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LiDAR and PACE for Vineyards



Final Report to Wine Australia

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Abstract

We aimed to improve accuracy of spray placement and dosing in dynamic vineyard environments. Our LiDAR and RADAR-based systems for assessing canopies before and during spraying were evaluated throughout the season, using variable rate Pulsed Width Modulation. Our novel electronic leaves with transmitters verified and audited deposition. Using a recycle sprayer or our ducted sprayer with LiDAR, we reduced chemical use rates for the same spray coverage throughout the season. Savings were 50-90% in sparse canopies with large gaps through to 10-50% for dense canopies without gaps. A commercial retrofit sensor system will be available in Australia in late 2020.

Executive summary

This is a project involving novel sensors to improve dosing of chemical sprays applied to vine crops according to each unique canopy, as part of a larger Digital Viticulture project.

Research was conducted in wind tunnel and field trials to develop and evaluate systems for optimisation of spraying in vineyards according to the dynamic canopy environment. 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 purpose of this project was to develop and assess various systems which can be applied as modifications to existing spraying systems or through investment in a specialised sprayer when new equipment is purchased. Our research considered existing Apps such as VitiCanopy, PIX4D imaging, PARbar ceptometers and other existing LAI measurement systems. We also progressed new systems to automate spraying with LiDAR sensors for canopy characterisation in real-time. A RADAR unit measures the speed to offset the timing of activation of solenoids to deliver variable spray rates through each nozzle according to both the target surfaces (leaves and woody vine materials) and local canopy density. An alternative dose and drift management support approach was also tested in the form of recapture/ recycle spraying, which unlike the LiDAR application management approach was commercially available at the start of the project.

We developed and tested electronic leaf spray coverage systems with an aim to replace water sensitive papers and fluorescent dyes with digital sensors for spray coverage and auditing. We explored the use of unmanned application systems as robotic platforms for future spraying.

Our research showed that manual assessments of spray canopy structure and target locations can be replaced or supplemented with automated systems to control the spray placement and dose rate in real time, offering equal spray coverage with reduced spray volumes. Such systems will be available around September 2020 for modifying existing sprayers. The commercial system has some changes from our test system such as a different LiDAR system, the use of GPS rather than RADAR and improved solenoid systems for higher spray pressure use. We found that recapture/ recycle sprayers could also offer similar results of improved spray placement and dosing without spray losses through drift and runoff, for cases where end-users would decide to invest in a new sprayer. In our tests, LiDAR-supported and recapture/ recycle spraying systems offered greater savings in chemical use and drift reduction with lower canopy density – in other words, the greatest benefits occurred earlier in the spray season with savings in chemical up to 70-90%, but with high savings (up to 30%) even at late growth stages when canopies are fully developed with fruit. For specific targets such as spraying only the woody materials for dieback disease management, chemical savings exceed 90% and targeting is precise, allowing 100% coverage automatically without human control with the use of appropriate nozzles/ pressures.

Drift reductions from LiDAR sensor spraying and recycle spraying closely matched the reductions in chemical use rates with 60% being typical.

Our research showed that pulsed width modulation (PWM) offers an effective way of delivering the optimal spray dose rate for each local canopy density. However, we established that unlike prior broadacre crop application work with flat fan nozzles and ground horizontal boom sprayers, the cone types of nozzles and higher pressures commonly used in viticulture do not always offer constant droplet size across the operating PWM duty cycle rates, so care must be taken to select nozzles that are compatible with spray angle and droplet size requirements. Otherwise, with many cone nozzles, when spray rate is higher (for dense canopies), droplet size will be smaller. This could help with canopy penetration and coverage which are advantages, but could also increase drift potential which is a disadvantage.

Robotic platforms can perform well, especially if spray placement is adjusted with changing weather conditions such as through swath displacement. In order to achieve sufficient canopy penetration with a drone sprayer, small droplets should be applied, but care must be taken to offset the aircraft position and avoid the spray missing the rows. Indeed, wind displacement of spray is an issue for LiDAR sensor sprayer applications as well, when canopy density is sparse. Our research suggests drones, and for sparse canopies ground LiDAR-equipped targeted sprayers, should only be used when the wind speed is below 10 km/h unless the application is made allowing for swath displacement (e.g. modify the time the solenoids open and/ or the sprayer position). On the other hand, recapture/ recycle sprayers increase the weather window for spraying all canopy densities to at least double this wind speed limit.

Electronic leaves are effective for assessing spray deposition and transmitting data back to the spray control system for auditing and verification of coverage.

We are acquiring a commercial system in the near future to evaluate as a final step for offering growers off-the-shelf LiDAR control systems later in 2020. It, along with a novel ground robotic platform, has been delayed in 2020 with the unexpected COVID-19 situation.

We would like to acknowledge the support from other groups which enhanced the findings of this project, such as the provision of dedicated project sprayer (Oktopus) and staff support from Silvan, the provision of sprayers and staff for field tests from FMR, access to vineyards, staff support and equipment use such as tractors and sprayers in several states including Vinland Estates (QLD), Ballandean (QLD/ NSW), Sergi Fresh (VIC), Treasury Wine Estates Cullulleraine (VIC) and planned tests in late 2020 of commercial systems in Langhorne Creek (SA). We appreciate the support of our colleagues for LiDAR control system work from USDA and comparison with European dosing approaches and field tests in Australia from Lleida University, Spain, dosing approaches in Australia, Geoff Furness and in the UK, Peter Walklate. We also wish to thank our colleagues from other organisations who assisted with equipment and/ or field test manpower such as NERCITA, Revolution Ag, Spectrum Electrostatics and Spraying Systems/ Teejet.

Our research revealed some interesting findings which were not previously known and which could benefit from additional future research such as the need to select appropriate nozzles for use with PWM, given that new nozzle designs such as air induction and modified cones are often different from prior types. Our work on electronic leaves could be further developed for integration within spray decision and accounting support systems, having shown proof of concept. The use of robotic platforms and aerial drones for spraying requires future research for optimisation across different vineyard types and pest control/ spray application needs. Future research is also suggested to look at alternative systems for individual nozzle variable rate spray release such as low-cost sensors and solenoids on each nozzle. We also believe that the whole area of digital spray targeting and traceability requires ongoing research as new sensors and changing regulatory and consumer demands concerning pesticide use evolve.

This project was supported by Wine Australia, through funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program, Horticulture Innovation Australia Limited and the University of Queensland.

Abbreviations and glossary

$D_{v0.5}$	Volume median diameter droplet size
LAI	Leaf Area Index
LiDAR	Light Detection and Ranging
NERCITA	National Engineering Research Centre for Intelligent Technology in Agriculture
PACE	Pesticide Adjusted for the Crop Environment
PAVE	Pesticide Adjusted for the Vineyard Environment
PWM	Pulsed Width Modulation
RADAR	Radio Detection and Ranging
UQ	University of Queensland
USDA	United States Dept of Agriculture
WSP	Water Sensitive Paper

1 Project rationale and objectives

This project is part of a larger research portfolio on Digital Viticulture which addresses the opportunities for digital systems to improve viticulture and other agricultural sectors. The present project covered the area of spray application for crop protection, weed and disease control.

For decades, spraying of vine crops has relied on principles and strategies of a) assessing the target or pest type and location, b) selecting optimal products, targeting and timing for spraying, c) deciding the appropriate spray volume for desired levels of coverage on upper/ lower leaf surfaces, the ground or woody crop materials, and d) avoiding spray losses, drift exposure to non-target sensitive areas and inappropriate crop residues. Given the dynamic nature of these parameters (e.g. spatially and temporally variable crop structures, weather patterns and regulations) and subjectivity in assessments, these factors should ideally be supported by the best available technologies which include recent developments in sensors for real-time assessments. It is well established that most drift from vertical crop spraying comes from spray over the top of the canopy, so having a way of turning off the top nozzles when there is no foliage adjacent to them and then turning them on when branches stick up intermittently along rows provides an important opportunity to avoid drift. Similarly, drift is highest when gaps in the canopy are largest, so adjusting the spray to avoid spraying in gaps is a key drift reduction strategy.

At the start of this project around late 2016, many vineyards were still using relatively old spray technologies such as axial fan airblast sprayers which present challenges to accurate spray placement in upper canopy areas when spraying from the ground up, and can produce relatively high spray losses through drift and runoff. As sprayers may be replaced every few years by many growers, or can be modified and upgraded with sensors and new nozzles for ongoing use, the use of better systems for replacement, or novel sensors for ongoing systems, was a logical area for our research. Even some of the best sprayers still rely on broadcast applications which mean the sprayer is fully on for an entire spray row rather than only being on when necessary for each target.

Over many decades, Australia has progressed to its current world-leading position in spray dose assessment using canopy leaf wall area where the spray volume to be applied per 100 m row length per m height of canopy forms the basis of application volume rate decisions. However, many labels and growers also reference spray rates in volume/ area units of L or kg/ha. Indeed, regulatory assessments require such inclusion in the process because the limits of off-target exposure to non-target sensitive areas are set as percentages of the application rate in mass/area units. For example, if an off-target exposure rate of 1 g/ha of pesticide X applied at 1000 g/ha to a vine crop can adversely affect a neighbouring crop, school, residential area or fish farm, the regulatory acceptable limit is stated to be 0.001 of the application rate. To convert this to spray volume per 100 m per 1 m of crop height, factors such as row spacing need to be included in the assessment.

Our project aimed to progress the concepts of dosing and targeting through the use of sensors for the canopy and spray, and the inclusion of or consultation with stakeholders from various industries (grower, applicator, regulator, pesticide registrant, researcher and sprayer

manufacturer). We believe the industry needs better tools for assessing and achieving optimal spray dosing both for planning spraying and for real-time variable rate and variable placement uses, and we aimed to help meet these needs through our research and extension.

The optimal volume of spray for foliage to achieve the first point of runoff is approximately 1.3 to 3.6 μL/cm^2 of target surface area. If upper and lower leaf surfaces need to be covered, this needs to double and for each additional "layer" of a 2-D crop target, the value needs to increase linearly. For example, a crop with a leaf area index (LAI) of 1 in early season or a young canopy will require half the spray volume rate of a crop twice as dense later in the season with an LAI of 2.

One objective of this project was to use currently used digital tools to assess LAI to support manual dosing calculations using tools such as the Wine Australia App, VitiCanopy.

A second objective was to use new tools to assess crop density and target location, using appropriate sensors such as PIX4D and LiDAR.

A third objective was to automate the spraying process using systems such as robotic platforms or spray control units that operate in real time without needing a human operator. Given that some spraying can be done by aircraft (e.g. herbicides and spraying with suitable downwash for canopy penetration for foliar sprays) which can easily be fitted with sensors, this included drone systems. For ground spraying, an integrated approach to measure target (e.g. leaf or woody material) location with LiDAR, spray timing offset using RADAR to account for driving speed and solenoid variable duty cycle to deliver variable rate spraying for variable canopy densities was used.

A fourth objective was to use digital sensors to replace or supplement more manual techniques such as sampling with water sensitive papers, for assessing spray coverage on the target. This involved digital leaves with transmitters to send the voltage readings correlated with liquid coverage back to a computer.

An alternative real-time dosing system was also assessed in the form of a recapture/ recycle sprayer because unlike the LiDAR approach, such commercial sprayers were already available at the time of this project and we believed these offered one of the best ways of addressing dosing and drift issues so could form a "current best practice" technique for comparison against our novel sensor sprayer approach.

The study covered different canopy growth stages and vine types/ locations for wine and table grapes.

The project did not aim to manufacture and sell a commercial spraying or spray management system, but rather to prove concepts and best approaches for vineyard spray dosing and targeting support to build on prior work in these areas for apples by our collaborator scientists from the USDA, UK horticulture sector and University of Catalonia, and sprayer manufacturer companies such as FMR and Silvan as well as to encourage an Australian marketing and support company for possible future commercial systems, Vuetech.

2 Method and project locations

The following table lists the test locations for the studies in this project.

Name & type of site	Street Address	State	Postcode
Campbell, Vinland Estates (Field site)	Fletcher Road, Fletcher	Queensland	4381
Ballandean Estate Wines (Field Site)	Sundown Road, Ballandean	Queensland/ New South Wales	4382
S&J Sergi (Field site)	Nardoo Road, Red Cliffs	Victoria	3496
Treasury Wine Estates (Field Site)	Beer Road, Lake Cullulleraine	Victoria	3496
Sam Puglisi Table Grapes (Field Site)	Beverley Road, Severnlea	Queensland	4352
The University of Queensland, Gatton Campus (Laboratory)	Warrego Highway, College View	Queensland	4343



Map showing Queensland/ New South Wales border region vineyard locations where field work was undertaken.



Map showing vineyard locations in Victoria where field work was undertaken.

Field studies for Variable Dosing Spraying

LiDAR/ RADAR/ Pulsed Width Modulation Sprayer

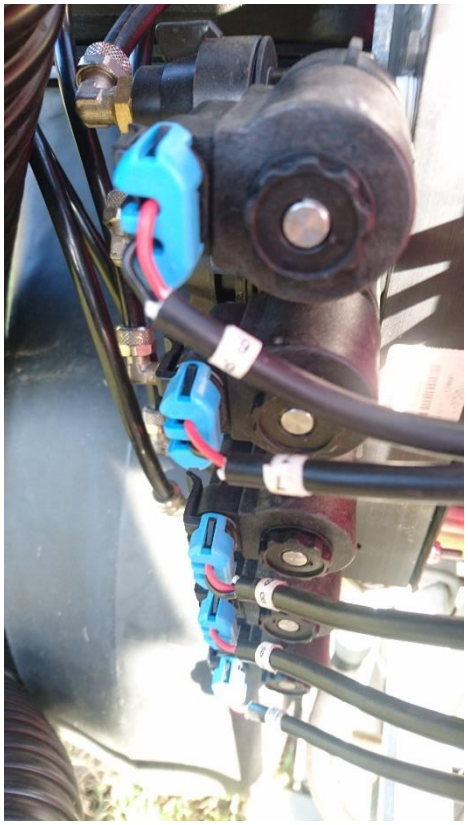
Initial research involved a SICK LMS100 LiDAR system which was used to assess vine canopies along with PIX4D data collection. By early 2017 we replaced this with a more portable and robust system as descried below.

An experimental automated spray application control system was used to operate in real time on a modified Silvan Oktopus sprayer and detect the location and density of all crop surfaces using a Hokuyo UTM 30LX LiDAR. This was selected because its <30 m range was ideal for covering the <3 m row spacing of our vineyards and its 270^{o}scanning angle arc was easily set to cover the ground up, for scanning the vine row on each side of the sprayer. The price was also reasonable for use in actual spraying situations, being no more than a few thousand dollars. It is known to perform well in field conditions with dust, vibration and heat, and is highly portable and small/ non-intrusive. The LiDAR is shown below, mounted on our sprayer system.



LiDAR mounted on sprayer.

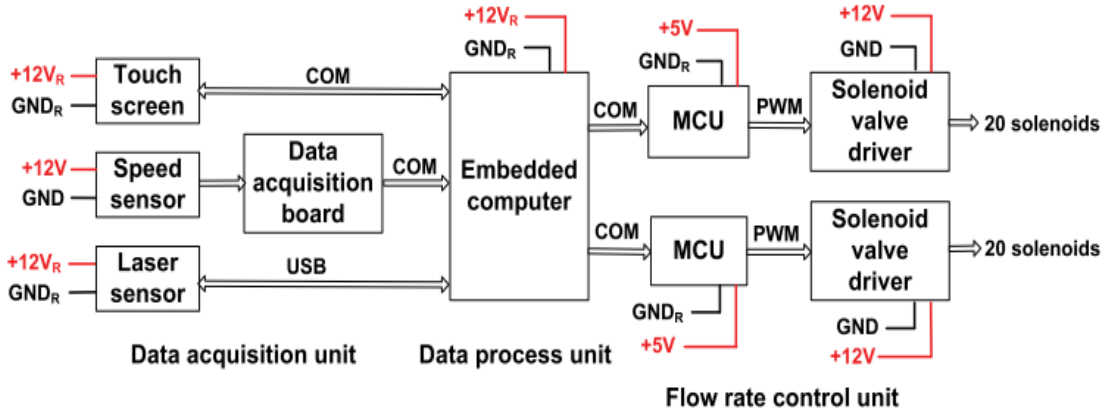
A RADAR (RVSIII radar velocity sensor) was used to measure the driving speed of the sprayer. The measurements, along with those from the LiDAR were automatically input to a Matrix MXE 1005 embedded fanless computer with Microsoft Visual C++ software and used to control the timing of the spray release for each detected target surface. The nozzle required to spray that target was activated by the system sending a signal to its solenoid (Teejet AAB144P) to open. The spray was pulsed using pulsed width modulation with the duty cycle set to that required for each application volume rate for spraying the detected canopy width/ density. For example, an area 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. The solenoids and nozzles are shown below, mounted on our sprayer system.

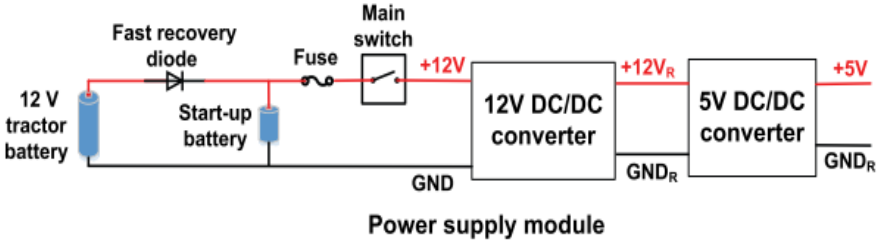




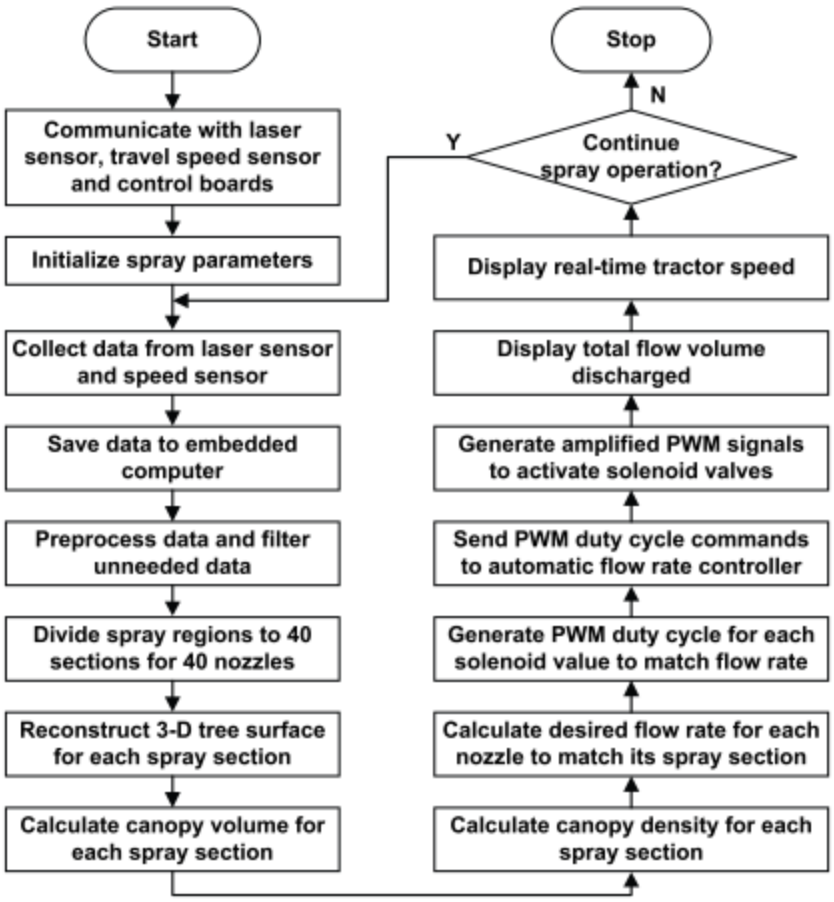
Solenoid array on one side of sprayer **Nozzle on air duct on sprayer**

The following diagram shows the automatic flow rate control system and power supply.





The following flow chart shows the Visual Basic C++ flow chart for the variable rate sprayer control system.



The Oktopus sprayer had ten air/ nozzle manifolds (5 on each of two sides) which were set in height to cover the canopy height range for each crop. The spray control system developed by USDA was configured with each nozzle range height (e.g. nozzle 1 covering targets from 0.3 m to 0.6 m above ground, nozzle 2 covering 0.6 to 0.9 m and so on – but with actual values depending on the foliage extent of the specific canopies) and the distance to the nearest foliage as well as the row spacing for each vineyard. The system was then operated in each of two "modes". Firstly it was operated with the sprayer on at 100% PWM duty cycle (i.e. full rate applications) the entire time that an application was to be made, referred to as "LiDAR OFF". Secondly, it was operated with the "LiDAR ON" configuration where the nozzles were turned on and off as targets were detected or absent at each location and the solenoids were open for durations specific to the detected canopy density. For example, for the main canopy area with most foliage the spray might be on at 100% PMW duty cycle but for the occasional branch sticking up at the top of the canopy it might be only on for a few seconds at a time and for a duty cycle around 10%. Each nozzle is therefore independently operated and controlled according to the sensed targets when the sprayer is operated in "LiDAR ON" mode, which would be expected to require less chemical for an application compared to the *spray always-on* configuration. For both modes, the sprayers were still set up with application rates that were considered appropriate for the canopies. This was true for all sprayers in the entire study. In other words, the sprayers were always setup optimally in terms of nozzle spray directions and maximum application volume rates for each canopy as advised by the local vineyard owners/ spray applicators for normal best practice.

The following photo shows the Silvan Oktopus sprayer with LiDAR system in use in Stanthorpe.



Silvan Oktopus sprayer with LiDAR spray control system.

Some tests were done with a novel electrostatic charging system to add a positive charge to the spray droplets which can help attract them to the target and offer wrap-around to both sides of leaves. For this purpose, one side of the sprayer was modified by adding charging metal rings connected to a high voltage supply. Atomisation is achieved by the nozzle and pressure and not affected by the electrical voltage. The purpose of the high voltage is to add a high electrohydrodynamic charge to the droplets once they have been formed. Similar to a lightning bolt, they then seek to be grounded as soon as possible so are attracted to the foliage. The nozzles were the same as the other side of the sprayer but with these charging units added, as shown below for two nozzles (the ATR80 nozzles can't be seen but are inside the metal rings at the nozzle body outlets):



Electrostatic nozzles on sprayer

FMR Recapture/ Recycle Sprayer

An FMR R-series recapture/ recycle sprayer was used for the applications with the spraying system which can be set to a relatively high normal maximum application volume rate for a canopy and any excess spray that runs off leaves is drawn in by the opposing fan and reused rather than being available to runoff to the ground or be lost as airborne drift.

The following photo shows the FMR sprayer in use in our studies for a sparse, young canopy of table grapes in Red Cliffs, VIC.



Recapture/ recycle sprayer.

Spray Deposition Sampling

Spray deposition within the canopies was assessed using a range of techniques.

The main approach was to use bromoethyl blue water sensitive papers (WSP) which turn from yellow to blue when contacted by water. Droplet percent coverage following each spray application was then assessed in the laboratory using image analysis with a Swath Kit camera package and custom software from UQ. The WSP were attached to the top and bottom of leaves at three canopy positions: upper, middle and lower, and for mature canopies at inner and outer canopy locations. They were also attached to the woody materials such as the trunk and cordon. WSP were also used to assess swath displacement (particularly for aerial applications with drones) and near-field drift to 20 m. The following photos show examples of WSP placed in canopies in these field studies.



Water sensitive papers on canopies to measure spray coverage.



Water sensitive papers on canopies to measure spray coverage.



Water sensitive papers on canopies to measure spray coverage.

We used Mylar cards in some studies to assess deposition on the canopy and drift. In these tests, a fluorescent tracer dye, Pyranine 10G, was included in the spray mix at a rate of 0.4 g/L (which is similar to some pesticide use rates). Following applications, samples were placed in labelled Ziplok® bags and returned to the laboratory where they were rinsed with 27 mL deionised water and read with a Pyranine-calibrated Shimadzu RF5301-PC multispectral fluorometer to show the deposition rates.

Electronic leaves were included in field trials conducted in Stanthorpe, QLD, to assess coverage using a digital approach with the aim of at a future date linking these into a feedback loop that would verify spray coverage particularly in difficult-to-reach inner canopy areas and alert the spray control system when to increase application volume rates or prompt the applicator to re-calibrate his spraying system to achieve better coverage where it is insufficient.

The electronic leaves comprised leaf wetness sensors with antennae attached and portable self-contained battery power to transmit a voltage signal back to a laptop computer through a USB antenna. The voltage signal was then used to show relative deposition and coverage rates which would increase as spray deposited on the sensor and then decrease as the water evaporated soon thereafter. Up to 20 of these electronic leaves were placed next to water sensitive cards for direct comparison of voltage signal against coverage of spray per square centimetre.

The following photograph shows (left to right) Mylar, WSP and an electronic leaf in a vineyard for spray coverage tests in this study.



Mylar card, water sensitive paper and electronic leaf (left to right) on canopy to measure spray coverage.

Application Volume Rate Determination

A combination of the LiDAR sensor spray control system and the Silvan ARAG Bravo 180S spray rate measurement system was used to measure the applied spray volume rate for each application, to allow a determination of the amount of chemical saved when using the LiDAR system to detect targets and control each nozzle with the solenoids.

Pulsed Width Modulation and Droplet Size for Different Nozzles and Pressures

Pulsed width modulation is usually selected for spraying systems because it offers control of droplet size independently of the spray application volume rate or liquid nozzle flow rate. However, prior research in this area has only verified performance for nozzles available at the time of such studies and for specific application types. Most research was previously conducted with conventional (i.e. non air induction) flat fan nozzles for relatively low pressure broadacre boom sprayers. These typically operate with pressures around 3 bar. In vineyard spraying, a different kind of nozzle is more common, i.e. the conventional or air induction hollow or full cone and spray pressures usually exceed 4 bar. The sprays are much finer than most ground broadacre spray applications and the nozzle operates in a high velocity and high volume air flow whereas ground boom sprayers do not. We evaluated several nozzle types and pressures for this research. In particular the spray angles were smaller (80 degrees) than most ground boom sprayers which commonly use 110 degree angles. The inclusion of air induction nozzle types can present challenges to PWM systems because at certain duty cycle pulse rates, the cone may not fully form with entrained air.

Three nozzle types (Albuz ATR 80 Red, Teejet TXB 8001 and Teejet AITX 8001) were mounted in a conventional Teejet body nozzle (QJT8360-NYB) equipped with an electric solenoid shut-off valve (55295-1-12-15, Teejet). The solenoid valve was mounted in the diaphragm check valve position. To energize the electric solenoid using a PWM signal an Arduino Mega board with a specific electronic circuitry was connected. The working frequency of the generated signal was 10 Hz. 20, 60 and 100 % duty cycles were included. When a duty cycle of 100% is used, the valve is always open, that means no flow rate reduction. Experiments were conducted in the wind tunnel at the University of Queensland, Gatton Campus with a wind speed of 9 m/s. The different nozzles and PWM values were tested with water at two different pressures, 4 and 6 bar. The droplet size distribution was measured using a Sympatec HELOS laser diffraction particle size analyser (Sympatec, Clausthal, Germany) with dynamic size range 0.5-3500 µm. Each measurement was compared with the BCPC/ ASABE S572 (British Crop Protection Council/ American Society for Biological and Agricultural Engineers) nozzle classification scheme allowing classification of each nozzle into these droplet categories: Very Fine, Fine, Medium, Coarse, Very Coarse, Extremely Coarse.

Four replicate measurements were made for each combination of nozzle and PWM. Each replicate was a complete traverse of the nozzle vertically through the laser. The average of each measurement was analysed and the maximum of standard deviation of all curve points was calculated.

Automated (Robotic) Sprayer

Our studies involved applications with a fully-automated system where human intervention and input was only for setting up the sprayer, filling the chemical spray tank with the required spray material, driving the tractor and turning on and off the entire canopy sensing and liquid delivery system. The fully automated aspects included the following:

- 12V battery-powered LiDAR to continually scan the canopy on both sides of the sprayer to detect the target location, upper and lower extent and depth in real time
- 12V battery-powered RADAR to measure sprayer speed

- Control box to process data from LiDAR (canopy target locations) and RADAR (driving speed) to determine when and for how long to open each solenoid for each spray nozzle and the spray duration for the target depth
- Separate electronic leaf system collecting data on spray deposition and coverage at selected canopy locations and logging these data for auditing and verification of pesticide use

We attempted to source a self-driving tractor to remove the need for a driver but were unable to obtain one within Australia. However, these are available overseas and the manufacturers such as CASE International and John Deere are planning to sell them in Australia in the future. We have been working with Vuetech on a robotic tractor for future testing once available. The data will be provided to Wine Australia once available (probably after the current UQ COVID-19 travel restrictions are lifted, to allow testing in the field).

We tested an X-Aircraft P20 unmanned automatic aircraft which was programmed to spray without a pilot for vineyard applications of foliar products such as fungicides as well as herbicide applications for weed control. The rotary nozzle on the aircraft was used to deliver different droplet size spectra for each application by changing the rotation rate (slower for coarser herbicide sprays and faster for finer fungicide sprays). Field tests evaluated the aircraft position to offset for swath displacement in the wind and height to achieve optimal spray coverage on the target. Some of the tests are shown below.



Drone spraying dormant vineyard.



Drone spraying foliated vineyard.

Vine characterisation with imaging system and PIX4D

Work conducted in November 2016 and February 2017 looked at using an imaging system to characterise the vine canopy. This system had previously been used successfully to create three-dimensional mosaic images of crop canopies when mounted on an aircraft. The imaging system consisted of a natural colour camera (Canon 5D mark III) to capture red-green-blue (RGB) images and a GPS receiver to geotag the images. Given its success when mounted on an aircraft flying at 200 km/h it was expected that it would provide even better results when used on a 4.0 metre high boom mounted on a slow-moving tractor.



Camera and GPS system used for the PIX4D imaging work.

The camera recorded red, green, blue (RGB) images of the vines and a GPS that was attached to the camera allowed the individual images to be geotagged. PIX4D image processing software was then used to create a three-dimensional mosaic or composite image from the RGB images. This work was done in collaboration with colleagues from the United States Department of Agriculture (USDA, College Station, Texas, USA). These scientists had conducted earlier imaging work using aircraft mounted cameras flying at a speed of 200 km/h to develop high resolution three-dimensional images of various crop canopies, including grape vine canopies. In the work at Stanthorpe the collected images were of very good quality but there was an unforeseen issue with the GPS device which failed to geotag all the images correctly. Consequently, the image processing software was not successful in creating a complete mosaic of the canopy. For the PIX4D image processing software to work correctly the GPS needs sub-metre or sub-decimetre accuracy. This level of accuracy is available with real time kinematic (RTK) systems which can achieve accuracy to 1.0 – 2.0 centimetres. RTK systems are packaged with commercially-available drones and these systems can capture both RGB and near-infrared images that are used to monitor crop health. Vineyard operators who use drones with imaging systems to monitor crop health could use this technology to quantify the LAI value for use in a PACE approach in lieu of using other methods such as the VitiCanopy App.



Imaging system mounted 4.0 m above ground level.



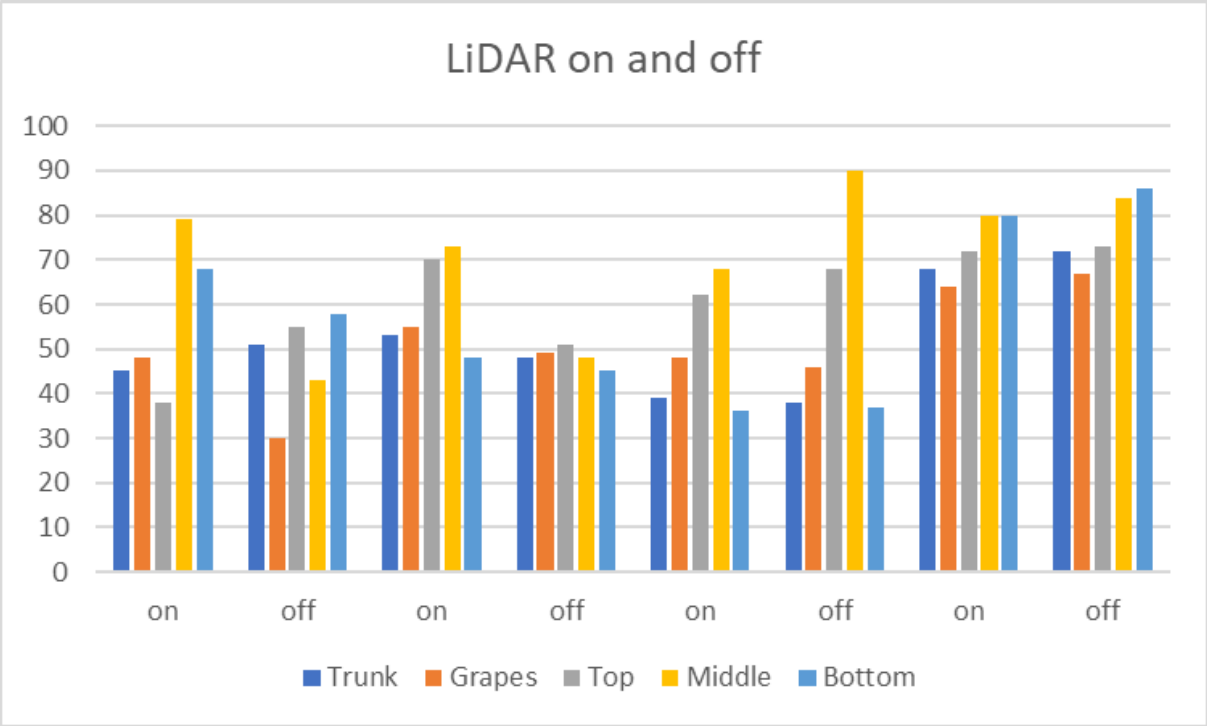
Image taken with the boom-mounted RGB camera for processing with PIX4D software.

3 Project results and discussion

3.1 Project level achievements

LiDAR Controlled Automated Spraying System and Recapture/ Recycle Sprayer

In the initial tests with the LiDAR system, in wine grapes in Stanthorpe and Ballandean (QLD/ NSW), the LiDAR-controlled system was able to provide the same level of spray deposition coverage but using 47-64% less chemical as shown in the pair-wise comparisons below. The photographs below each pair of bars show the vineyard for the tests and the pairs of bars show the percentage coverage of leaves, grape bunches and trunk for the sprayer with the LiDAR system on versus off.



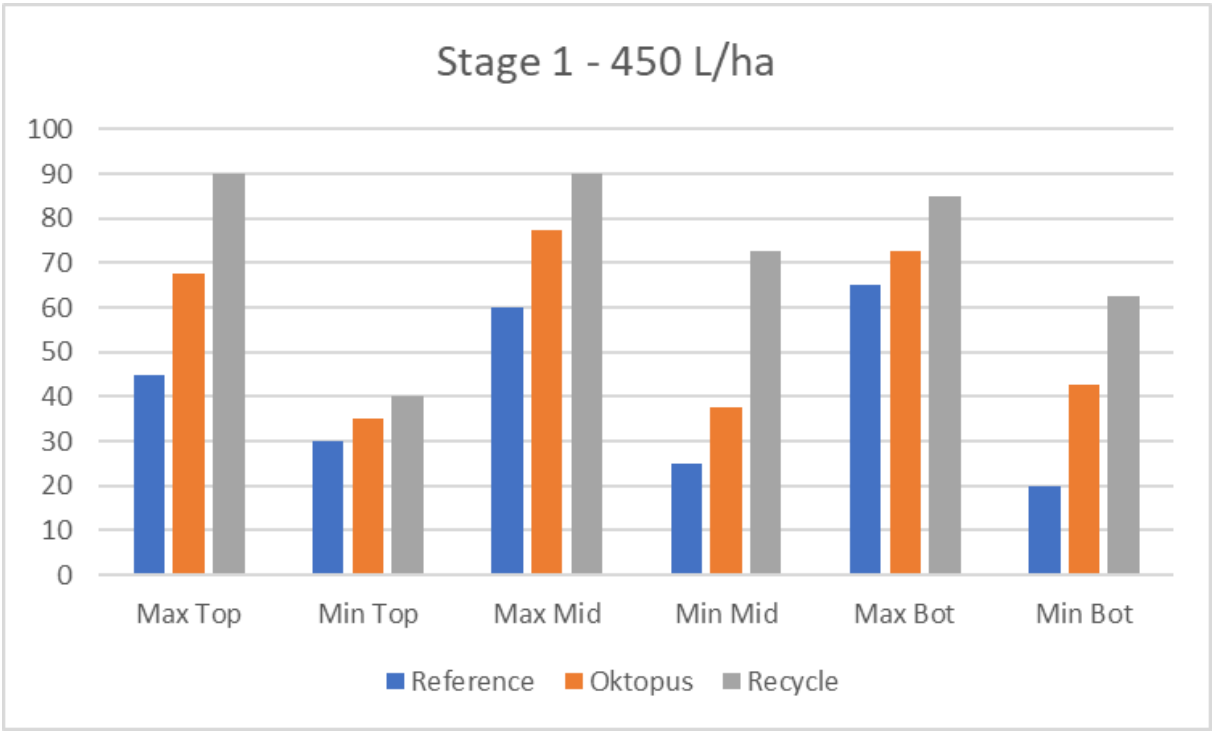


In the Mildura area of Victoria (Red Cliffs and Cullulleraine) and Granite Belt region of QLD/ NSW (Stanthorpe and Ballandean), tests for the LiDAR sprayer and Recapture/ Recycle sprayer covered several table and wine grape varieties at different growth stages. The data are summarised in the graphs below with example photographs of canopies.

Stage 1 (young, widely spaced vines with large gaps) canopy with LAI 0.3-1.1:

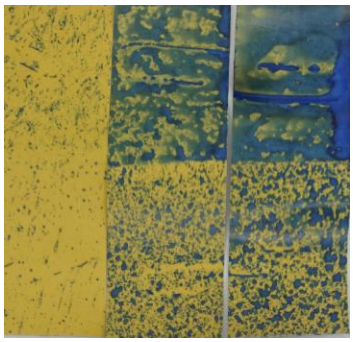


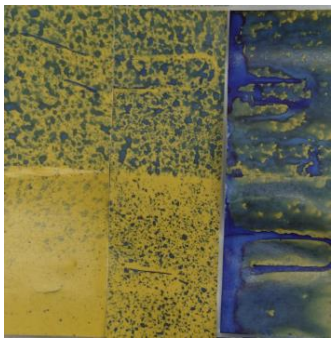


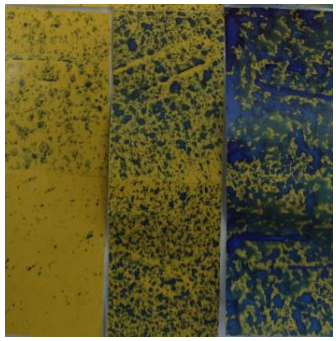


Max

Min







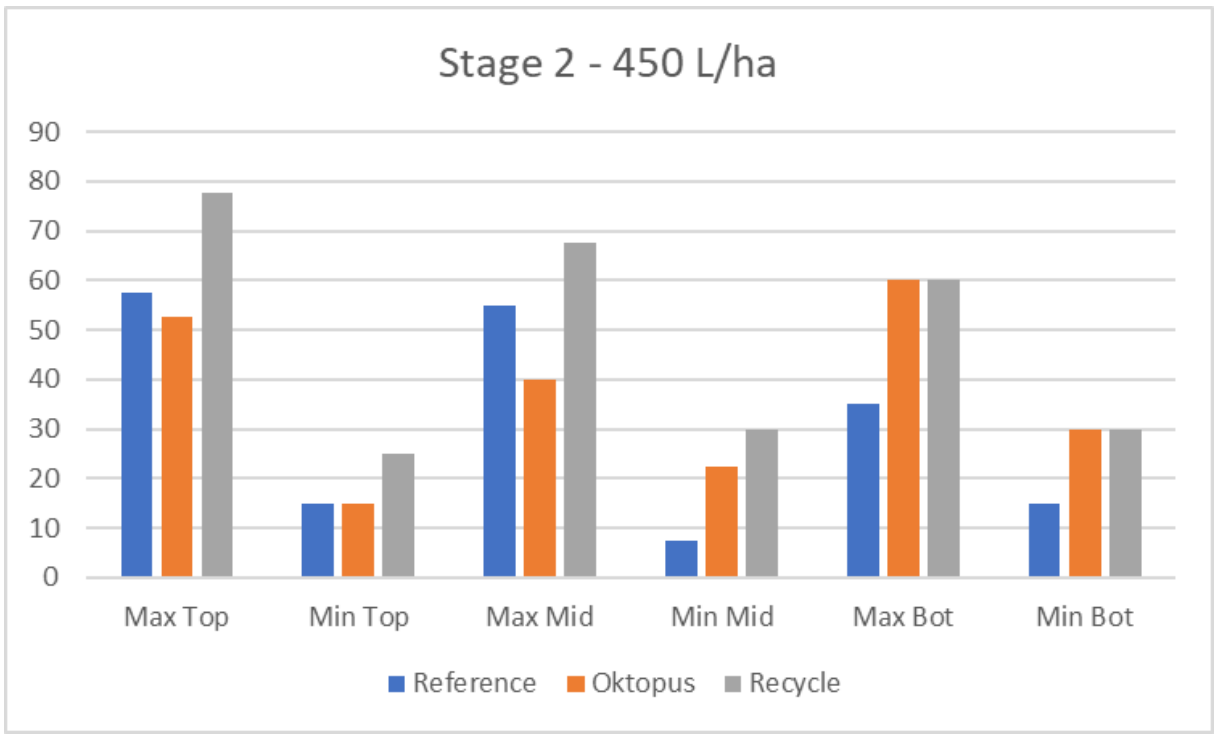
In this low foliage density scenario, the LiDAR-equipped Oktopus sprayer provided superior coverage to the reference, non-LiDAR sprayer but the best coverage was achieved with the recapture/ recycle sprayer.

The LiDAR system allowed a chemical savings of 70-90% while the recapture/ recycle sprayer gave a savings of 50-80%.

Stage 2 Medium canopy with fewer gaps and spaces and LAI 1.3-2.3:







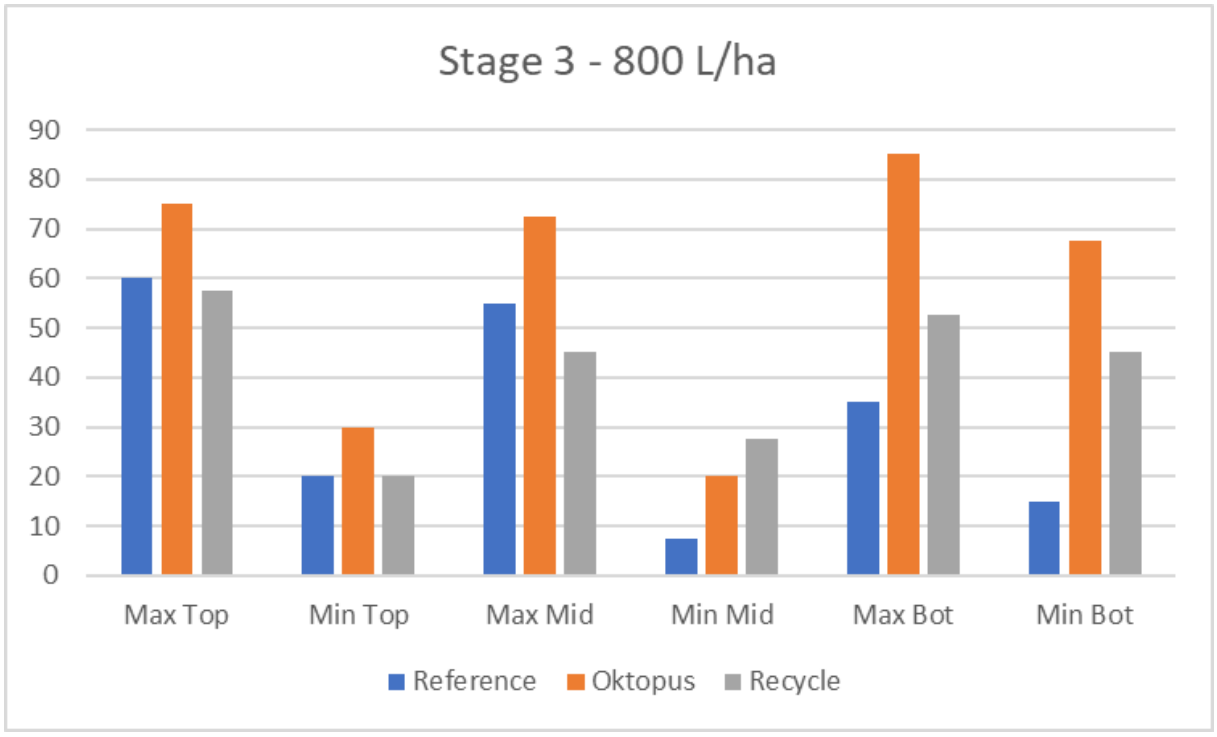
In this medium foliage density scenario, the LiDAR-equipped Oktopus sprayer provided similar or superior coverage to the reference, non-LiDAR sprayer and recapture/ recycle sprayer.

The LiDAR system allowed a chemical savings of 60-80% while the recapture/ recycle sprayer gave a savings of 50-70%.

Stage 3 Medium/large canopy with LAI 1.4-2.6:





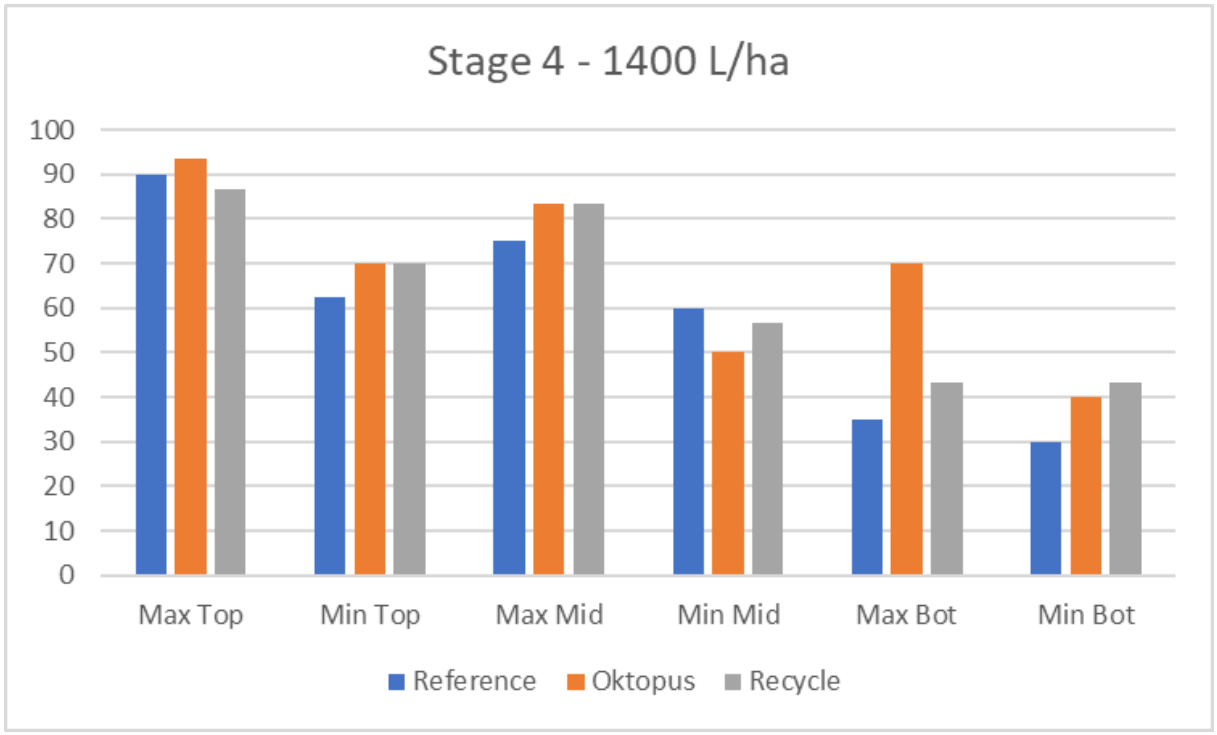


For this canopy, the best coverage was generally with the LiDAR-equipped sprayer. Chemical savings rates were 40-60% with both the LiDAR and the recapture/ recycle sprayers.

Stage 4 Mature canopy with LAI 2.0-4.2:

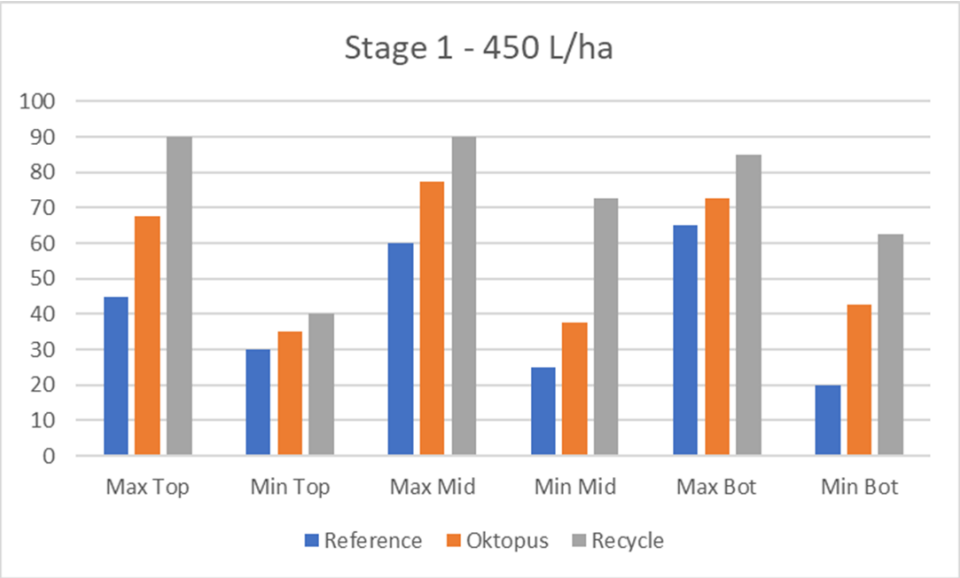


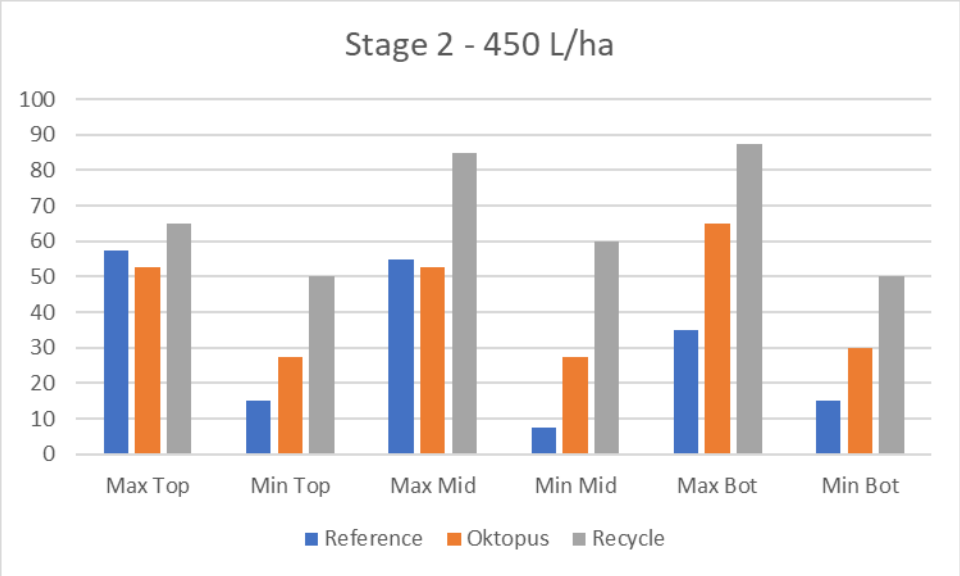


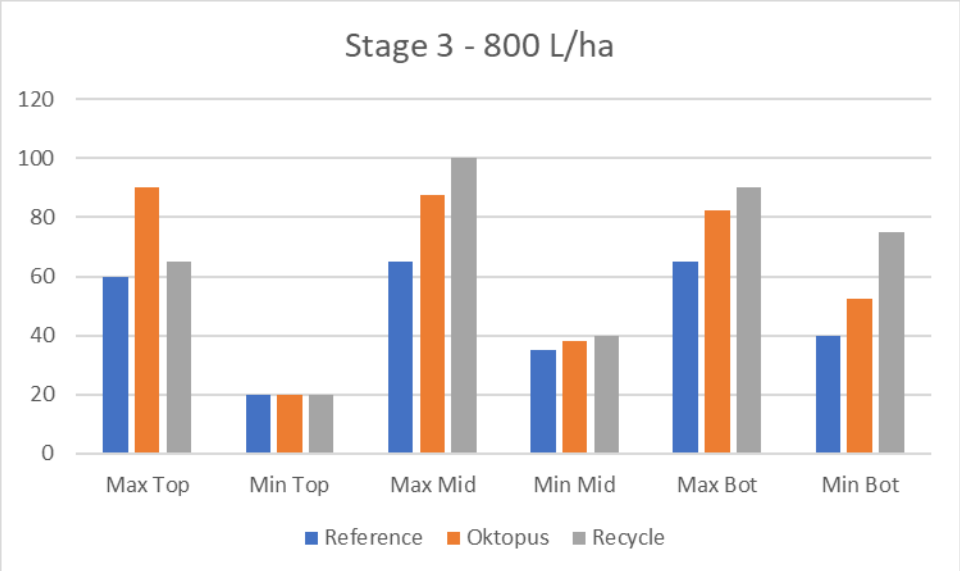


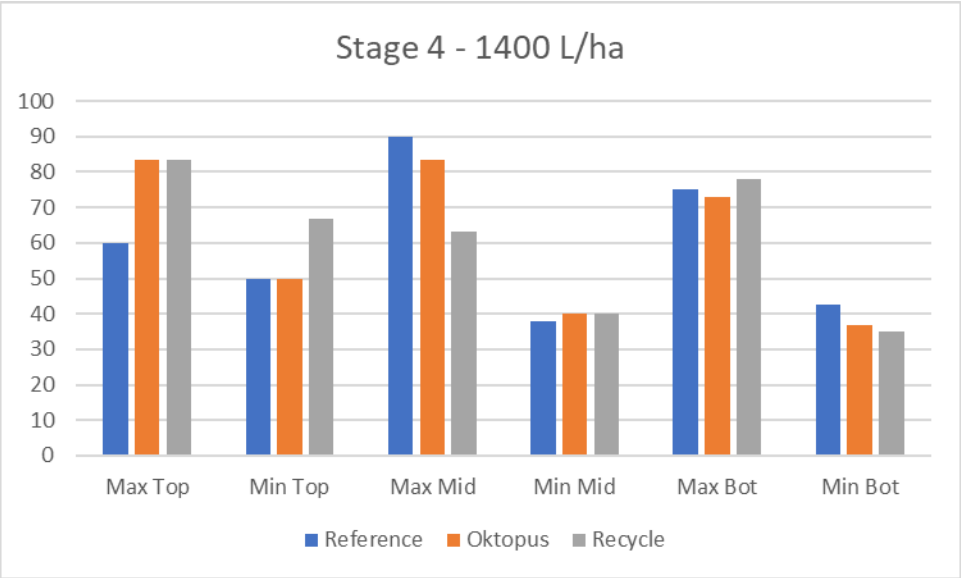
At the high application volume rate of 1400 L/ha, good coverage was obtained with all the spraying systems but with 10-50% less chemical with the LiDAR sprayer and 10-20% less chemical with the recapture/ recycle sprayer.

The previous figures showed the inner canopy coverage (the hardest areas to reach with spray in many scenarios). The following graphs show the data for the outer canopy coverage in each case.

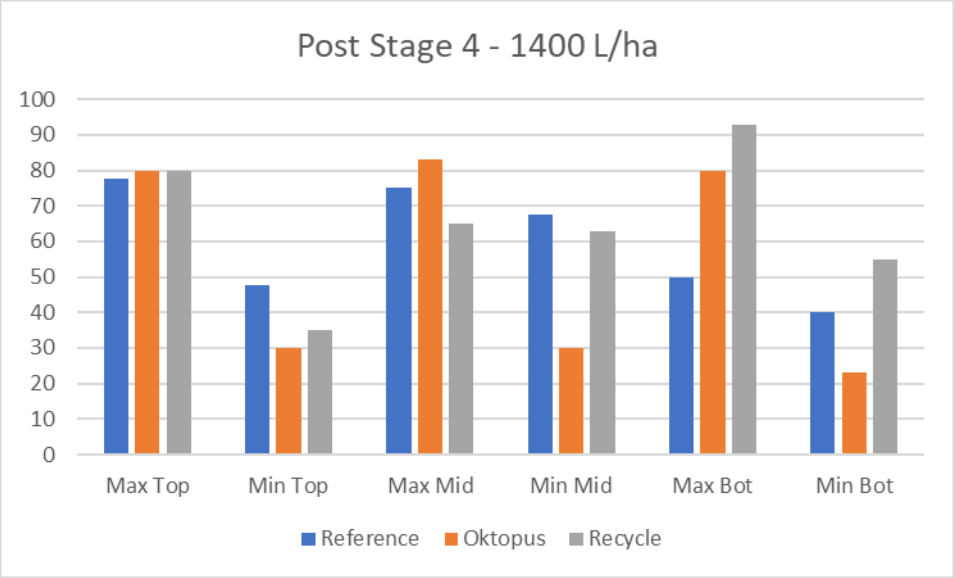

Stage 1 - 450 L/ha
100
90
80
70
60
50
40
30
20
10
0
Max Top
Min Top
Max Mid
Min Mid
Max Bot
Min Bot
Reference
Oktopus
Recycle


Stage 2 - 450 L/ha
100
90
80
70
60
50
40
30
20
10
0
Max Top
Min Top
Max Mid
Min Mid
Max Bot
Min Bot
Reference
Oktopus
Recycle


Stage 3 - 800 L/ha
120
100
80
60
40
20
0
Max Top
Min Top
Max Mid
Min Mid
Max Bot
Min Bot
Reference
Oktopus
Recycle



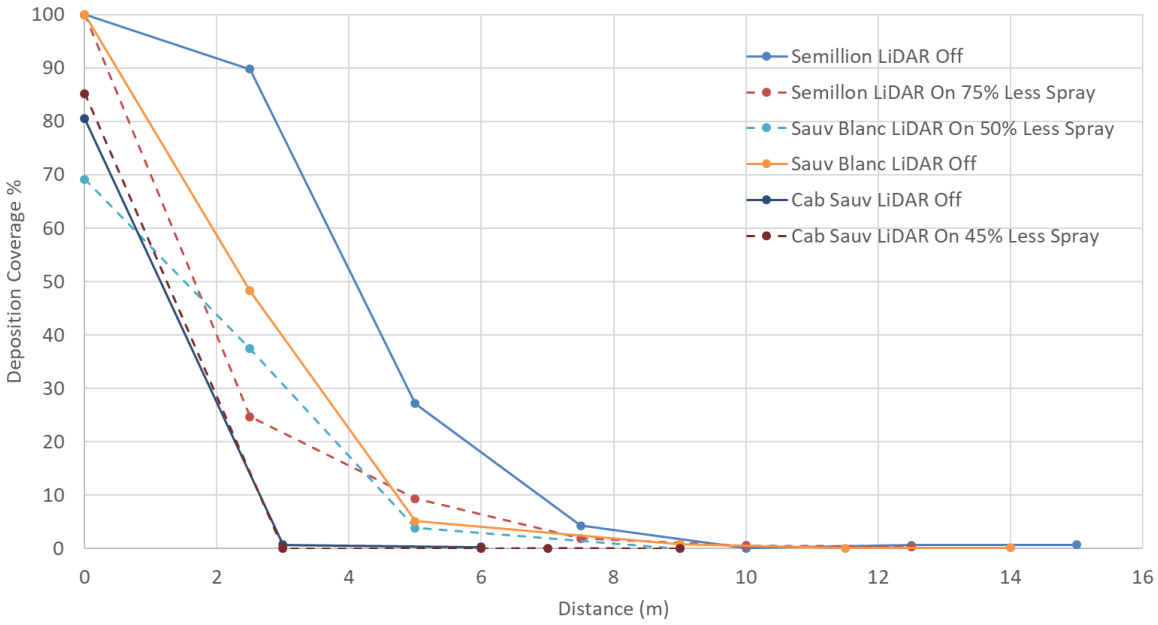
As Stage 4 (mature canopy with dense foliage) progresses into a Stage 5 later in the season where leaves and fruit are still on the canopy but the leaves are dying and thinning, the performance looked as follows:



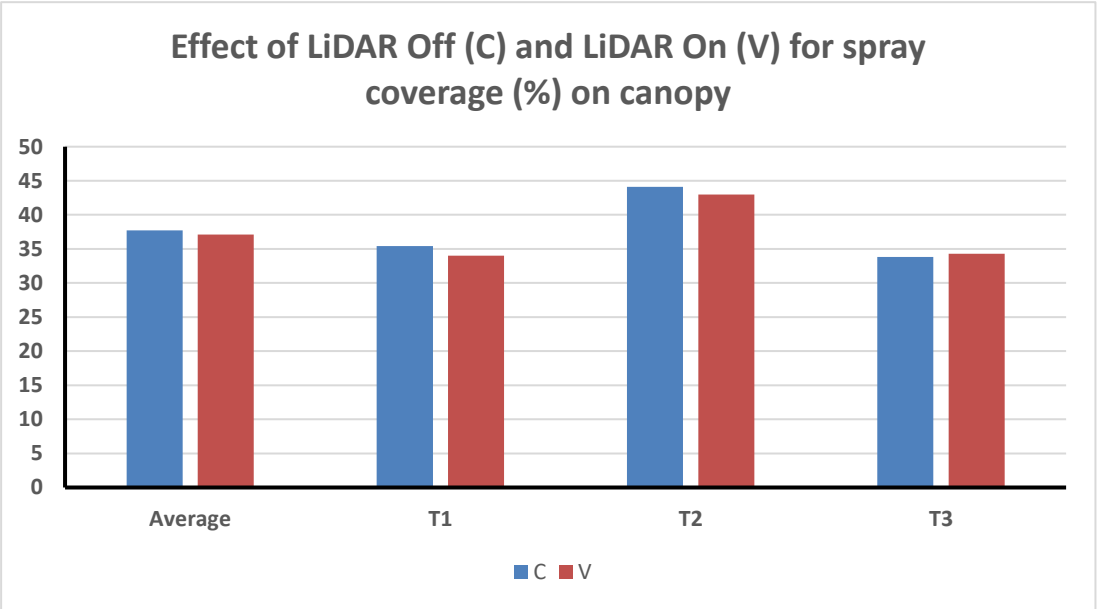
In this very late canopy stage, there was 20-50% less chemical with the LiDAR sprayer and 20-30% less chemical with the recapture/ recycle sprayer.

It should be noted that while we conducted tests to study spatial and temporal dose and targeting optimisation in a range of vineyards, the exact performance of any system will depend on each unique sprayer, operator, vineyard and meteorological conditions. Even a basic sprayer can give superior performance to a top range sprayer when operated and setup optimally, and vice-versa. The approaches evaluated in this project do not replace the most important factor in any spraying operation which is setting up a well calibrated sprayer to optimally target the required canopy regions. Once this has been done, the approaches described here can further optimise the spraying and make the applicators job much easier through automation and precision.

Another key consideration when spraying vineyards is the avoidance of chemical wastage and trespass. Spray drift is an important issue in many parts of Australia and avoiding spray direction over the top of the canopy as well as avoiding spraying through canopy gaps and in high wind are the most important ways to mitigating drift. Drift studies showed that the LiDAR system could not only reduce chemical use rates but also reduce off-target drift rates as shown below, from tests in Stanthorpe, QLD.



The following graph shows equal spray coverage on Shiraz canopies of different LAI values for tests in Stanthorpe, QLD with colleagues Zhu, Clark and Doklovic from USDA following minor changes to the system setup to further optimise the nozzle position cross-reference in the onboard computer. LAI, measured using VitiCanopy, was 3.4, 3.3 and 2.9 for treatments 1, 2 and 3 respectively (T1, T2, T3). The spray coverage was not statistically significantly different for the LiDAR off (constant rate application, C) versus the LiDAR on (variable rate application, V) but the LiDAR on setting provided a savings of 50% in chemical use for this equal coverage rate and a 60% reduction in total off-target drift measured out to 20 m.

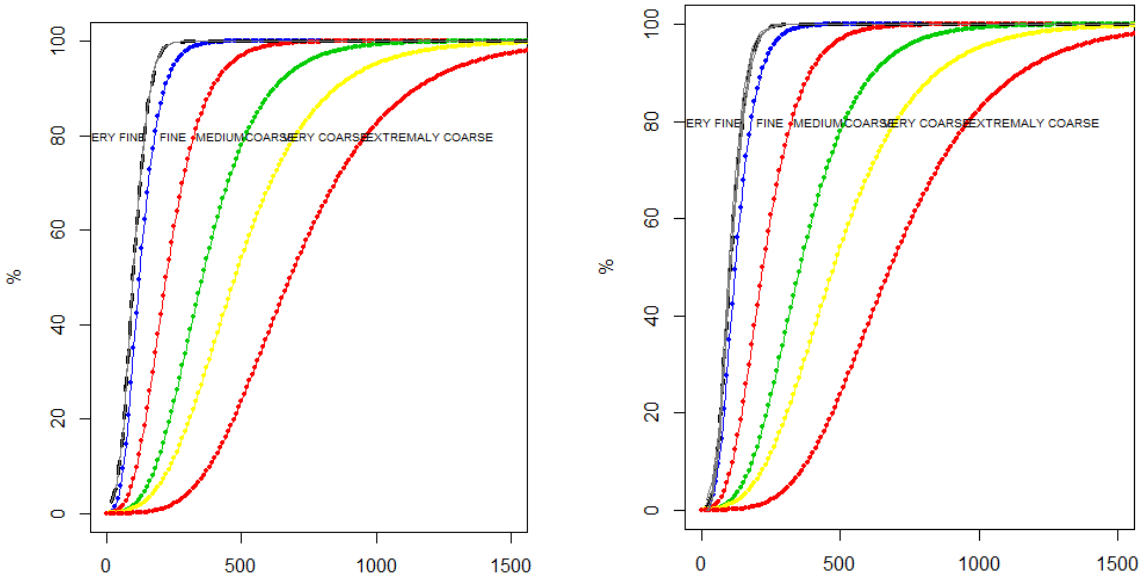


A challenge for many growers is the control of Eutypa and Botryosphaeria dieback where 100% spray coverage is required on woody canopy surfaces for >60% control (SARDI). The amount of chemical wasted if a sprayer is turned on the whole time while driving down rows for such an application will exceed 90% compared to applications targeting only those woody materials. We verified that the sensor system could accurately detect these surfaces and then activate the spray only onto them, to save >90% chemical while achieving 100% coverage as shown below.

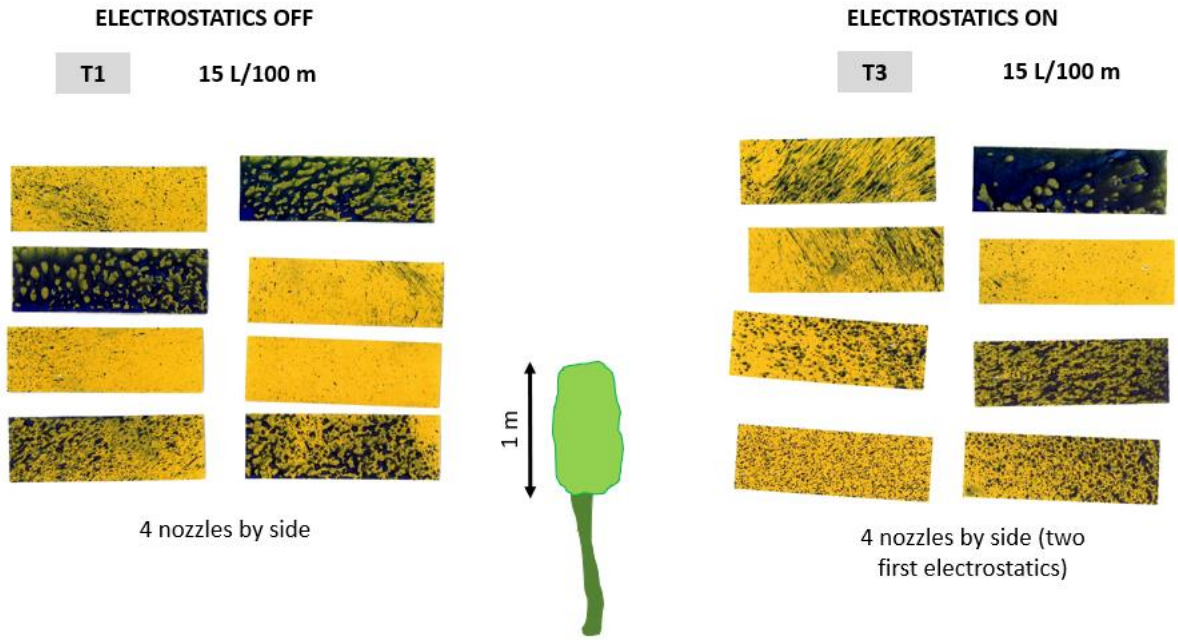


The electrostatic charging ring did not cause a significant change to the droplet size spectrum from the ATR80 nozzle as shown with the black lines below (the coloured lines show the boundaries between droplet size classes Very Fine, Fine, Medium, Coarse and Very Coarse, from left to right).

Cumulative Volumetric Droplet Size Spectra for Electrostatic charge On (Left) and Off (Right):

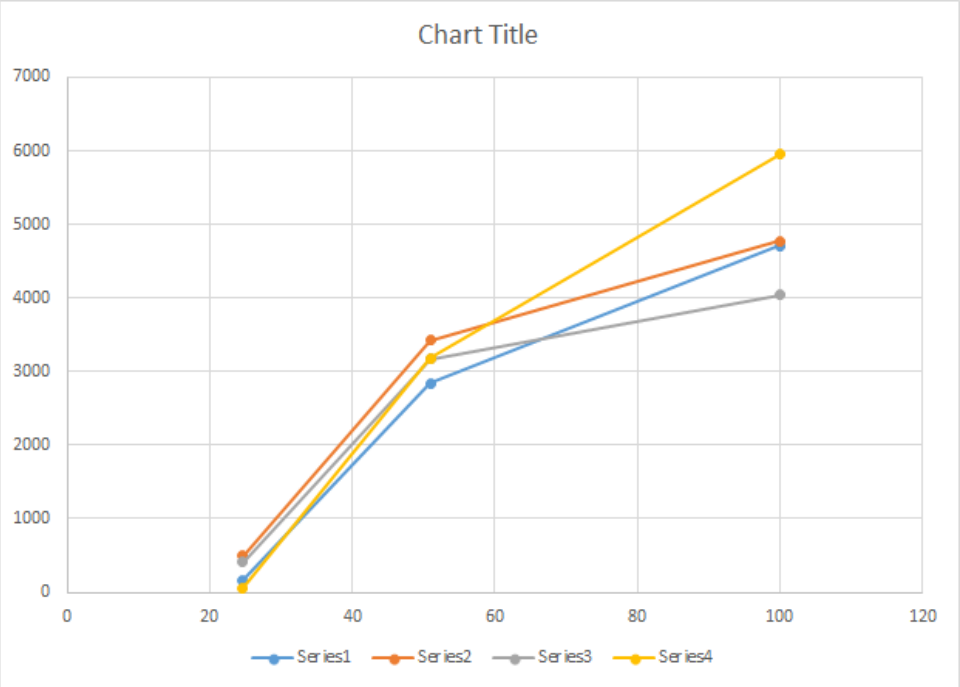


The electrostatic charge did not improve the spray deposition or coverage performance of the spraying system as shown below, probably because electrostatics is better suited to sprayers without air. The air tends to be a greater force than the smaller force of electrostatic attraction for these Very Fine droplets.



Electronic Leaves

A correlation was established between the voltage signal from the electronic leaves and the spray coverage percentage on adjacent water sensitive papers as shown below for 4 example leaves (x axis shows percentage coverage with spray and y axis shows voltage signal from electronic leaf):

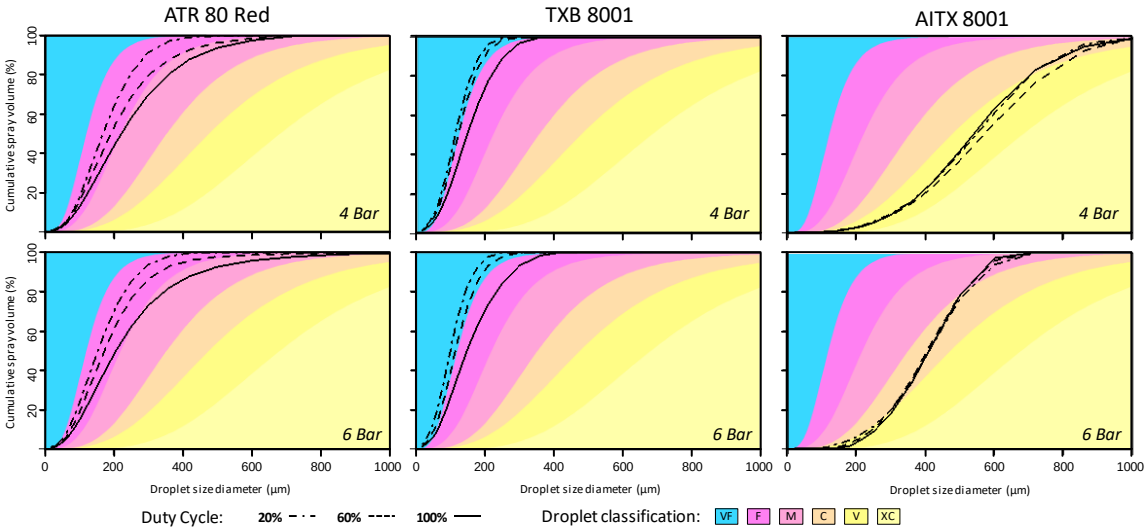


As the water evaporated from the leaves, the voltage proportionally fell back to zero.

Pulsed Width Modulation and Droplet Size for Different Nozzles and Pressures

An essential part of any spray system is the nozzle and its spray. We selected PWM to control spray rates independently of droplet size based on prior research but needed to determine whether this would be true for nozzles and pressures used in typical vineyard spraying.

The figure below gives the results of the droplet size measurement at every duty cycle tested, for each nozzle analysed and for two pressures studied. On each graph, the droplet size classification is shown according to the BCPC/ ASABES572 colour-coded systems. Conventional (no low drift) nozzles present bigger differences in droplet sizes (see grey lines in Figure 1 and $D_{v0.5}$ Volume Medium Diameter values in the Table) compared to low drift nozzles. There were large differences in droplet size between duty-cycle with the ATR nozzle. Specifically, these differences make that the droplet size classification changes from Fine to Medium when the PWM system changes from 100 to 20 % of the duty cycle. For TXB nozzle experienced the same type of change, but between Very Fine and Fine classes. No large changes in droplet size occurred for the AITX nozzle.



			ATR			TXB			AITX	
	PWM	*n*	*max sd.*	*VMD*	*n*	*max sd.*	*VMD*	*n*	*max sd.*	*VMD*
Pressure 4	20	4	2.21	224	6	4.02	146	8	16.91	550
	60	4	0.78	191	5	2.33	120	5	13.38	562
	100	4	2.62	164	4	3.83	109	8	10.82	550
Pressure 6	20	7	2.69	210	4	1.79	150	6	6.88	409
	60	7	4.15	175	4	1.70	114	6	8.74	405
	100	5	0.62	154	4	5.27	96	5	5.03	409

These results suggest that our system would achieve the required goal of efficient spraying for some nozzles and pressures but not others. This is mentioned later in the report in the context of future work and advice for growers.

Drone spraying

The unmanned aircraft was successful in delivering spray to vineyards for foliar deposition and the ground for herbicide applications in weed control 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. The example below shows an Extremely Coarse spray produced at the lowest rotation rate where the $D_{v0.5}$ volume median diameter measured with a Sympatec laser diffraction instrument in the UQ wind tunnel was 550 µm.

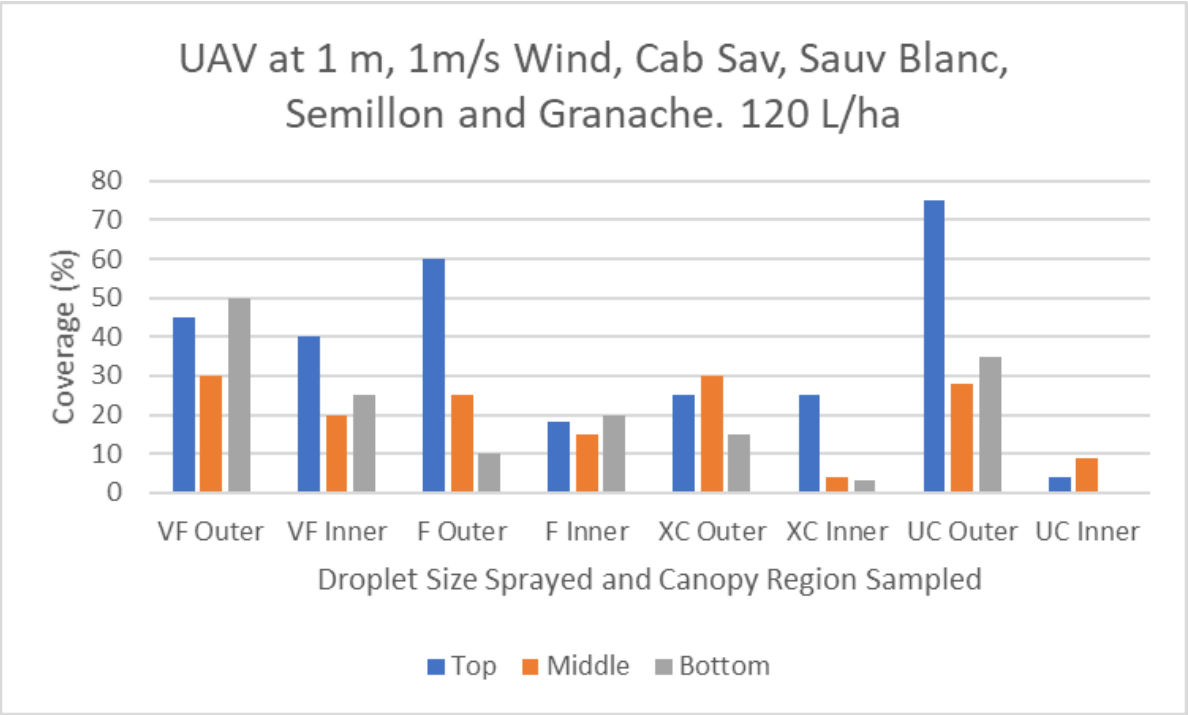


For vine spraying, applications were compared for atomiser rotation rates producing Very Fine, (VF) Fine (F), Extremely Coarse (XC) and Ultra Coarse (UC) sprays (approximately 13,000, 7,000, 2,000 and 1,000 rpm respectively). The optimum flight height was determined to be 1 m above the canopy. Flying at 1 m/s, we applied approximately 200 L/ha of spray to four grape variety vine types: Semillon, Cabernet Sauvignon, Grenache and Sauvignon Blanc. The crosswind speed was 9-13 km/h which required an aircraft offset in the upwind direction as tabulated below – this was measured in order to provide guidance to growers when using drones in different conditions. All values assume applications in 2.5 m/s wind speeds. Release heights are above the canopy.

Swath Offset Required for Different Droplet Sizes and Aircraft Heights in 2.5 m/s Wind

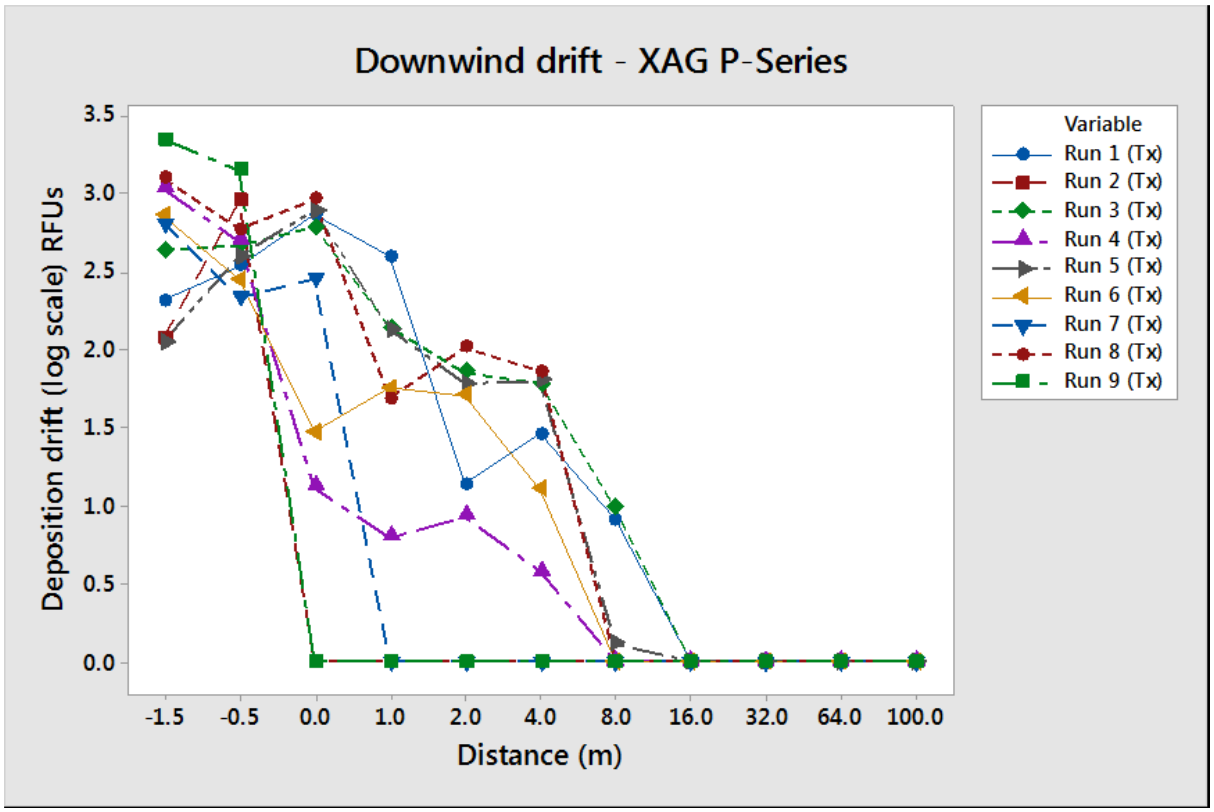
Spray Quality	0.3 m	0.5 m	1.0 m	1.5 m	2.0 m
Very Fine	2	4	9	14	21
Fine	2	3	4	6	8
Medium	1	1	2	3	5
Coarse	0.5	1	2	2	3
Very Coarse	0.5	1	1	2	3
Extremely Coarse	0	0.5	1	1	2
Ultra Coarse	0	0	1	1	2

The following graph shows the spray coverage at the top, middle and bottom of the canopy for outer and inner canopy regions for each droplet size spray.



The data show that when spraying from above the canopy, as expected, the deposition rates tend to be highest at the top and outside of the canopy. However if canopy penetration is required (which it normally would be), the best way to achieve this is with a finer spray. Such sprays are more prone to displacement in the wind, so our studies showed that for aerial spraying with drones, the wind speed should be as low as possible and ideally in the range below 10 km/h while also avoiding local surface temperature inversion conditions which may occur if the wind speed is below 2-3 km/h.

The drone was able to spray canopy and ground applications with low spray drift deposition risk as shown the following graph where drift was zero beyond 16 m.



The applications for these 9 treatments covered droplet sizes between Fine/ Medium (200 and 285 µm) and Extremely Coarse (550 µm), aircraft heights of 1 and 2 m above ground and application volume rates between 19 and 78 L/ha, as listed below.

Run No.	Drop size (um)	Flying Ht (m)	Flying speed (m/s)	Carrier volume rate (L/ha)
1	550	2.0	2.0	38.8
2	550	1.0	2.0	38.8
3	285	2.0	2.0	38.8
4	285	1.0	2.0	38.8
5	200	2.0	2.0	38.8
6	200	1.0	2.0	38.8
7	285	2.0	4.0	19.4
8	285	2.0	2.0	77.8
9	550	2.0	2.0	77.8

Overall

In all the agreement's research areas, the project achieved the objectives of developing and demonstrating spray optimisation with manual and automated systems that assess the vine

characteristics and adjust the spray dose to achieve optimised coverage at reduced spray volume rates.

The project agreement described the approach in the same general manner as the actual progress, which was as follows:

- Use of a reference group to guide the project. This was achieved through consultation with stakeholders from grower, chemical company, applicator, equipment and regulator organisations and annual updates were also provided at meetings organised by Wine Australia in Adelaide for the over-arching Digital Viticulture project. At the end of the project there were videoconference calls (in lieu of face-to-face meetings due to COVID-19 restrictions in 2020) with stakeholders from the National Working Party on Pesticide Application (which covers all major government, academic and industry stakeholders applicable to spraying of vine crops) and specific wine industry groups.
- Consultation and collaboration with experts on dose adjustment and spray targeting. These included Peter Walklate who developed a PACE scheme for apples in the UK, USDA scientists who worked on related LiDAR canopy targeting work for apples, the University of Catalonia who developed dosing models for vineyards in Spain and Geoff Furness who pioneered work in Australia on leaf canopy wall area dose adjustment.
- Development of technologies using the screening and controlled environment conditions of the wind tunnel at The University of Queensland, Gatton.
- Evaluation of dose adjustment systems with manual approaches and automated/ robotic systems in wine and table grape vineyards in at least 2 states for at least 4 canopy density stages (dormant/ sparse, early budding, full foliage, full foliage with fruit). Evaluations to assess sensors and dose adjustment processes as they relate to spray coverage and chemical use rates/ savings.
- Workshops for growers.

A key focus of the work was the inclusion of sensor technologies with a backup option of conventional (non-sensor)/ manual approaches to offer choice to growers. Our sensor systems were based on initial work with PIX4D imaging which was best suited to aerial platforms, followed by the use of a moderately large/ heavy SICK LMS100 LiDAR for assessing canopies and then a Hokuyo UTM 30LX small, highly portable LiDAR which was linked with RADAR and solenoids to provide real-time canopy sensing and variable rate spray targeting adjustment for the leaf/ trunk locations in the field. We also included a novel electronic leaf sensor concept to show that spray coverage on foliage could be verified in real time to provide a feedback loop and audit trail of chemical use and placement. Finally, we explored the use of electrostatics to help carry the droplets toward the target when highly charged.

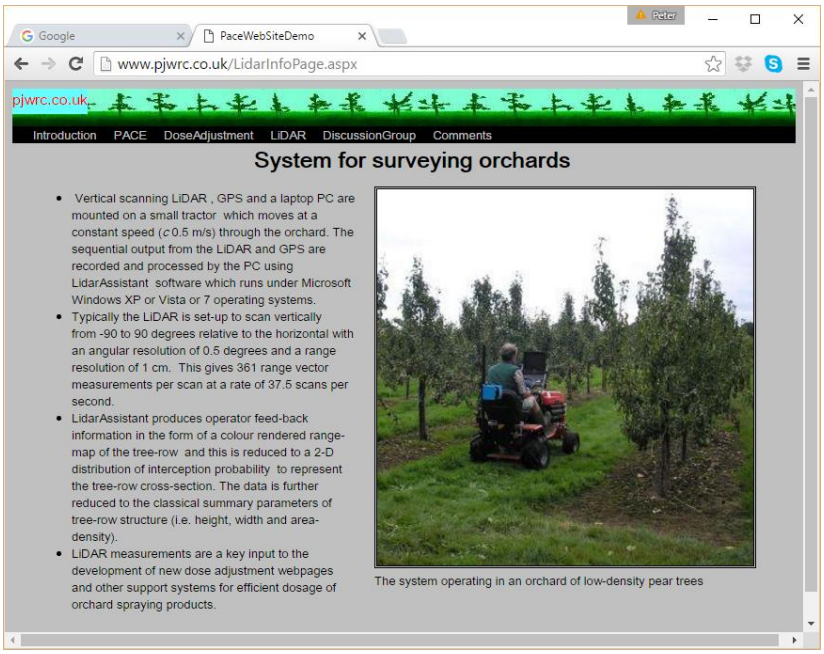
Although we worked mostly with a multiple ducted sprayer (Silvan Oktopus), the LiDAR/ RADAR/ PWM system could be attached to almost any sprayer to upgrade it to precision/ variable rate targeted applications.

As a non-sensor approach to dose optimisation in dynamic vine crop environments, we also evaluated a recapture/ recycle sprayer. This offered similar benefits to the sensor system. Both approaches offered a reduction in chemical use >10% (canopies with no gaps) to >50% (canopies with many gaps) and in many cases up to 90% while maintaining excellent spray coverage on foliage, fruit and woody canopy materials.

PACE for Vineyards (PAVE) – Pesticide dose rate Adjusted for the Vine canopy Environment

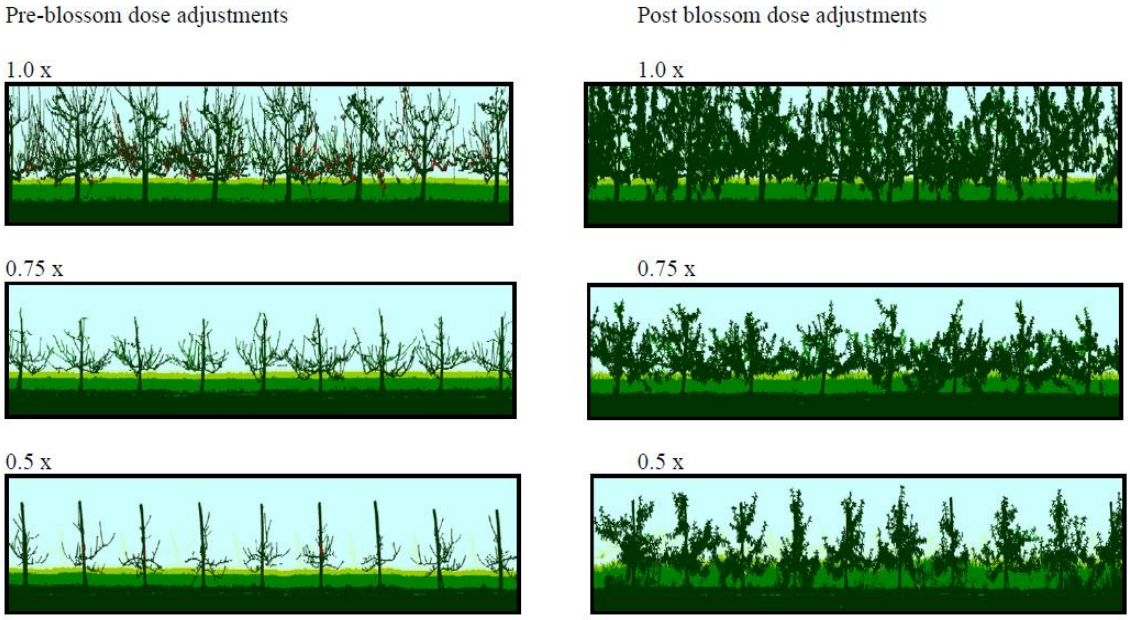
Pesticide labels for tree and vine crops commonly prescribe the dose as an amount of product to be applied per unit ground area. This has probably been implemented as a matter of convenience because chemical regulators use area-based calculations in their risk assessments. This method of dose expression 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 our project team) and Jerry Cross in the United Kingdom to provide a more realistic method of dose expression. These researchers found that there was a six-fold difference in the amount of pesticide deposited between different apple orchards and that 80% of this variation was due to differences in canopy density with canopy density coupled with height accounting for 90% of the variation. Walklate and Cross put forward a fairly simple rationale that if the label recommended dose rate gives an average deposit which is effective on taller trees with dense canopies then the same average deposit can be achieved with a lower dose rate on smaller trees and there should be no reduction in efficacy. The PACE scheme therefore achieves constant average deposits with a wide range of different crop and or canopy densities/growth stages throughout the season. Farm managers will still need to consider if a dose rate reduction is appropriate under local conditions. If pest or disease pressures are high then it would be unwise to reduce the maximum allowable dose but under low to medium risk scenarios then a dose rate reduction could be appropriate.

Walklate and Cross introduced Light Detection and Ranging (LiDAR) technology to assist with the rapid characterisation of tree canopies and used data from the scanner to create pictograms to assist farm managers identify various growth stages and the corresponding dose adjustment that could be considered.

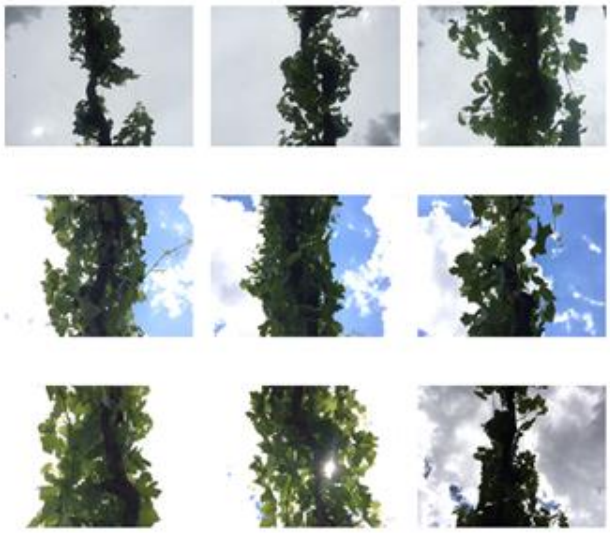


PACE online platform.

Although a recapture/recycle sprayer or an Intelligent (LiDAR) sprayer will automatically achieve what the PACE scheme is designed to do we recognise that not all vineyard operators can justify the capital investment in these types of machines so a simple technique analogous to the PACE scheme of Walklate and Cross was developed. A couple of approaches that would allow smaller-scale vineyard operators to utilise a PACE-type scheme were considered and tested. In the end it was decided to use direct Leaf Area Index (LAI) values to estimate canopy density in lieu of pictograms or aerial imagery to quantify the growth stage of the grape vine. LAI measurements in this project were made using the VitiCanopy App that was developed by The University of Adelaide in conjunction with Wine Australia. The App is relatively easy to use and runs on both Android and iOS platforms. We found that repeatable LAI measurements were obtainable if the measurements were taken at exactly the same height from the main cordon and if the smartphone was held at the same angle.



Pictograms indicating dose reduction factors for canopy density in the UK PACE scheme developed by Walklate and Cross. These pictograms were developed from LiDAR scans.



PAVE uses LAI values captured using the VitiCanopy app in lieu of pictograms.

Our approach was a modified version of PACE called PAVE (substituting C, Crop for V, Vineyard).

The PAVE formula is simple enough that is doesn't need to be hosted on a web page or even in a spreadsheet. The calculations can be performed using a simple electronic calculator or even manually with a notepad and paper. In its simplest form the PAVE formula can be written as:

L/100m = Target Deposition Rate (µL/cm^2) × LAI × Row Spacing (m) ÷ Spray efficiency (0 - 1)

The **Target Deposition Rate** is 1.3 to 3.6 µL/cm^2 depending on whether both lower and upper leaf surfaces need to be uniformly sprayed and depending on droplet size and evaporation rates. Our research suggested that the upper end of this range is preferable to assure spraying to point of first runoff.

LAI – value from VitiCanopy (for a row of 100 m in length the operator should take the average of 12-15 measurements).

Row Spacing – usually known by the manager/operator or a simple measurement if not known.

Spray Efficiency – needs to be determined only once for each individual sprayer and spray scenario. This test can be conducted with water-sensitive cards placed on outer and inner leaves and then assessing the coverage. An App called SnapCard can assist with assessing coverage on water-sensitive cards. A sprayer that achieves only 0.1 (10%) efficiency will need to increase the rate by a larger amount than one which achieves 0.5 (50%) efficiency. For example, in the Table below: Column 5 (L/100m) = Column 1 x Column 2 x Column 3 ÷ Column 4.

Target deposition rate (µL/cm²)	LAI	Row spacing (m)	Sprayer Efficiency (0 – 1)	L/100m required
3.6	0.78	2.5	0.5	14.04
3.6	0.78	3.0	0.5	16.85
3.6	1.14	2.5	0.5	20.52
3.6	1.14	3.0	0.5	24.62
3.6	0.78	2.5	0.3	23.40

3.2 Contribution to programme objectives

This research has shown that productivity in spray application can be improved through optimised dosing and targeting using modified or new equipment based on one of two principles: B) assessing the canopy using LiDAR and applying a precise dose to each region of the canopy through control of the sprayer with variable rate and variable placement application. Furthermore, actual deposition rates can be verified using electronic sensors such as leaf wetness sensors linked to a computer for data collection and analysis. Alternatively, B) a recapture/ recycle sprayer can be operated at a relatively high application rate for the target vine crop with the knowledge that when spray is applied to the point just beyond first runoff, any excess liquid will be captured and reused later in the same vineyard. Losses of chemical to the environment are avoided through the air shield afforded by opposing air jets on either side of each vine row.

The study showed that chemical savings increased as canopy density decreased. In other words, the greatest savings in chemical, 50-90% was achieved for the most sparse canopies with the lowest LAI values (<0.5) as in a) early season budding/ dormant/ recently planted canopies where the large gaps between a small amount of foliage most supports the concept of targeted variable rate or recycle dosing. As the leaves grew and the canopy filled the gaps to provide LAI values around 1, savings of 50-80% chemical was achieved. At denser foliage with LAI values around 2, savings around 40-60% were achieved and with full foliage and fruit on the vines with LAI values around 3, fewer gaps meant that the chemical savings was down to 10-50%. A range of values is applicable because many other factors affect spray coverage and chemical use rates such as canopy structure and uniformity, pruning, 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.

For some specific applications, the value of this system may be particularly high as alternative approaches may require labour-intensive manual spraying with backpack machines. One example we tested was spraying of the woody materials on a vine for the control of dieback disease. In this case, sensing the actual target and only spraying the target saves >90% chemical compared to broadcast spraying. The systems we tested provide more “tools in the toolbox” for many unique application cases like this.

We are delighted that at the end of this project a new commercial system was introduced for growers to invest in if they are interested in upgrading their existing sprayers with LiDAR

sensing systems or buying a new sprayer with such a system already installed (from approximately August, 2020 onwards), in addition to recycling sprayers which are already available.

Additional outcomes of this project included new data on robotic automated platforms for spraying such as drones where it is hoped future work will add sensors to offset the drone flying position as the wind changes, given our findings that aircraft position is the most important factor affecting spray coverage on vines, and the introduction of a novel system for assessing spray coverage using electronic leaves that transmit data to a computer and could be wired into future spray decision-support and spray accountability systems.

Barriers to adoption of improved spraying include cost factors associated with the purchase of a new sprayer. Our approach offers a modification system for existing sprayers which means the grower doesn't need to purchase an entire sprayer but can modify his existing machine(s) to achieve 10-90% savings in chemical from densee to dormant/ spare canopies. Other barriers include the complexity of spraying where many factors need to be considered and adjusted for a dynamic canopy. The automated sprayer using LiDAR does the hard work for the applicator so he can simply drive the tractor and address chemical mixing, loading and cleanup. The recapture/ recycle sprayer also removes the complexity of targeting the spray and delivering the optimal dose rate by allowing a relatively high rate to be applied without fear of losing spray to runoff or airborne drift as surplus spray is simply captured and reused.

While both systems offer excellent management of dosing and avoidance of spray drift, they have their own ideal use scenarios. For example, the sensor system is best suited to use when the wind speed is as low as possible and ideally below 10-15 km/h because at higher wind speeds the spray may be displaced with some sprayer types (especially those with finer sprays and low air velocity) which could cause droplets to miss the target. Conversely, the recapture/ recycle sprayer is well suited to a wide range of wind speeds and allows the spraying window to be extended above the limit for conventional sprayers. The sensor system is well suited to situations where a new sprayer is not within the budget or plans because a simple kit can be added to modify any sprayer and upgrade it into a sensor one. For recapture/ recycle spraying, a new sprayer would normally need to be purchased which may have higher cost initially though with excellent chemical savings over time. There may be a higher risk with sensor systems as they are completely new to the market and have components such as LiDAR and solenoids as well as computer control systems that have not yet been operated for years to establish durability and maintenance requirements.

This project has linked several groups to work together on spray decision-support. The link with the National Working Party on Pesticide Application in particular will guarantee long-term progress and uptake of ever-improving spraying systems to benefit growers through improved pest, weed and disease control using less chemical and with less impact on non-target areas and improvements in traceability and sustainability.

Our new links with innovators such as Vuetech in Brisbane will help assure ongoing innovation and growth in the areas of digital systems for spraying in Australian agriculture as we continue to discuss other new ideas and systems.

3.3 Productivity and profitability

The systems studied in this project will offer economic, productivity and environmental/ social benefits to growers. When spraying is more effective, crops are better protected and more productive and should yield greater incomes. Savings in chemical use, fuel for vehicles and staff time will deliver economic value while protection of the environment and humans from pesticide exposure will provide sustainability and compatibility with neighbours and workers which are important for the industry in the long-term.

Assuming an applicator selects suitable nozzles for use with the PWM system to achieve the required droplet size and spray angle for full coverage across all application rates, the LiDAR system has clear advantages for both new sprayer investments and for modification of existing sprayers.

We have assessed the payback time for investment in the sensor and recapture/ recycle sprayer systems as follows.

LiDAR sprayer - $60,000 to 80,000 estimate for complete commercial LiDAR system and maintenance/ support (e.g. through Vuetech Australia/ Smart Guided) to adapt a 2-sided sprayer plus $70,000 for purchase of a new sprayer if required – TOTAL maximum cost $150,000.

Assuming an average 30% chemical savings on $1,000 (wine grape) - $2,000 (table grape)/ ha/ year costs = $1,500 to $3,000 per ha per 5 years, which suggests the system is paid back in 2.5 - 5 years for a 100 ha vineyard or half that time if applicator already had a good sprayer and only needed the LiDAR conversion.

Recapture/ recycle sprayer – up to $100,000 for purchase of sprayer and maintenance.

Assuming average 30% chemical savings on $1,000 (wine grape) - $2,000 (table grape)/ ha = $1,500 to $3,000 per ha per 5 years, which suggests the system is paid back in 1.7 – 3.4 years for a 100 ha vineyard. This is for a 2-row sprayer.

Additional Factors

In all these comparisons, the actual chemical costs will vary among growers probably in a range of $200-$2,000/ha/year so simply multiply accordingly to adjust for different baseline reference chemical costs. Also, the sensor sprayers are a new concept so system prices will probably reduce over time.

These examples were based on conservative estimate of mean 30% savings in chemical but this could be doubled or tripled for some canopies/ scenarios.

It should be noted that additional savings can be realised for larger systems. Multiple rows can be sprayed with appropriate units.

If a new sprayer is needed anyway, we need to compare costs based on the same purchase cost (e.g. ~$70,000 base price for a reasonable sprayer anyway).

Recycle sprayers in particular can significantly extend the spraying window during conditions of higher wind speeds without incurring drift exposure risks.

Labour costs and sprayer operational costs such as fuel and water are lower for recycling sprayers due to productivity increasing approximately 30% (~3.2 v 2.4 ha/h).

Reliability is an unknown in this assessment – "down time" can also be costly. In our prior work, we heard about some issues with some multi-row sprayers. We would expect sensor sprayers to have potentially more issues, at least initially.

Both these systems offer considerable benefits to humans, non-target sensitive areas and the environment through more targeted, reduced chemical use rate applications. Increasingly, global consumers are keen to support "clean, green" sectors and reputation is important for the Australian grape and wine industries in the longer-term for competitiveness.

An alternative approach to assessing cost:benefit relationships for equipment changes is as follows:

Assuming a sprayer is needed anyway for chemical application, the difference in cost between a sensor or recycle system is a better approach to assessing chemical savings potential. If we assume a $70,000 base price for an "average 2-row good sprayer" and baseline chemical costs of $200 to $2000 per ha depending on each grower/ region/ crop type and pest/ disease pressure, then the additional cost for a LiDAR system is ~$80,000 and $15-30,000 for a recycle system. The high savings in average chemical use of for example 30% yields ~$60 to $600/ha/year which means for the higher chemical users, they will need >25-50 ha of crop to cover the cost in the first year and thereafter be ahead with recycle sprayers or >130 ha for the same savings with the LiDAR sprayer.

4 Collaboration

This project involved extensive collaborations across stakeholder groups within and beyond Australia. Many of these were already in place prior to this project and all of these existing as well as the new ones will continue for many years into the future as this ongoing spray improvement area continues to progress and advance spray use in vertical crops. Scientists from the University of Queensland collaborated with colleagues from the following sectors.

Vineyard

We were pleased to work with vineyards who showed a strong interest in the research and supported the studies not only by providing access to their sites and machinery but also in providing help with some of the research activities.

Sprayer and equipment manufacturer:

Silvan, a Melbourne and Brisbane-based sprayer manufacturer provided a Silvan Oktopus sprayer and staff support for the LiDAR sprayer testing. By working with Silvan we assured that at least one major Australian sprayer manufacturer will look at providing sprayers already fitted with sensor systems optimised for Australian use.

FMR, a South Australia-based manufacturer of various sprayers including the recapture/ recycle R-series unit tested in these studies, provided sprayers and staff to support field studies. By working with an Australian innovative company, we assured that equipment tested in this research is applicable to Australian uses and needs.

We also consulted with other sprayer and nozzle manufacturer companies in Australia during this research, including Croplands and Teejet.

For modification systems to existing sprayers using the LiDAR sensor system, we collaborated with Vuetech, a Brisbane-based company agricultural technology company. Vuetech will serve as an Australian distributor and support company for the commercial version of our test system via GroundTruth, an Illinois-based company committed to the success of sustainable spraying.

Academic researcher:

The United States Dept of Agriculture Agricultural Research Service (USDA-ARS). We collaborated with two USDA-ARS groups and had visits to and from both these groups during the project. The lead scientists for our collaborations were Drs Heping Zhu (Ohio – LiDAR sensor systems) and Chenghai Yang (Texas – PIX4D imaging). Given our shared interest in similar goals (though for different crops – the Ohio group focussed on airblast spraying of apples while the Texas scientists focussed on aerial applications to cotton and broadacre crops) and our long history of collaborations in research and technologies, 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.

The University of Catalonia. We welcomed Dr Jordi Llorens to join our research for several months

East Malling Research and Peter Walklate Associates. Drs Peter Walklate and Jerry Cross in the UK previously developed a dosing system for apple spraying called Pesticide Adjusted for the Crop Environment (PACE), on which we based our initial vineyard dosing system using the common thread of LiDAR to characterise canopies. However our research progressed this to real-time canopy assessments using LiDAR in conjunction with other components to build on their research with other scientists also looking at these approaches such as USDA and JKI in Germany.

National Working Party on Pesticide Application:

The National Working Party on Pesticide Application (NWPPA) includes all major stakeholder groups in Australia for pesticide application. We involved the NWPPA in the research throughout the project with regular updates at their meetings in Canberra. Through this linkage we involved the Australian Pesticides and Veterinary Medicines Authority and state regulators of chemicals.

5 Extension and adoption activities

The project information was extended to stakeholders throughout the project, for example through the following, in addition to materials listed in section 8.2:

- At presentations by Hewitt at the annual meetings of the over-arching Digital Viticulture portfolio with representatives from Wine Australia, HIA Ltd., CRDC, the research organizations and grower organizations.
- At conferences (AVSO in Mildura VIC, July 2018) and workshops in NSW (Griffith, Leeton and Yanco, August, 2017), TAS (near Hobart and Launceston, January, 2018) and QLD (annually 2017, 2018, 2019 and 2020 at the Vineyard Walks, Stanthorpe) as invited presentations by Hewitt and O'Donnell.
- At updates to partner stakeholders during the research.
- A planned workshop near Canberra, ACT for dozens of stakeholders in April, 2020 had to be cancelled due to COVID-19 travel restrictions and was replaced with a ZOOM call in July with all stakeholder groups present.
- Working with pesticide companies through Nufarm on label changes to accommodate sprayers, to initially seek approval for reduced buffer zone sizes for the sensor and recapture/ recycle sprayers and then use that example to propose future additions as needed.
- We are working with the regulatory and pesticide use bodies at the federal and state levels through our long-term links with APVMA, PIRSA, NSW EPA and others to progress credit for growers who use the technologies tested in this study to reduce chemical use and environmental/ human exposure. This work is ongoing as pesticide regulations continue to change. A primary example is that data from our studies for the wine industry can be the first ones of which we are aware to ever be entered to the Spray Drift Management Tool introduced by APVMA to provide a mechanism for buffer zone reductions where appropriate.

We believe there are several ways that the project outcomes can be adopted by industry to improve pesticide placement, safety and use. Gaining regulatory support is important as noted above. We are working to progress this with pesticide companies and regulators.

We are aware that in some countries, improved equipment has received incentives through tax rebate schemes, which in some cases mean that investment in safer systems actually is 100% offset by tax credits. A precursor idea to the current project was encouraged in this way in California for almonds. That work involved sensors to detect entire trees and the gaps between them, to turn the entire sprayer on and off for trees and gaps respectively. Our project has taken that concept to the individual leaf level rather than the entire tree.

Extension, demonstrations and further publications aimed at growers is the best way to progress uptake of the techniques and concepts covered in this report and we are pleased and willing to do this over the next months and year, without needing additional funding.

6 Lessons learnt

Project challenges and lessons include the fact that equipment, weather and crop working situations can be unpredictable. During workshop participation we learned that if you ask 10 growers to offer an optimal spray dose rate for a given canopy, you may get 10 different answers. In high value table and wine grape crops, growers may be reluctant to risk cutting chemical rates for fear of not achieving adequate pest control. This may mean that actual savings in chemical use rates from recapture/ recycling and/ or targeted sensor sprayers may be even higher than achieved in this research because where sprays are applied well beyond the point of first runoff with non-targeted systems, a fine-tuning of rates to the required level can support a large reduction in chemical use. The deposition sensors studied in this research may be of high value for verifying such spray rates.

We appreciate that actual spray performance is largely a function of the operator and while the automated sensor variable rate system can help remove or ease many of the operator tasks, it is still essential for applicators to set sprayers up correctly for their canopies. For example, we were surprised at the impact of PWM duty cycle rate on droplet size and spray angle for some nozzle types and operating pressures, which suggests care should be taken in nozzle choice and use.

Having optimised spray application through either recycling the spray with powerful opposing fans surrounding the canopy or through the use of LiDAR to sense the target leaves and cordons and adjusting the dose in real time while spraying, we showed that electronic leaves can provide feedback during spraying to support auditing and verification of coverage. This concept could be progressed with integration into feedback loops to further adjust the spray during application We attempted to improve spray placement through the additional a high voltage electrostatic charge but did not find that this further increased spray coverage or wrap-around because our spray unit had a high velocity and volume of carrier air which provides a greater force than that of the attraction charge. Future tests could combine LiDAR spraying with a high pressure spraying system without air.

The approach we and our colleagues from USDA evaluated to LiDAR sensor spraying showed the high value of adding a basic modification to a sprayer to digitise the application process. As we close out this project, a commercial system is becoming available for use in Australia and we expect delivery of this by late August, after which we will validate it to show that its modifications against the approach we took (i.e. GPS replacing RADAR, improved spray control and options for multi-row spraying) offers similar benefits in chemical saving and targeting precision. We also aim to link this system with a ground robotic platform with Vuetech Australia. We are pleased to do this work for no additional budget to close out the current project (assuming in-kind support for equipment, staff and vineyards from Silvan, FMR, Vuetech and Treasury Wine Estates) and will also measure spray drift reduction for the sensor sprayer and a recycling sprayer in the format required by pesticide companies and APVMA for addition to the Australian government Spray Drift Management Tool. We expect this supplemental work to be complete by summer, 2021 but with sparse canopy data being critical to show maximum drift and chemical use reduction for highest regulatory and pesticide label value.

7 Recommendations

We are working with pesticide companies to look at adding systems such as those in this study to labelling and encourage the use of such systems for future improved spraying, with regulatory credit and support. In some countries, incentives are offered for growers to invest in equipment that can offer environmental protection. It would be good to see such ideas introduced in Australia.

We would like to see the spray coverage assessment aspect of this research progressed, for example through integration of the electronic leaf concept into spray decision control packages for future use by growers. At present the research only showed the proof of concept.

We would be pleased to extend the research findings at grower workshops in the future, as speakers and for practical field demonstrations.

Efficacy is a key to equipment optimisation in spraying. Future studies could evaluate efficacy for different kinds of pests when using systems studied in this project.

Some experts in spray application such as Dr Peter Trilloff in Germany believe that the most important factor in setting up sprayers for vertical crops is adjusting the airflow to deliver the correct speed, volume and direction for spraying the intended target and not beyond that target. Trilloff suggests many sprayers are set too high for air velocity and the spray travels far beyond the target, causing high risk of drift losses. A future optimised system could remove this decision more from the spray operator and adjust the air automatically in real time as the sprayer travels through the vineyard. In other words, after adjusting the liquid flow in the current study, a logical next step is to adjust the air which carries that liquid toward the target.

Further developments in robotics would be of value to build on this research.

As noted in Section 6, we aim to close out this exercise on real-time dose-adjusted, targeted spraying with a new commercial LiDAR spraying system and a recycle sprayer by collecting data on chemical use and drift reduction in the field trial format required for regulatory use of the data by APVMA and pesticide manufacturers, for direct use with the new Australian government Spray Drift Management Tool which should offer shorter buffers and incentives to use these approaches to spray optimisation and chemical use and exposure reduction. We await final delivery of the commercial system by spring 2020 and expect completion of this supplemental work at no cost to Wine Australia by summer, 2021.

8 Appendix - additional project information

8.1 Intellectual property

No IP is owned by the project because all equipment and concepts were worked on in collaboration with other groups.

8.2 Project, media and communications material

Hewitt, A.J. and O'Donnell, C.C. (2017) Setting the PACE in Spraying Developments. Wine Australia RD&E News.

Hewitt, A.J. (2018) Digital Spraying. Frontline Pest and Disease Management for Healthy Vineyards. AVSO July, 2018.

Hewitt, A.J. and O'Donnell, C.C. (2018) New Spraying System Bring Big Savings in Chemical. Wine Australia RD&E News.

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.

Llorens, J. and Hewitt, A.J. (2019) Droplet Size Effects in a PWM System. First Results to Improve Orchard Spray Application. Suprofruit 2019. 15thWorkshop on Spray Application and Precision Technology in Fruit Growing East Malling, United Kingdom, 16 – 18 July 2019.

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.

Also presentations and equipment demonstrations by Hewitt and O'Donnell at wine grower workshops in Stanthorpe each year for the project (Vineyard Walks) and in 2017/ 2018 in NSW, TAS and VIC.

8.3 Equipment and assets

A SICK LMS100 LiDAR was purchased at the start of the project. No other equipment and assets were purchased from project funds but were provided as in-kind support to the project so are owned elsewhere.

8.4 References

ASABE (1999) S572 Standard. Spray Nozzle Classification by Droplet Spectra. ASABE, Niles, Michigan, USA.

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SHEN, Y., ZHU, H., LIU, H., CHEN, Y. y OZKAN, E., 2017. Development of a Laser-Guided, Embedded-Computer-Controlled, Air-Assisted Precision Sprayer. *Transactions of the ASABE*, vol. 60, no. 6, pp. 1827-1838.

8.5 Staff

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8.6 Evaluation report

Objective 1: Sensor use for dynamic canopy upper and lower limit and width/ density spatially and temporally to support variable rate precise applications (i.e. sense the canopy and turn nozzles and off when targets are present and absent respectively, as well as adjust the dose rate for the canopy width at each sprayer nozzle height).

Outcomes: This work was successful. A LiDAR was mounted on a multi-ducted Australian air-assisted sprayer and used to map out the 3-D canopy in real time while the tractor and sprayer drove along each vine row. 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. It was also found that wind speed and direction may require this to be modified which could be further developed in the future or the system could be recommended for use only at lower wind speeds when canopies are sparse. 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. Surprisingly, some nozzle types and operating pressures were affected more than others by changes in operating duty cycles, with some tending to produce coarser sprays at lower duty cycles which could actually be of benefit to assure less drift for those canopy regions because such conditions would be for gaps and also for dormant canopy applications. The LiDAR system allowed sprayers to be modified to offer performance similar to what we considered among the best approach currently available for dose management and drift avoidance, i.e. recapture/ recycling spraying. Both the LiDAR approach and the recycling approach offered greatest chemical savings (50-90%) while maintaining excellent coverage for dormant canopies, early season canopies, gap situations and specialised applications to specific areas such as trunk and cordon spraying for dieback disease management. As the canopy fills out during the season, the chemical savings decrease but still offer at least 10-50% even for dense, foliated canopies with fruit. The project also offered a novel electronic leaf system for measuring spray coverage and transmitting the measured data to a remote computer or even 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.

Objective 2: Develop a ground-based proximal sensing method for canopy LAI.

Outcome: LiDAR was shown to successfully detect LAI in real-time and link with spray decision-support as in Objective 1. We also evaluated PIX4D but found that rather than being optimal for ground platform use, it worked best on a drone for aerial surveying. The Wine Australia App, VitiCanopy, also was found to offer an excellent assessment of LAI for input to a manual dosing model that was developed during this project. Ceptometry using PARBars was also explored but given the value of LiDAR and VitiCanopy for automated and manual assessments respectively, it was felt that other systems were not needed. The acronym for (automated and manual) pesticide adjustments for the crop environment is PACE which was originally developed for apple spraying in the UK and adapted in this project for vineyards.

Objective 3: Computer based method to convert LAI and structure to a form that can be used for decision-making temporally.

Outcome: Objective 1 was linked with this objective and achieved through the LiDAR system for real-time canopy assessments to support decisions temporally and spatially in vineyards. A manual approach using VitiCanopy as explained in Objective 2 provided an alternative approach where LiDAR-type sensors were not available or desired.

Objective 4: Extension and outreach to grower and applicator groups as well as other stakeholders.

Outcome: Throughout the project the work involved close collaboration between industry, researcher and grower groups. Presentations were given at grower and stakeholder events such as AVSO Mildura, grower workshops in QLD and VIC and project meetings in SA. Videoconferencing calls with the larger stakeholder national group occurred in winter, 2020 and a similar event is scheduled at the end of the project in August, 2020 for grape industry representatives. The extension will continue through 2020 and 2021 as commercial versions of the systems are launched for growers in Australia.

8.7 Acknowledgments

This project was supported by Wine Australia, through funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program, as well as Horticulture Innovation Australia. We received in-kind support from Silvan (long-term sprayer and staff), FMR (sprayers for individual field trial dates and staff), Treasury Wine Estates (vineyard, tractor, staff), Vinland Estates (vineyard, tractor, staff), Domenic Sergi (vineyard, tractor), NERCITA (electronic leaves), Spectrum (electrostatic nozzles), Ballandean Estates (vineyard, tractor, staff) and USDA (equipment, staff).