology Workshop, 21-24 July 2019, Adelaide SA.
- Jones J, Close D, Dambergs B, Rodemann T, 2019, 'Taking grapevine yield forecasting into the digital age: assessing bud fruitfulness non-destructively', Crush – the grape and wine science symposium, Adelaide, September 2019.
- Digitising the vineyard: developing new technologies for viticulture in Australia. E.J. Edwards, M.R. Thomas, S. Gensemer, P. Moghadam, T. Lowe, D. Wang, R. Lagerstrom, C. Hargrave, J. Ralston. (2019) Poster presentation at the 21st GiESCO meeting, Thessaloniki.
- Digital opportunities: from the vineyard to the winery door. E.J. Edwards, M.R. Thomas, S. Gensemer, P. Moghadam, T. Lowe, D. Wang, R. Lagerstrom, C. Hargrave, J. Ralston. (2019) Oral presentation and conference paper at the 17th Australian Wine Industry Technical Conference. Adelaide.
- Intelligent systems for commercial application in perennial horticulture. Edwards, E. J. and Moghadam, P. (2020). Oral presentation at TropAg 2019, Brisbane. Abstract published in: Multidisciplinary Digital Publishing Institute Proceedings, 36(1):59.
- Phenotyping vineyards by means of airborne hyperspectral imaging. U. Knauer, E.J. Edwards, A. McGrath, U. Seiffert (2018) Poster presentation at the 5th International Plant Phenotyping Symposium, Adelaide.
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- Digitising the vineyard: developing new technologies for viticulture in Australia. E.J. Edwards, M.R. Thomas, S. Gensemer, P. Moghadam, T. Lowe, D. Wang, R. Lagerstrom, C. Hargrave, J. Ralston. (2019) Poster presentation at the 21st GiESCO meeting, Thessaloniki.
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- Intelligent systems for commercial application in perennial horticulture. Edwards, E. J. and Moghadam, P. (2020). Oral presentation at TropAg 2019, Brisbane. Abstract published in: Multidisciplinary Digital Publishing Institute Proceedings, 36(1):59.
- Digital twin for the future of orchard production systems. Moghadam, P., Lowe, T., and Edwards, E. J. (2020). Poster presentation at TropAg 2019, Brisbane. Abstract published in Multidisciplinary Digital Publishing Institute Proceedings, 36(1):92.
- Dambergs, RG (2017) Hyperspectral imaging of Botrytis in grapes CRUSH 2017, 13-14 November, Adelaide. This presentation was awarded ‘best snapshot presentation’.
- Dambergs, RG (2018) Hyperspectral imaging of Botrytis in grapes CRUSH 2018, 25-26 September, Adelaide.

- Dambergs, RG (2019) Digital solutions for grape quality measures at the weighbridge EvokeAG, Melbourne 19-20 February 2019
- Frost and Heat Mapping for Vineyards Using Drones Anthony Finn, Australian Wine Industry Technical Conference, Adelaide Convention Centre 21-24 July 2019, Adelaide, 2019
- Hewitt, A.J. and O'Donnell, C.C. (2018) Dose optimisation through recapture/recycle spraying and sensor (LiDAR) spraying. Dose Expression Workshop 6-7 November, 2018, Association of Applied Biologists. Universitat Politècnica de Catalunya, Barcelona, Spain
- Hewitt, A.J. and O'Donnell, C.C. (2020) Viticulture drift reduction technologies. National Working Party on Pesticide Applications virtual workshop, 28 May 2020
- Llorens, J. and Hewitt, A.J. (2019) Droplet Size Effects in a PWM System. First Results to Improve Orchard Spray Application. Suprofruit 2019. 15th Workshop on Spray Application and Precision Technology in Fruit Growing East Malling, United Kingdom, 16 – 18 July 2019
- Ratcliff, C., Gobbett, D. and Bramley, R. 2018. PAT and QGIS – your new best mates for PA data analysis. Proceedings of the 21st Symposium of Precision Agriculture in Australasia. 10-11 September, Adelaide Oval, Adelaide. SPAA / University of Sydney. pp. 47-49
- Ratcliff C, Gobbett D, Bramley R. 2019. 'PAT' – Making Precision Viticulture data analysis tools accessible. Proceedings of the 17th Australian Wine Industry Technical Conference, Adelaide, July 2019. In press.
- Ratcliff C, Gobbett D, Bramley R. 2019. PAT': Accessible tools for precision agriculture data analysis. Proceedings of the 19th Australian Agronomy Conference, Wagga Wagga, September 2019. In press.

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- Duy P. Le & Aphrika Gregson, 2019. "Alternaria leaf spot of cotton seedlings grown in New South Wales, Australia is predominantly associated with *Alternaria alternata"*. Australasian Plant Pathology https://doi.org/10.1007/s13313-019-0617-9
- "Verticillium wilt of cotton: identification and detection of the causal pathogen and its control". Duy P. Le, Karen Kirkby, Carlos Trapero, Thao T. Tran and Linda Smith. In press.
- Chapman, T. A., C. G. A, K. A. Kirkby and R. M. Jiménez-Díaz (2016). "First report of the presence of *Verticillium dahliae* VCG1A in Australia." Australasian Plant Disease Notes 11(13): 1-4.
- Young. S., Kirkby. K., Roser. S and Harden. S. "Method for estimating *Verticillium dahliae* inoculum in Australian cotton soils". Submitted to Crop and Pasture Science 9/3/20.
- Dadd-Daigle. P. Kirkby. K., Chowdhury. P., Labbate. M and Chapman. T. "Literature review - The Verticillium wilt problem in Australian cotton". Submitted to Australasian Plant Pathology 22/11/19.
- Dadd-Daigle. P. et al. "Virulence not linked with Vegetative Compatibility Groups in Australian cotton *Verticillium dahliae* isolates". Accepted for publication in Australian Journal Crop Science

- Dadd-Daigle. P., Kirkby, K., Roser. S.,Lonergan. P., Chowdhury. P., Labbate. M and Chapman. T. "Virulence varies in Australian cotton *Verticillium dahliae* isolates". Draft manuscript
- Dadd-Daigle. P. et al. "Whole genome analysis of Australian *V. dahliae* Vegetative Compatibility Group 1A". Draft manuscript
- Dadd-Daigle. P. "Verticillium wilt in Australian cotton: examining the relationship between Australian Verticillium dahliae isolates and virulence" In press
- Jones JE, Eyles A, Claye C, Rodemann T, Dambergs RG, and Close DC. 2020. "Prediction of starch reserves in intact and ground grapevine cane wood tissues using near infrared reflectance spectroscopy (NIRS)", Journal of the Science of Food and Agriculture https://onlinelibrary.wiley.com/doi/abs/10.1002/jsfa.10253
- "Canopy density estimation in perennial horticulture crops using 3D spinning LiDAR SLAM". Lowe, T, Moghadam, P. Edwards, E.J. & Williams, J. Submitted to the Journal of Field Robotics and is under review.
- "Preliminary evaluation of atmospheric temperature and wind profiles obtained using unmanned aerial vehicle based acoustic tomography" A. Finn, K. Rogers, J. Meade, J. Skinner, and A. Zargarian. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W13, 283–287, https://doi.org/10.5194/isprs-archives-XLII-2-W13-283-2019, 2019
- "Extraction of vineyard macrostructure from sub-optimal sequences of aerial imagery" A. Finn, A. Melville-Smith, and R. Brinkworth. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., IV-2/W5, 103–110, https://doi.org/10.5194/isprs-annals-IV-2-W5-103-2019, 2019
- "Accurate group velocity estimation for unmanned aerial vehicle-based acoustic atmospheric tomography" Kevin J. Rogers and Anthony Finn. The Journal of the Acoustical Society of America 141, 1269 (2017); https://doi.org/10.1121/1.4976818
- "Spatio-temporal observations of temperature and wind velocity using drone-based acoustic atmospheric tomography" Anthony Finn, Kevin Rogers, Joshua Meade, Jarrod Skinner and Amir Zhargarian. The Journal of the Acoustical Society of America 145, 1903 (2019); https://doi.org/10.1121/1.5101906
- Tang, Q, Zhang, R., Chen, L., Deng, W, X, M., Gang, L., Longlong and Hewitt, A. (2020) "Numerical simulation of the downwash from an unmanned helicopter for crop spraying". Computers and Electronics in Agriculture 174
- Zhang, R. Longliong, L., Wang, F., Chen, L., Tongchuan, Y., Qing, T. and Hewitt, A.J. (2019). "Spraying atomisation performance by pulse width modulated variable and droplet deposition characteristics in wind tunnel". Trans CSAE 35(3): 42-51.

Videos published online

- "Managing Fusarium wilt" (launched June 2018) [CottonInfo: connecting growers with research] https://youtu.be/Cygy6XiRDcw
- "Reniform nematode in cotton" Linda Smith (launched June 2018) [CottonInfo: connecting growers with research] https://youtu.be/QgBn4vfkOzI

- "Verticillium wilt in cotton" Linda Smith (launched June 2018) [CottonInfo: connecting growers with research] https://youtu.be/hgiatA52nNw
- "Biosecurity top tips: prevent disease transfer between fields" Tim Shuey (launched September 2018) [CottonInfo: connecting growers with research] https://youtu.be/bXIEsY87CXo
- "Biosecurity top tips: disease surveys find out what is (and isn't) in your fields" Linda Scheikowksi (launched September 2018) [CottonInfo: connecting growers with research] https://youtu.be/fHWzrlmgUy4
- "Predicting bud fruitfulness" University of Tasmania. 2020. https://www.youtube.com/watch?v=dHmOmCeEApM&feature=youtu.be

5.2 Intellectual property

Intellectual property created or arising from the project is listed below.

Sub-project	Project IP description
CRD 1601	• Geospatial database containing disease survey data
	• Laboratory-based pathogen suppression potential assay was developed which provides a quantitative measure of a cotton soils ability to support or inhibit soil-borne fungal pathogens such as *Verticillium dahliae*
	• Optimisation of the *Verticillium* molecular and quantification assay for soil and plant tissue
UT 1601	• Library of NIR spectral images of Pinot Noir and Chardonnay buds
	• Algorithm for model predicting bud fruitfulness using Ocean Optics Jaz NIR instrument
	• Algorithm for model predicting bud fruitfulness using ARCoptix Rocket NIR instrument
	• Web based portal for applying fruitfulness prediction model in a vineyard, developed by Indicium Dynamics for the project
	• Hand-held NIR trigger and associated sound alarms for automated use in the field
CSA 1602	• Models for discriminating between shrivelled and non-shrivelled fruit based on proximal hyperspectral measurements
	• Calibration models for predicting fruit compositional parameters, such as total soluble solids, titratable acidity, anthocyanin content, based on proximal hyperspectral measurements
	• Corrected proximal hyperspectral reflectance data sets of both individual berries, labelled with shrivel status, and whole bunches with paired visually assessed % shrivel score
	• Paired proximal hyperspectral reflectance and ground-truth data sets for berry composition calibration models; including total soluble solids, titratable acidity, anthocyanin content and other parameters
	• Detector for identifying and marking (with a rectangular boundary box) grapevine inflorescences in colour digital images, based on machine learning tools (third party IP)
	• Detector for identifying and marking (with a rectangular boundary box) grape bunches in colour digital images, based on machine learning tools (third party IP).
	• Tracking algorithm for following detected grapevine parts (e.g. inflorescences and bunches) through video frame sequences
	• Data processing pipeline (series of scripts) for counting grapevine parts (e.g. inflorescences and bunches) in videos, utilising detectors and tracking algorithm listed above
	• Data set of video frames, with grapevine inflorescences hand labelled (with a rectangular bounding box)
	• Data set of video frames, with grape bunches hand labelled (with a rectangular bounding box).
	• Radar datasets, including ground-truth fruit weights

Sub-Project	Description
CSA 1601	• Models for discriminating between vine tissue types (fruit, leaves, cane, tendril, inflorescence and shoot tip) based on *proximal* hyperspectral measurements.
	• Calibration models for predicting canopy composition (Chl, N and cations) based on *proximal* hyperspectral measurements
	• Calibration models for predicting canopy composition (Chl, N and cations) based on remote (aerial) hyperspectral measurements
	• Calibration models for predicting canopy function measures (photosynthetic capacity) based on proximal hyperspectral measurements
	• Models for discriminating between healthy and infected (powdery mildew) leaves based on proximal hyperspectral measurements
	• Corrected proximal hyperspectral reflectance data sets, labelled with grapevine tissue type.
	• Paired proximal hyperspectral reflectance and ground-truth data sets for calibration models; including chlorophyll, nitrogen, cations (measured by ICP-OES) and photosynthetic capacity (maximum carboxylation rate).
	• Paired remote hyperspectral reflectance and ground-truth data sets for chlorophyll, nitrogen, cations (measured by ICP-OES) calibration models.
	• Corrected proximal hyperspectral reflectance data sets, labelled with powdery mildew incidence.
	• Data processing pipeline to determine leaf area index from upward facing RGB video recordings (taken below vine canopy). Multiple tools held together with scripts to be interoperable.
	• Method to determine leaf area per unit of 3D space from LiDAR ray-cloud data using CSIRO AgScan3D+ ray-cloud library (BIP, row 9). Mathematical concept.
	• Data processing pipeline (series of scripts) to determine grapevine ground cover from UAV RGB images, based on separating ground and canopy using 3D data determined from multiple 2D images using photogrammetry. Uses OSS or commercial software to generate 3D data, pipeline processes the generated 3D data of interest.
USA 1601	• Method to determine vine row orientation and dimensions from UAV imagery

5.3 Equipment and assets

Equipment or assets created or acquired during the period covered by the project.

Sub-project	Equipment or asset created or acquired
CSA 1601, CSA 1602	Headwall eVNIR Micro hyperspectral camera
	Ximea NIR hyperspectral linescan camera
	Hammatsu Point-spectrometer
	Viticulture Dataset: Grapevine Inflorescence Detection. v1. CSIRO. Data Collection. https://doi.org/10.25919/5de4546aeacce
AWR 1601	Specim FX10 hyperspectral camera
UQ 1601	SICK LMS100 LiDAR
CSA 1603	PAT - Precision Agriculture Tools. v1. CSIRO. Software Collection. https://doi.org/10.25919/5c731a813b91a.
	pyprecag - a Python package for the analysis of precision agriculture data. v1. CSIRO. Software Collection. https://doi.org/10.25919/5c731a41954ce.
	PAT - Precision Agriculture Tools. v2. CSIRO. Software Collection. https://doi.org/10.25919/5d23f9fb58722

5.4 Budget

Project funds were received and expended according to budget. The Final Financial Report will be submitted by the agreed deadline.

5.5 Agreement execution dates

Partner organisations and the dates that project agreements were executed

Research Partner	Project code	Project Agreement signed	Program Management Agreement signed
The Australian Wine Research Institute	AWR 1601	23/5/2017	19/5/2017
Cotton Research & Development Corporation	CRD 1601	10/1/2017	22/11/2016
CSIRO	CSA 1601 CSA 1602 CSA 1603	12/10/2016	19/1/2017
The University of Queensland	UQ 1601	17/11/2016	8/12/2016
The University of South Australia	USA 1601	7/11/2016	8/12/2016
The University of Tasmania	UT 1601	7/11/2016	25/11/2016
Industry partner			
Accolade Wines		-	23/11/2016
Barton Vale Technologies		-	21/11/2016
Horticulture Innovation Australia Limited		-	24/11/2016
Lastek Pty Ltd		-	11/5/2017
Pernod Ricard Winemakers		-	9/6/2017
Tolpuddle Vineyard Pty Ltd		-	22/11/2016
Treasury Wine Estates		-	25/11/2016