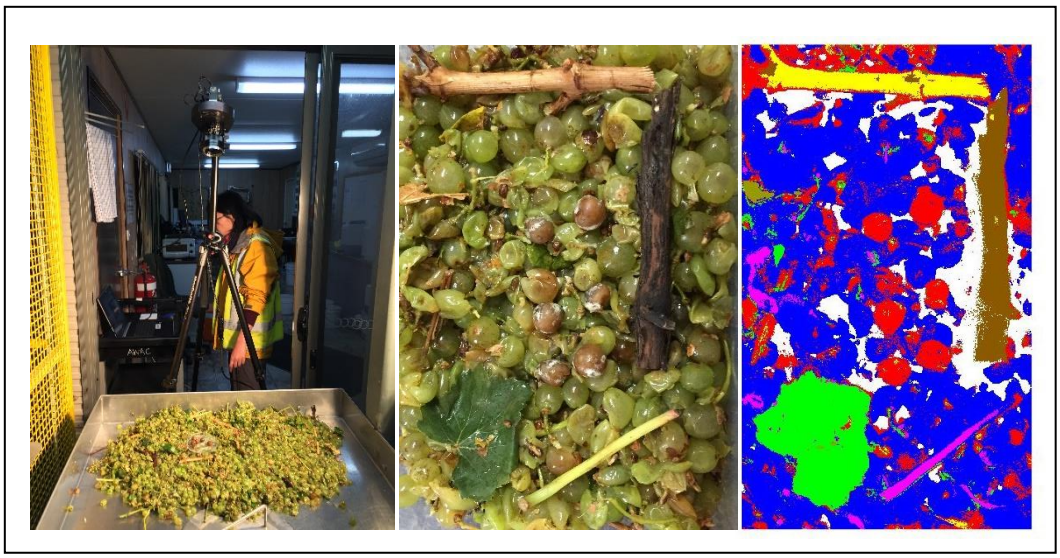
Australian Government

Wine Australia

The Australian Wine Research Institute

DIGITAL SOLUTIONS FOR GRAPE QUALITY MEASURES AT THE WEIGHBRIDGE



FINAL REPORT TO WINE AUSTRALIA

This project was supported by Wine Australia, through funding from the Australian Government Department of Agriculture as part of its Rural R&D for Profit program, and The Australian Wine Research Institute.

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Abstract

This project applied rapid digital methods to assess grape quality on delivery to the winery, in particular *Botrytis* infection and presence of matter other than grapes (MOG). The primary method used was hyperspectral imaging, initially laboratory-based with a full spectral linescan camera (400-1000 nm wavelength), using both laboratory-infected *Botrytis* samples and field samples. Eight wavelengths were then selected for use with a filter-based multispectral snapshot camera, which was more applicable for use at the winery weighbridge and in the vineyard. Spectral imaging identified *Botrytis* infection and MOG, differentiated types of fungal infection and identified grape sunburn and shrivel.

Executive summary

The primary objective of this project was to develop digital methods for rapid assessment of grape quality on delivery to the winery. The key parameters were the identification of *Botrytis*-infected grapes and assessment of the amount of matter other than grapes (MOG) in mechanically harvested loads. A secondary objective was to determine whether these methods could also be applied in vineyards for non-destructive *Botrytis* assessment of grapes on the vine.

Images were taken with a laboratory-based hyperspectral linescan camera (Specim FX10) that collected spectral information over the 400-1000 nm wavelength range for individual pixels. The spectral information was used to classify each pixel with regard to what material class it belonged to, and this classification was applied as a false colour image to highlight spatial information. The image analysis software packages used were Scyven and ENVI.

Hyperspectral imaging (HSI) could discriminate clean and infected red and white grapes, for both laboratory infections and field samples. The calibrations were not dependent on growing region, grape variety and *Botrytis* strain. HSI could also discriminate *Botrytis* infection from sour rot (mixed fungal and bacterial infection of grapes). Washing sporulating berries with grape juice or smashing berries, to simulate mechanical harvesting, did not prevent identification of *Botrytis*. HSI could also identify sunburn in white grapes and shrivel in red and white grapes. HSI could discriminate other grapevine components that often form MOG in mechanically harvested grape loads (i.e. canes, wood, petioles, leaves and insects).

Key wavelengths that discriminated different materials were used to select filters for a multispectral camera (Ocean Optics SpectroCam) that operated in a snapshot mode, similar to a normal still camera, and did not require the sample to be moved under the camera as with the FX10 linescan camera. This made it more suitable for use in the field, at the winery weighbridge or in the vineyard. Laboratory tests were performed to compare LED and halogen lighting. Images collected under LED lighting indicated insufficient output in NIR wavelengths (790, 860, 918, 972 nm) and only the first four filters (444, 531, 680, 717 nm) could be used for multispectral imaging (MSI). Halogen lighting was suitable over the whole wavelength range.

When samples of grapes and grapevine material were imaged under LED lighting, shadows on the background matrix were classified as infected grapes and separate spectral libraries had to be made for the shadows to correct this. Under halogen lighting, lighter shadows could be included in the general background spectral libraries to provide correct classification but darker shadows remained an issue.

The SpectroCam was tested in a winery environment at a grape weighbridge testing station. Grape loads arrived in very large trucks that were unsuitable for direct imaging, but the testing station used a load sampling system that could deliver samples to a tray for analysis. Samples were imaged as a mass on the sample tray, in small tubs and spread out on a polymer board that was also scanned by the FX10 camera. Most of the intake was at night and samples were imaged with either halogen or LED lighting, but other lighting conditions were also tested: full sunlight with halogen fill-in and the shaded testing tray area with halogen plus some ambient daylight.

When samples were spread out on a board, MOG, clean grapes and infected grapes could be discriminated, but with LED lighting required spectral libraries for shadows on the backboard. Specular reflections were a problem with material from mechanically harvested loads that was wet with grape juice. Some incorrect classification occurred at the edges of objects, where there may have been dark shadows and mixed pixels. Spectral differences in these regions were identified using the full spectral scan from the FX10 camera. When bulk samples were imaged either on the testing station sample tray or in sample tubs, shadows within the samples caused incorrect classification. This could be compensated for to a degree, using spectral libraries to classify shadows, but unlike shadows on a sample board the shadows on a bulk sample contained a variety of backgrounds, so were difficult to define.

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

The RotBot app was also tested in the vineyard. RotBot can discriminate clean and *Botrytis* infected white grapes but must be used with a blue background. For correct infection level classification there must only be grapes visible in the image: bunch rachis, petioles, immature canes are classified as clean grapes; lignified canes, grapevine bark, dried petioles, dried leaves, sunburnt or shrivelled grapes and powdery mildew berry scars are classified as infected grapes. RotBot can handle shadows on samples but overexposed regions are incorrectly classified.

In conclusion, multispectral imaging is capable of discriminating material in mechanically harvested grape loads. However, to avoid problems caused by shadows within the sample, imaging would be best done with samples spread out on a conveyor belt with a linescan camera or spread on a static backing board with a snapshot camera. This provides a uniform background with reduced shadow, and any shadows would be on a constant background. Some issues with image analysis need to be addressed, with mixed pixels causing incorrect material classification on the edge of samples. Specular reflectance on wet samples is an issue but could be mitigated with diffuse lighting. Further work should be done with LED lighting systems suitable for use in the NIR range as a replacement for halogen, which may soon no longer be available in Australia .

An important area of future work to encourage adoption would be to create a robust imaging system where software controls the camera and seamlessly runs the image analysis in the background and reports a result, with minimal user input. A vineyard imaging system requires development of portable devices with appropriate wavelength ranges and with onboard lighting and image analysis capability.

Abbreviations and glossary

MOG – matter other than grapes

SVM – support vector machine

Vis-NIR – visible-near infrared

MIR – mid-infrared

RGB – red green blue

HSI – hyperspectral imaging

MSI – multispectral imaging

1 Project rationale and objectives

Although it may be desirable in certain wine styles, infection of wine-grapes with *Botrytis cinerea* generally creates serious loss of quality and can promote growth of other spoilage organisms. *Botrytis* tends to be an ongoing problem in cool, wet climates but under adverse weather conditions it can also spread rapidly in regions that normally have a dry climate. An example of a challenging vintage was 2017, when many of the high-production inland areas experienced late summer rains at a time when the grapes were very susceptible to *Botrytis* infection. Most wineries inspect fruit in the field before harvesting, but when the conditions are very conducive to *Botrytis* growth the infection can expand exponentially in a matter of days. Fruit that has been assessed as 'clean' in the vineyard can quickly deteriorate prior to delivery to the winery.

Unlike powdery mildew, which forms a diffuse infection, *Botrytis* infects the whole berry and is easier to assess visually in bunches in the vineyard, particularly with white grapes. However, the machine harvest of *Botrytis*-affected fruit makes it very difficult to determine the detrimental effects of the disease at the weighbridge. *Botrytis* is also more difficult to detect visually in red grapes. If *Botrytis* is present in the load but not observed, the resultant wine may have a lower value (50-70% of potential). An objective method for *Botrytis* assessment at the weighbridge is therefore required to allow effective screening of fruit on intake. The aim of this project was to evaluate hyperspectral imaging for this purpose, as a rapid method for the real-time analysis of *Botrytis* with minimal requirements for sample preparation.

Matter other than grapes (MOG) is often present in the mechanically harvested load when it arrives at the weighbridge. This can consist of items such as leaves, petioles, canes, grapevine wood, insects and vine trellis material. Excessive MOG can cause taints and other quality problems and large foreign objects can cause damage to processing equipment. Most wineries perform visual checks at the weighbridge and reference against photographic charts (Allan 1996) to determine the level of MOG, which may result in downgrading of the price paid for the load or outright rejection. This subjective assessment can cause mistrust in the grape supplier about the load assessment process.

The development of a process to objectively measure *Botrytis* bunch rot and matter other than grapes (MOG) will provide greater transparency of the assessment process and help prevent the production of poor quality wine.

2 Method and project locations

Background

Visible near-infrared (Vis-NIR) and mid-infrared (MIR) spectroscopy have gained favour in food and agriculture as rapid methods of analysis, including in the wine industry (Dambergs et al. 2004, 2015; Cozzolino and Dambergs 2009). It has been demonstrated that Vis-NIR and MIR have potential for *Botrytis* analysis (Hill et al. 2013, 2014; Porep et al. 2015) but the error is too large to be used at the low infection levels specified by most wineries, particularly considering that the assessment may result in fruit rejection and therefore serious economic loss.

A recent variant of Vis-NIR spectroscopy is hyperspectral imaging (Sun 2010). A normal photographic image is an RGB image; that is, each pixel only contains information from red, green and blue wavelengths (650, 532 and 473 nm). A hyperspectral camera collects information from a large number of wavelengths, and this information is stored as a spectrum in each pixel of a digital image. Hyperspectral cameras may collect visible light information (400-700 nm) but usually include some NIR wavelengths (700-2500 nm). One of the most commonly used wavelength ranges is 400-1000 nm. All organic materials have a distinct NIR absorbance fingerprint, based on vibration of hydrogen attached to carbon, nitrogen and oxygen. The NIR spectral profiles of organic materials can be used to identify and quantify those materials. The spectral information in a hyperspectral image creates a third dimension within the image: X and Y for the spatial component and Z for the spectral information in each pixel; this is what is known as a spectral hypercube.

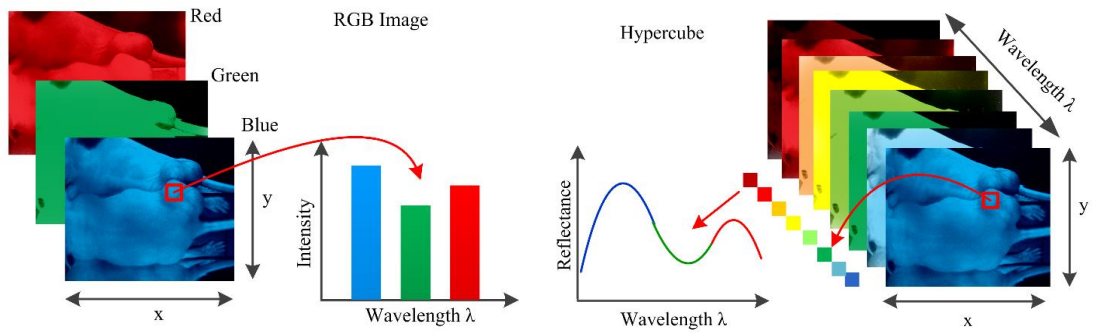


Figure 1. A standard three-wavelength RGB image compared with a hyperspectral image

The spectral information can be used to identify materials and create false colour overlays on the original spatial image, to visualise the distribution of the materials and allow quantification. This technology has been used mainly with satellites, fixed wing aircraft and more recently with unmanned aerial vehicles, for imaging of agricultural crops and mineral deposits. The technology has also been applied to land-based imaging in the field and in production environments, such as fruit grading. With the help of recent advancements in cameras, software, computer storage and computing power, this technology has become more affordable and accessible and offers great potential for use in agriculture.

Hyperspectral imaging of powdery mildew in white grapes has been demonstrated recently, using tandem cameras covering the full Vis-NIR range (400-2500 nm), but the 400-1000 nm range showed the largest spectral variation related to powdery mildew infection (Knauer et al. 2017). A simplified form of imaging using RGB images has been successful in identifying *Botrytis* in grapes and has been developed as a phone app (RotBot). However, RotBot will only work on white grapes and fruit must be photographed on a specific blue background (Hill et al. 2014). The aim of the current project was to develop hyperspectral methods to quantify *Botrytis* in both red and white grapes.

Hyperspectral cameras are commonly linescan (pushbroom) cameras that collect one row of pixels in each frame and join the frames to create the final image. This mode requires that either the camera or the sample are moved at a constant speed as the image is collected. While this suits imaging from satellites or aircraft, where the camera is moving at a known rate, ground-based imaging requires the use of a conveyer belt or moving stage to present the sample to a fixed camera.

With a smaller numbers of wavelengths (multispectral) it becomes possible to use 'snapshot' camera systems that image the whole scene and do not require the camera or sample to be moved to create the image.

Materials and methods

***Botrytis* samples**

Botrytis infected samples were collected from the field, and clean bunches were also inoculated with *Botrytis* spores from cultures provided by the PIRSA-SARDI Horticulture Pathology Laboratory (Urrbrae, South Australia).

Spore suspensions were prepared by washing sporulating culture plates with sterile distilled water plus a small amount of Tween 80 detergent. Spore suspensions were kept on ice to prevent germination until grapes were infected.

Bunches were sprayed with the aqueous *Botrytis* spore suspension (approximately 10^6 spores/mL) or individual berries on the bunches were injected with a 26G needle. Individual plucked berries were infected by immersing in a spore suspension for 15 minutes.

Inoculated grapes were incubated at room temperature in a humid chamber exposed to diurnal lighting. Infections typically developed fully within one week. Apparently clean bunches were also incubated in humid chambers for extended periods to express latent *Botrytis.*



Figure 2. From top left, clockwise: A sporulating *Botrytis* culture plate; infected bunches incubating in humid chambers; Merlot bunch with sporulating *Botrytis* infection; Colombard bunch with non-sporulating *Botrytis* infection.

Hyperspectral imaging

Hyperspectral images were collected under halogen lighting with a Specim FX10 camera (supplied by Adept Turnkey, Coburg, Victoria). This camera collects images using a wavelength range of 400-1000 nm and operates in a linescan mode; that is, a row of pixels is collected with each frame, so either the sample or the camera must be moved to create the full image. The camera collects frames for each image at video rates and the resolution of the image is defined by the width of the linescan (1024 pixels) and the length of the linear movement. In this case the samples were moved on a linear stage synchronised with the frame rate and exposure time of the camera to create an image with the full spectrum in each pixel. The camera and stage were controlled with LUMO software (supplied by supplied by Adept Turnkey, Coburg, Victoria).



Figure 3. Specim FX10 Vis-NIR hyperspectral camera with linear stage

Multispectral imaging

Initial work was performed with full spectral images from the FX10; however, this camera is difficult to operate in the field, requires a computer with a fast processor, fast data transfer and a large amount of RAM and storage. Images from the FX10 typically had a 1 Gigabyte file size. A more convenient field camera would need to operate in snapshot mode, to remove the need to move the sample to collect the image, and with fewer wavelengths to reduce the file size. Information from analysis of the images from the FX10 was used to select some key wavelengths for filters in a SpectroCam (Ocean Optics, Lastek, Adelaide, South Australia). This multispectral camera was used to collect images in the vineyard and at a winery weighbridge testing station. The SpectroCam consists of a digital camera body with a rotating filter wheel behind the lens. For each image scene the camera collects an individual image with each filter, using a stepper motor to move the filters. The single band images are compiled into a multispectral image containing eight wavelengths in each pixel to create the composite image. The wavelengths used were selected based on the results of the hyperspectral imaging: 450, 531, 680, 717, 790, 860, 918, 972 nm, with a 10 nm bandwidth for each filter. To ensure the images from each wavelength were perfectly registered, the camera was tripod mounted to collect images of a static sample.



Figure 4. The Oceans Optics SpectroCam

Lighting

Lighting is critical for hyperspectral imaging. Vis-NIR hyperspectral cameras normally operate in sunlight or use halogen lighting to get the full spread of irradiating wavelengths; the FX10 camera uses halogen lighting. A disadvantage of halogen lighting is that it generates a large amount heat and requires a large amount of power.

LED lighting technology is advancing rapidly and has the advantage of high light output with low power use and low heat output. The low power use enables the use of lightweight, portable, battery-operated lights that are suitable for field use. However, a disadvantage of LED lights is that they have very narrow wavelength ranges and most conventional LED lights emit limited amounts of NIR. A multi-wavelength LED light with adjustable colour temperature was tested with the SpectroCam.

RGB imaging

Botrytis infection in white grapes can be quantified using a standard smartphone RGB camera, using the RotBot App (Hill et al. 2014). RotBot was tested using an Apple iPhone 6 under laboratory conditions with fluorescent lighting, and in the field with natural lighting. Portability is an advantage of RotBot but a disadvantage is that it must be used with the bunch against a blue background and it only operates correctly on white grapes.

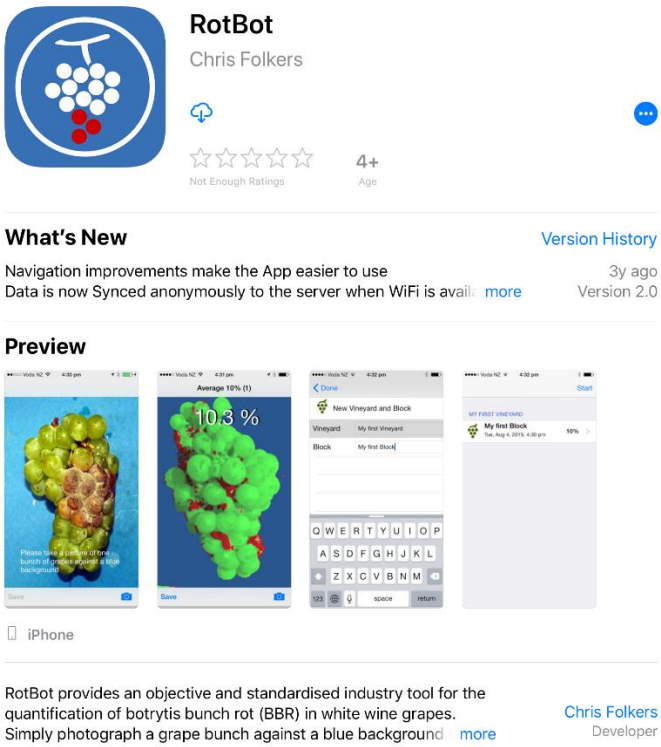


Figure 5. The RotBot application.

Image analysis

Images were initially analysed using Scyven software provided by CSIRO's Data61. Images imported into Scyven were analysed with a kernel fitting algorithm, support vector machine (SVM), and false colour images were created to identify materials. The Scyven false colour images were then analysed with ImageJ Fiji to achieve quantification based on the area of pixels for the various materials identified.

Further analysis was performed with ENVI provided by ESRI Australia. ENVI has built in capability to quantify the pixel classes identified and can also combine the single band images from the SpectroCam to produce a multispectral image.

Locations of project activities

Botrytis cultures were prepared at the PIRSA/SARDI Fungal Pathology laboratory at Urrbrae, South Australia.

The laboratory-based imaging work was performed at the Australian Wine Research Institute, Urrbrae, South Australia.

Grape samples were collected from vineyards in the Riverland, Padthaway, Wrattonbully, Coonawarra, Adelaide Hills and the Barossa Valley in South Australia.

The vineyard-based field work was performed in the Riverland, South Australia.

The winery-based field work was performed at the Accolade winery, Glossop, South Australia.

The research findings are applicable to all wine-producing regions of Australia and would also be applicable to table grapes and other fruit crops.

3 Project results and discussion

Laboratory-based hyperspectral imaging: proof of principle

Individual berries offer the simplest system as proof of principle for hyperspectral imaging of *Botrytis* in grapes. Figure 6 shows an RGB image and false colour overlays of material identified using a support vector machine (SVM) algorithm. It was used as an unsupervised method, which means the algorithm decides the spectral profiles that best discriminate various materials in the samples in a 'material discovery' process. Despite this unsupervised approach, uninfected berries were clearly discriminated from infected berries. The grape variety (Merlot or Colombard) was also clearly discriminated. The background material (in this case a polymer conveyor belt) could also be discriminated, but shadows on the background were identified as a different material, illustrating a potential problem with the methodology; lighting is critical to obtaining reproducible spectral signatures.

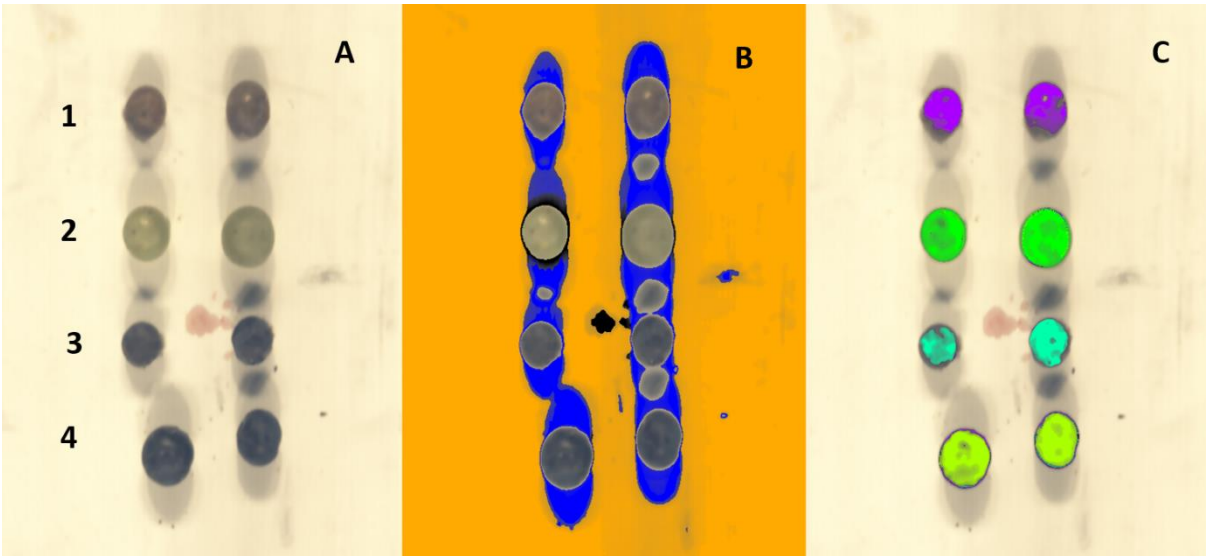


Figure 6. RGB image (A) of infected (1) and non-infected (2) Colombard berries and infected (3) and non-infected (4) Merlot berries. False colour overlay (B) of hyperspectral identification of the background material (orange) and shadows (blue). False colour overlay (C) showing hyperspectral discrimination of the grapes by variety and infection status.

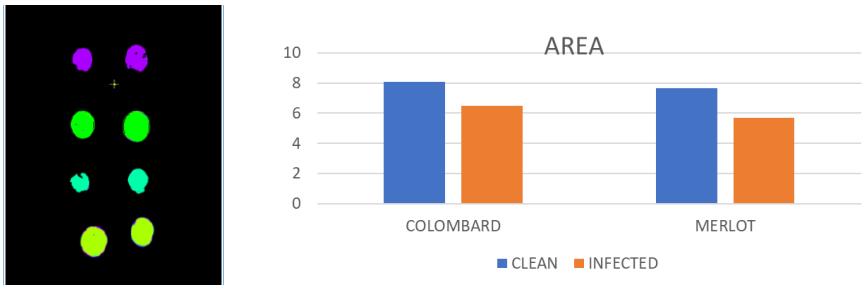


Figure 7. Extraction of false colour image pixel numbers from the image presented in Figure 6.

The false colour pixels from the image shown in Figure 6 were extracted from the remainder of the image using ImageJ Fiji and quantified to determine the relative area of infected and clean berries for the two varieties (Figure 7). As is often the case, the infected berries were smaller, likely due to dehydration. The majority of the image analysis was performed using a supervised SVM classification method with spectral libraries created for the various image regions to be classified.

Imaging of whole bunches

Whole bunches present more of a challenge with hyperspectral imaging, as a greater depth of field is required, and shadowing becomes more of an issue. This is illustrated in Figure 8. Using unsupervised SVM material discovery, uninfected berries (image B) were clearly discriminated from infected berries (image D) but the shadowed internal spaces were identified as different material (C). The fact that the deeply shadowed regions were classified separately by the unsupervised classification method implies that they are spectrally different, confirming that shadowing could present challenges for *in situ* analysis. Bunch scanning also presents challenges in that internal berries are obscured; however, this also occurs with traditional visual inspection of intact bunches. From this aspect, mechanically harvested grapes may be more effectively imaged, as samples can be spread out in a single layer under ideal lighting conditions. Image E illustrates classification of infected berries with multispectral imaging, using only three wavelengths chosen from the hyperspectral data. In this case the multispectral method performed slightly better at identifying small patches of infected berries.

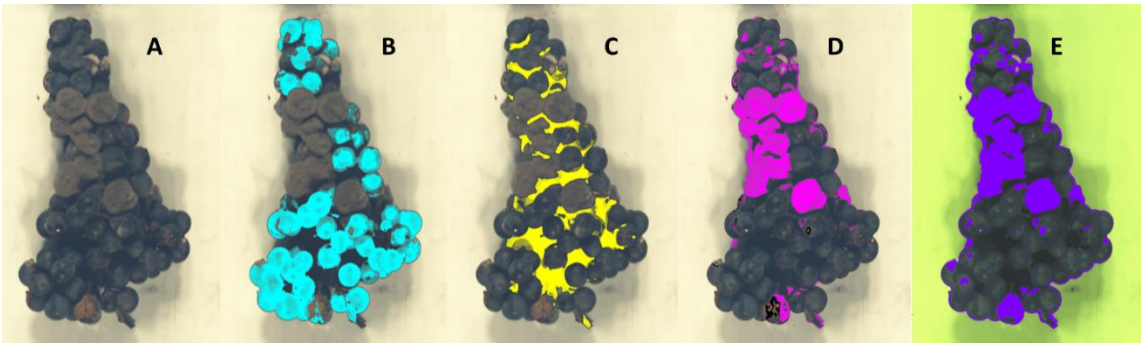


Figure 8. RGB image of a *Botrytis*-infected Merlot bunch (A); false colour overlay of hyperspectral analysis (400-1000 nm) showing uninfected berries (B), shadowed internal spaces (C) and infected berries (D). False colour overlay of multispectral analysis (550, 650, 850 nm) highlighting infected berries (E).

Selection of key wavelengths from hyperspectral classification data, matrix effects and simulation of mechanical harvesting

The hyperspectral images collected by the FX10 were classified into their components (see figures below), both to confirm the proof of concept and identify the critical wavelengths so that these could be used with the multispectral camera. In almost all cases the spectral reflectance from the components in the images allowed them to be clearly distinguished.

Grapes (Colombard) and grapevine material



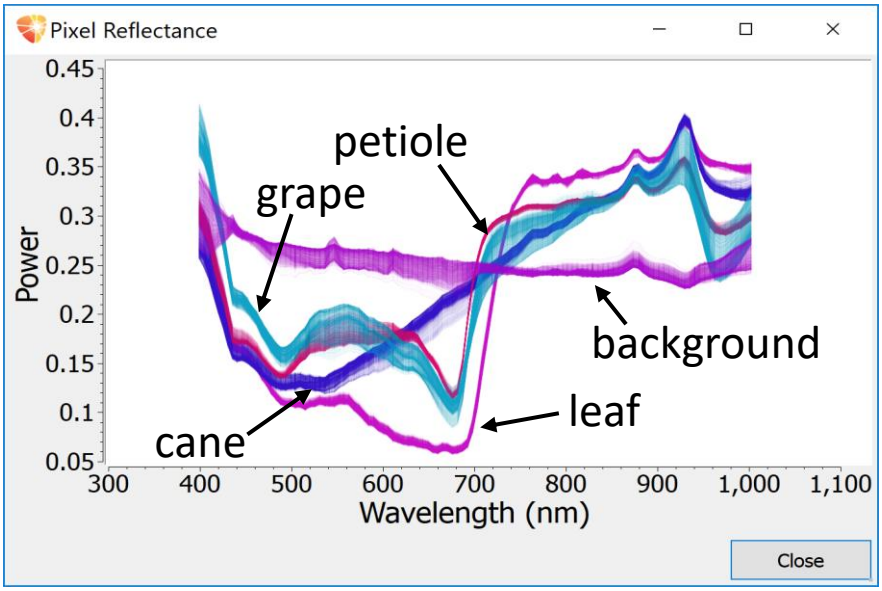
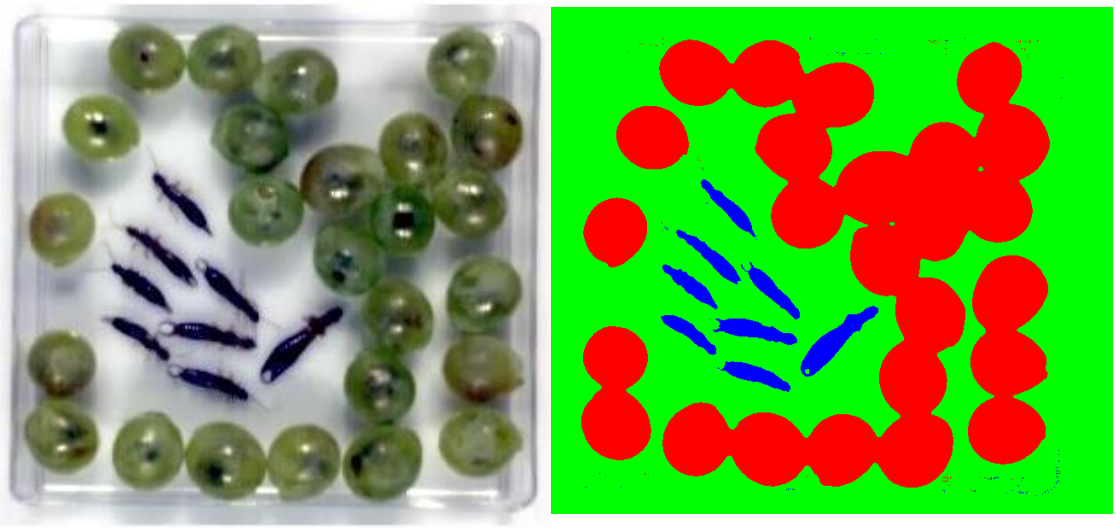


Figure 9. Standard RGB image and false colour image of SVM classification of cane, petiole, leaf and grapes and spectral libraries for the categories. Key wavelengths (selected as regions of difference): 490, 520, 650, 700, 780, 900, 980 nm

Grapes (Colombard) and insects



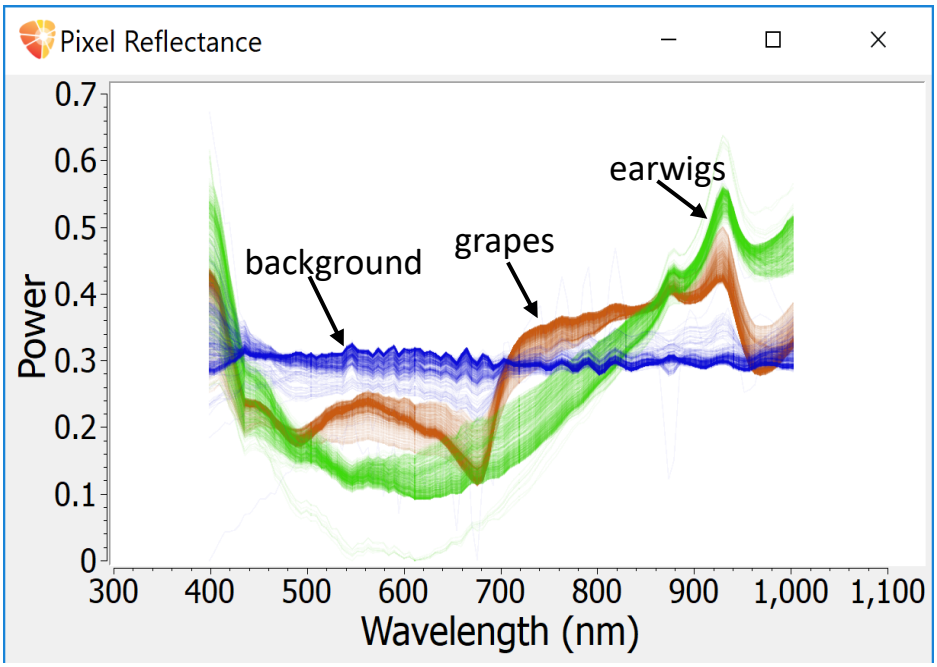


Figure 10. Standard RGB image and false colour image of SVM classification of earwigs and grapes and spectral libraries for the categories. Key wavelengths: 560, 760, 950, 1000 nm. Mealy bugs and snails could also be discriminated.

Wild *Botrytis* and sunburn in Chardonnay

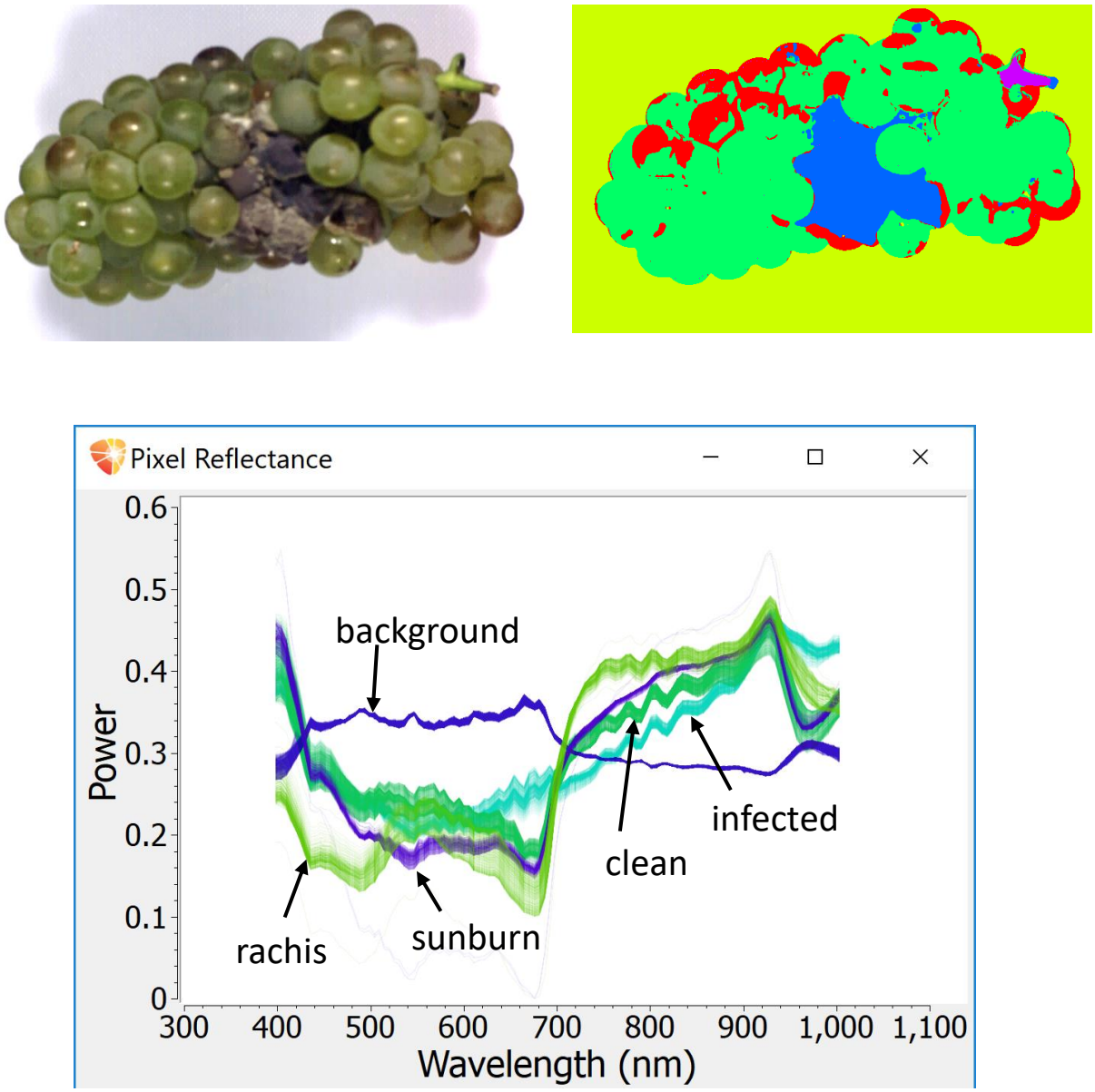
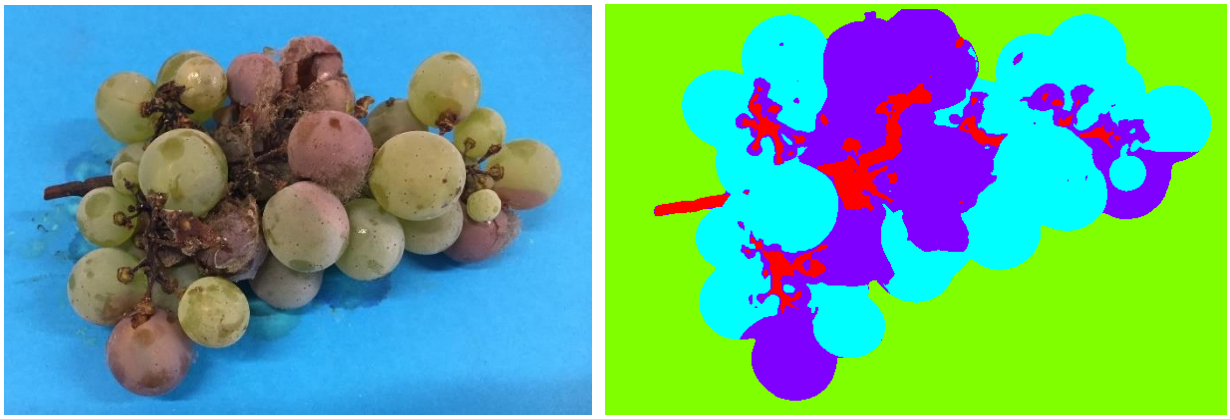


Figure 11. Standard RGB image and false colour image of SVM classification of grapes (clean, infected and sunburnt) and bunch rachis (stem) and spectral libraries for the categories. Key wavelengths (selected as regions of difference): 560, 760, 950, 1000 nm. Without creating a spectral library for sunburn it can be confused with non-sporulating *Botrytis*-infected grapes. Key wavelengths: 450, 550, 680, 790, 860, 1000 nm

Laboratory-infected grapes (Sauvignon Blanc)



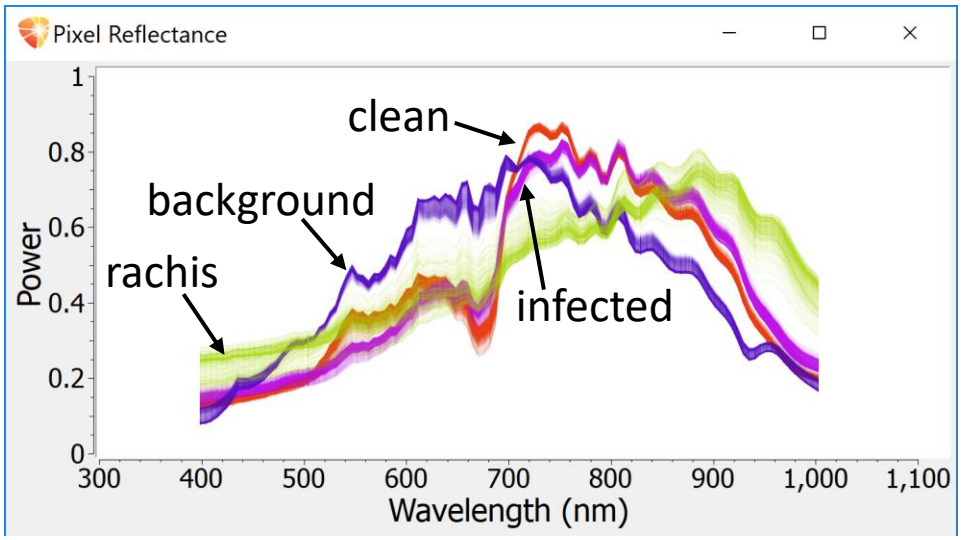


Figure 12. Standard RGB image and false colour image of SVM classification of grapes (laboratory-infected by incubating a bunch of grapes in a humid chamber to express latent *Botrytis*). Rachis, clean and infected grapes discriminated. Tips of peduncles are identified as infected; this may be due to the presence of some grape flesh in these area. Some shadowed internal spaces of the bunch are marked as infected. Key wavelengths: 450, 500, 550, 680, 750, 820, 920, 980 nm

Matrix effects: grape variety, growing region and *Botrytis* strain

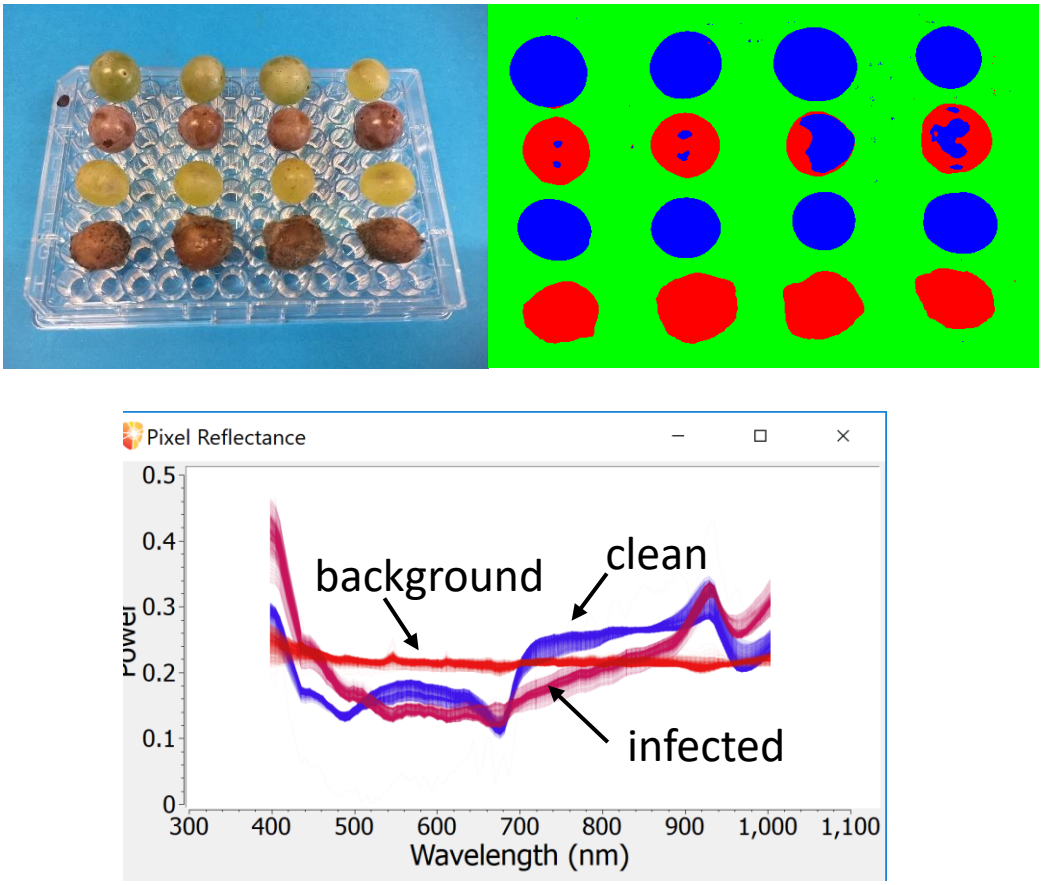
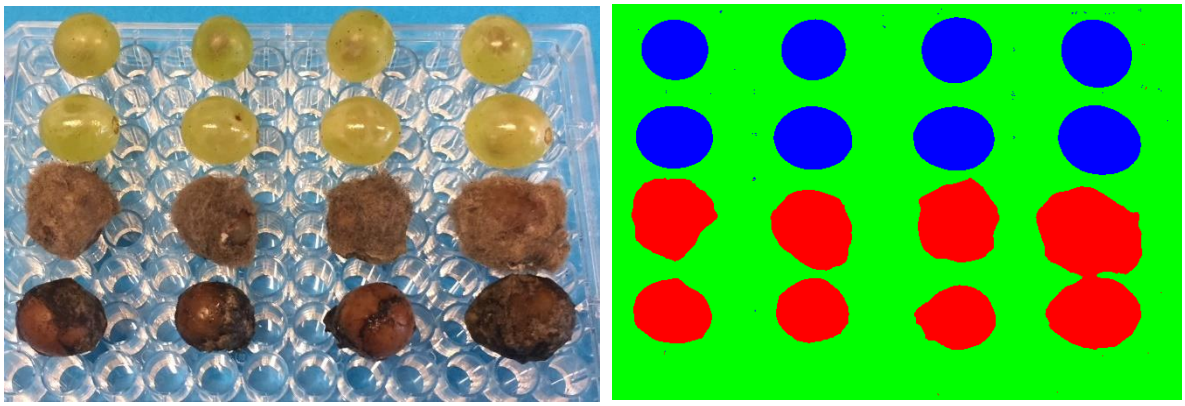


Figure 13. Clean and wild, non-sporulating *Botrytis*-infected Adelaide Hills Sauvignon Blanc (top two rows) and clean and sporulating laboratory-infected Riverland Colombard. Spectral libraries prepared with the Riverland Colombard could classify clean and infected Adelaide Hills Sauvignon Blanc. There was some patchy classification of Sauvignon Blanc but infection was non-sporulating and may have been lighter. Key wavelengths: 450, 490, 560, 680, 800, 940, 980, 1000 nm.

Simulation of berry washing with grape juice during mechanical harvesting



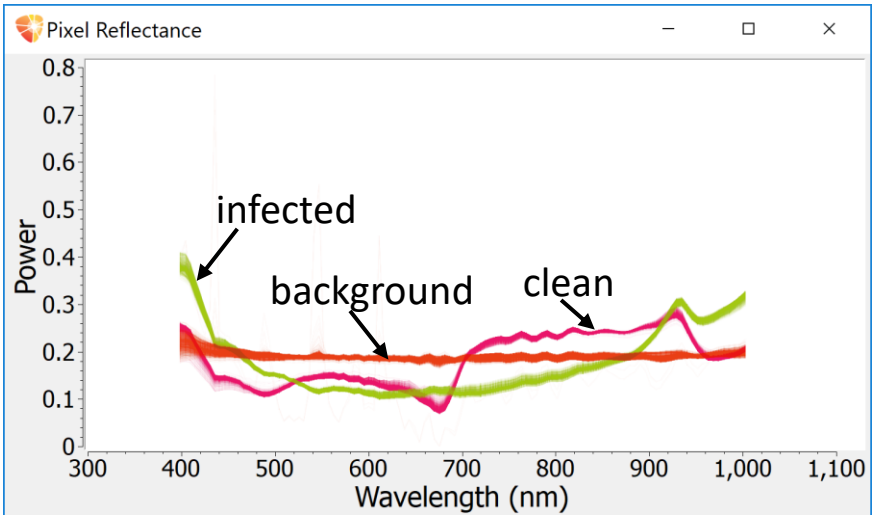


Figure 14. Laboratory-infected grapes tend to always sporulate; however, during harvesting sporulation material may be washed off. Harvesting was simulated with laboratory-infected Colombard by washing clean and sporulating *Botrytis* infected berries with grape juice. Top, clean grapes; second row, washed clean grapes; third row, sporulating grapes; fourth row, sporulating washed grapes. Spectral libraries from clean and infected berries could classify washed clean and infected berries. Key wavelengths: 420, 450, 480, 550, 680, 760, 880, 950, 1000 nm.

.

Simulation of berry washing and damage during mechanical harvesting

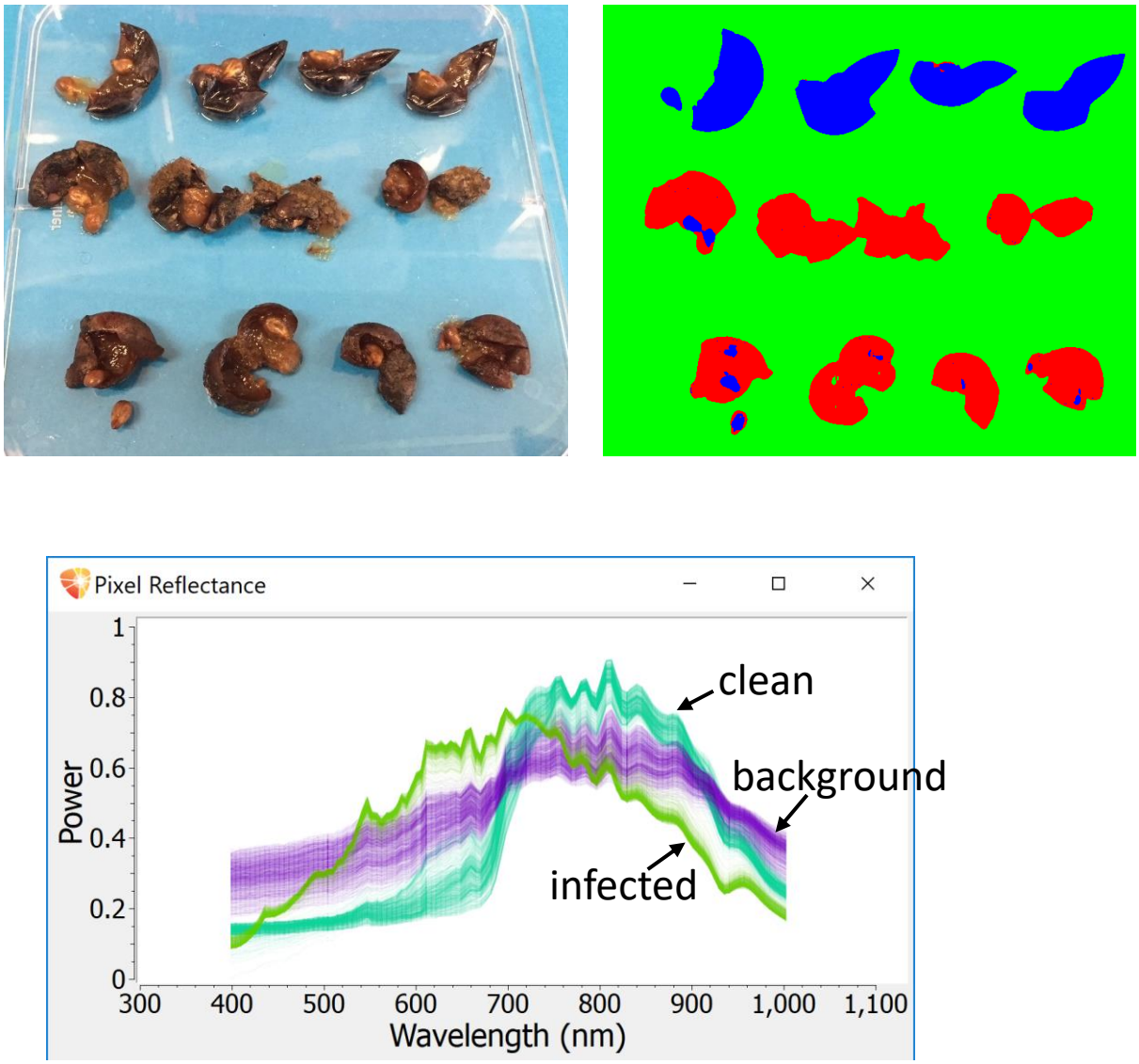
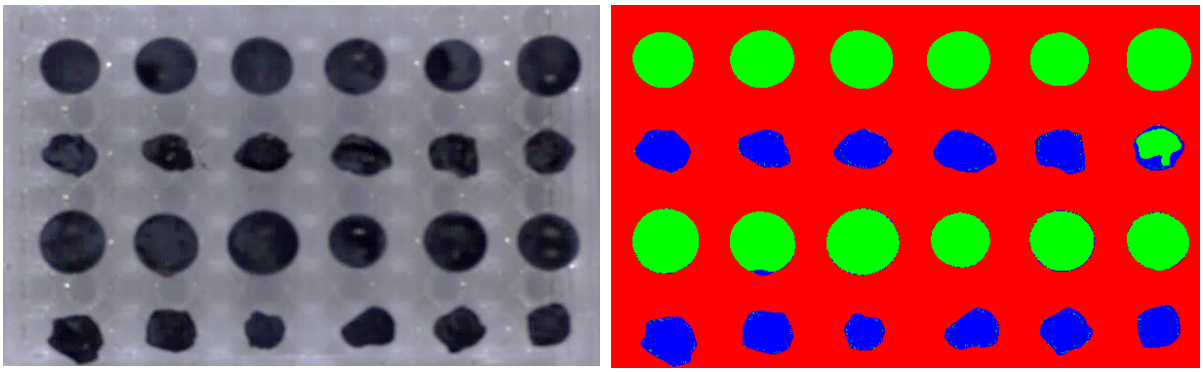


Figure 15. Merlot. Top row, clean smashed grapes; middle row, infected smashed grapes; bottom row, washed infected smashed grapes. Spectral libraries created with smashed clean grapes and infected grapes. Internal regions of clean and infected were correctly classified, some seeds from infected grapes were classified as infected and some as clean. Key wavelengths: 450, 550, 650, 680, 820, 900, 1000.

Shrivel in red grapes (Grenache and Shiraz)



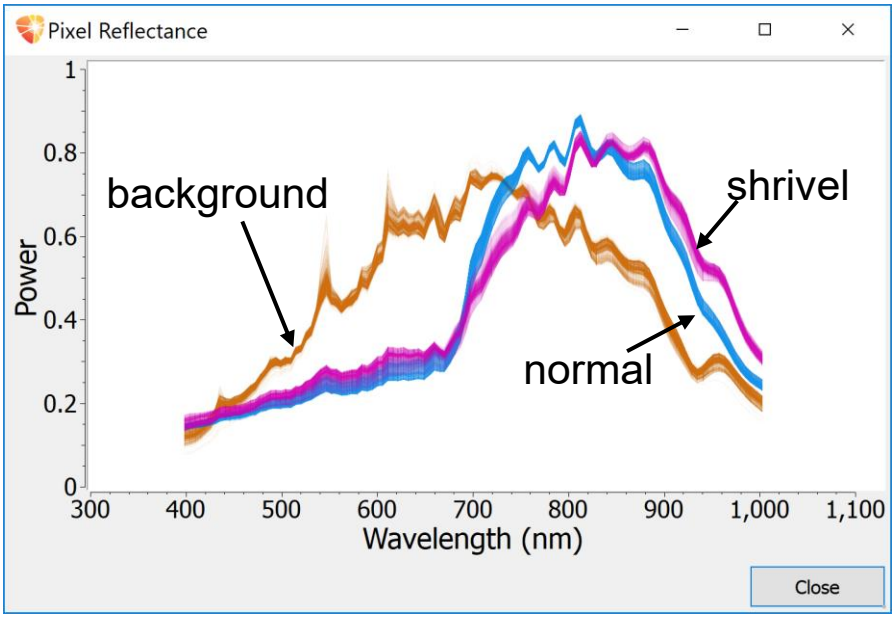


Figure 16. Top row, normal Grenache; second row, shrivelled Grenache; third row, normal Shiraz; fourth row, shrivelled Shiraz. Spectral libraries made with normal or shrivelled Shiraz could classify Grenache. The fact that one Grenache berry had a mixed classification suggests that a threshold could be set for degree of shrivel.
Key wavelengths: 550, 750, 780, 910, 980 nm

Shrivel in white grapes (Colombard)

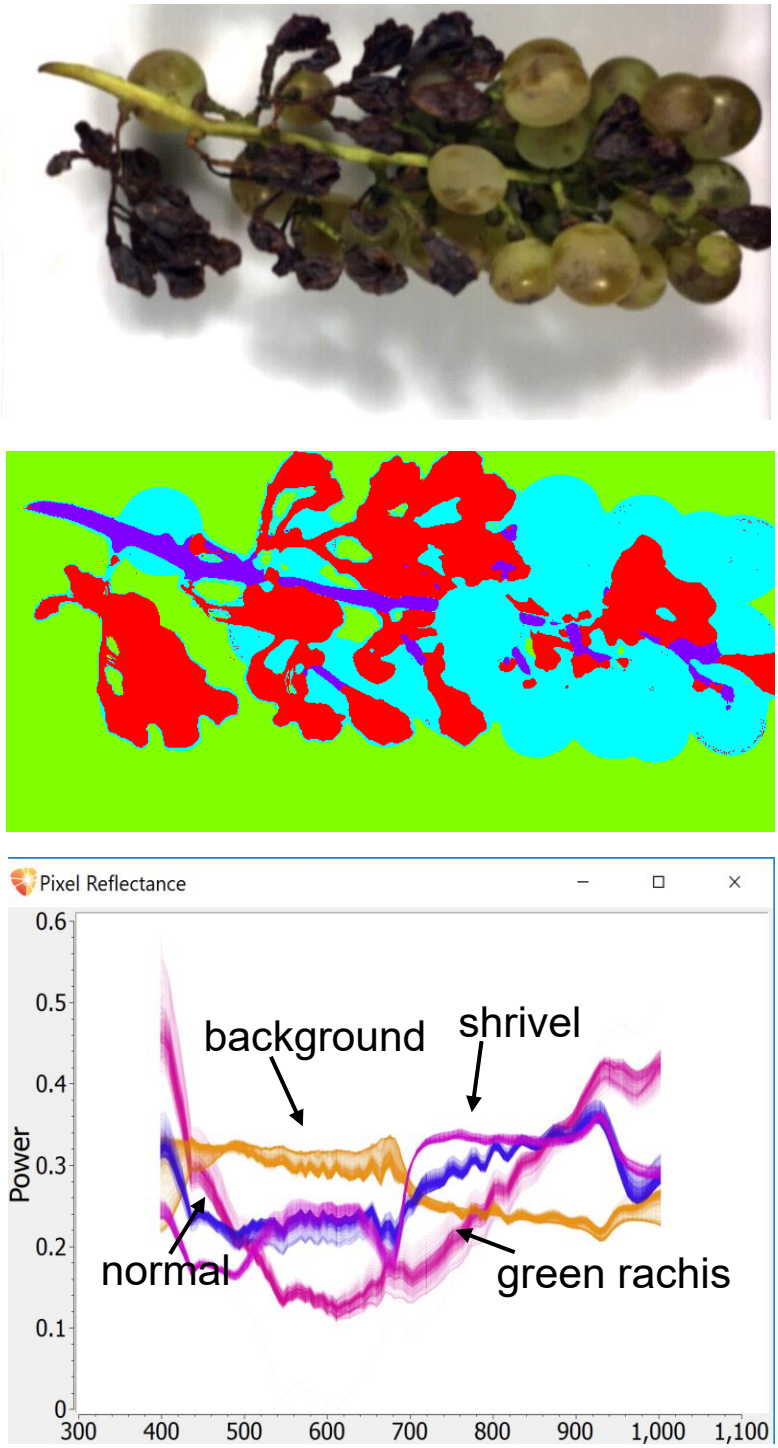


Figure 17. Severe shrivel clearly discriminated from sound grapes, including slightly sunburnt. Green rachis separately classified. Key wavelengths: 450, 650, 740, 950 nm

Discrimination of *Botrytis* and sour rot

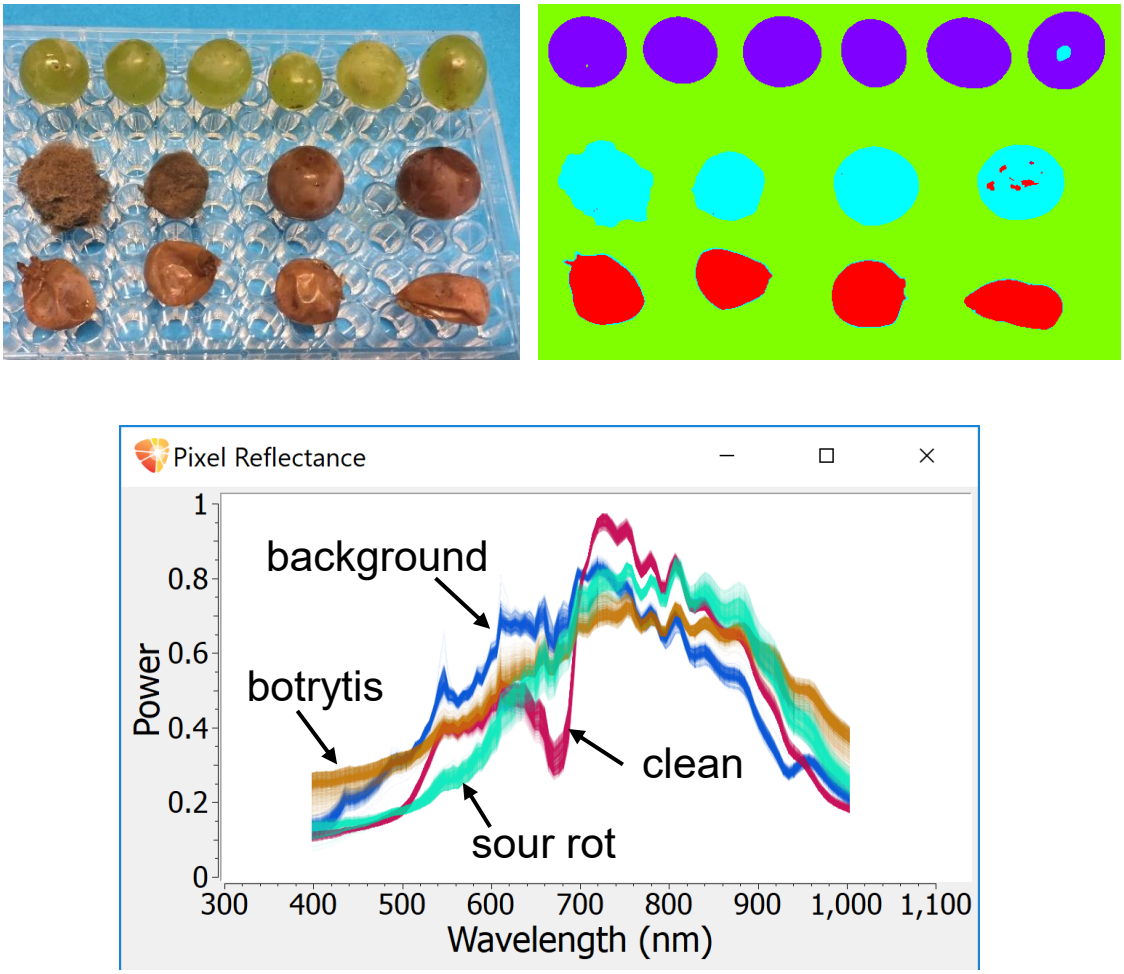


Figure 18. Colombard grapes. First row, clean grapes; second row, sporulating and non-sporulating laboratory-infected grapes; third row, sour rot (field samples). Sour rot is another disease syndrome also of commercial relevance and may have more severe consequences than *Botrytis*. Spectral libraries could discriminate between sour rot and *Botrytis*, some patches on non-sporulating Colombard were classified as sour rot and what appears to be a seed in a clean grape was identified as *Botrytis*-infected, but this may be able to be corrected with improved spectral libraries. Key wavelengths: 450, 550, 680, 760, 820, 850, 940, 980 nm.

Quantification of infection level with pixel count

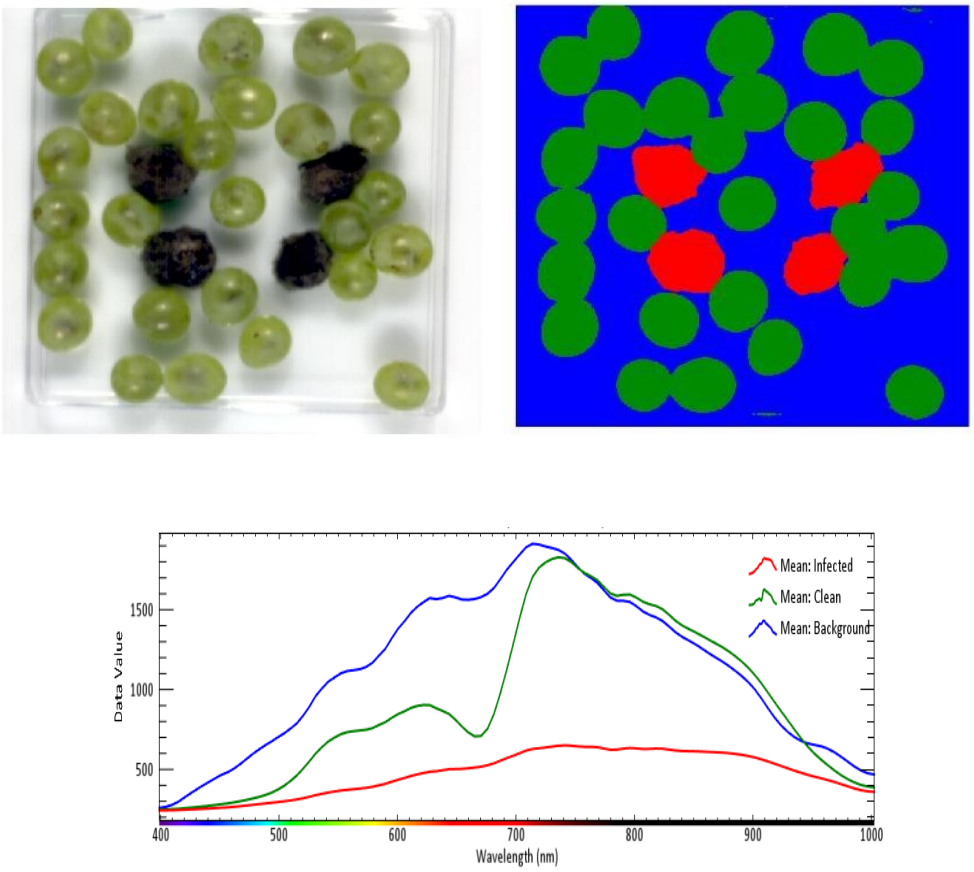


Figure 19. Classification of infected berries in mixtures with clean berries. In this simple system of background, clean and infected berry, mean spectra from spectral libraries show differences in almost every wavelength over 450 nm.

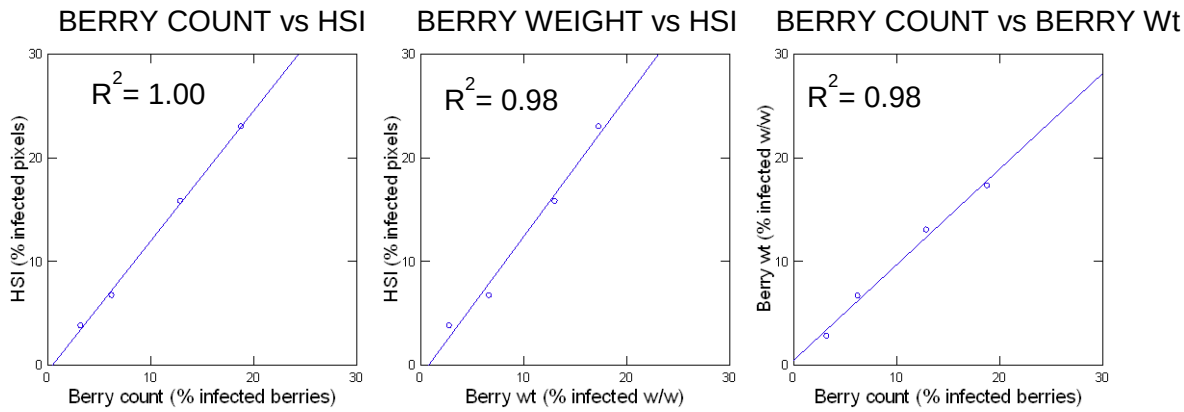


Figure 20. Using mixtures of clean and infected berries, correlation between infection level measured as % infected pixels using ENVI, % infection by weight and % infection by berry count.

Multispectral imaging

Information from the full spectral FX10 hyperspectral camera was used to select eight filters for use in the Ocean Optics SpectroCam. A limited number of specific wavelength filters were available in the 400-1000 nm range and the smallest bandwidth available for most filters was 10 nm, but peaks in that wavelength range are broad and there were broad regions of difference between different components using the full spectral data. The SpectroCam was initially tested in the laboratory with two lighting options: LED and halogen (see section 2 for a discussion on lighting).

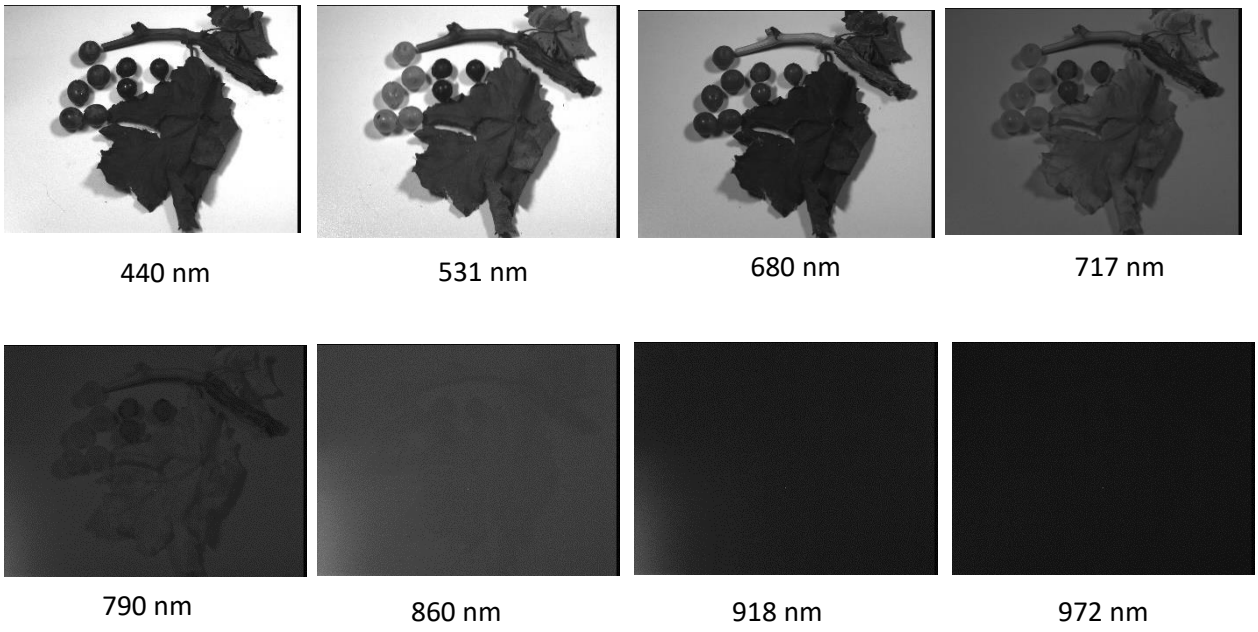


Figure 21. SpectroCam single band images from the eight filters collected under LED lighting at 3200K colour temperature. Only the first four wavelengths were usable, even at maximum exposure settings.

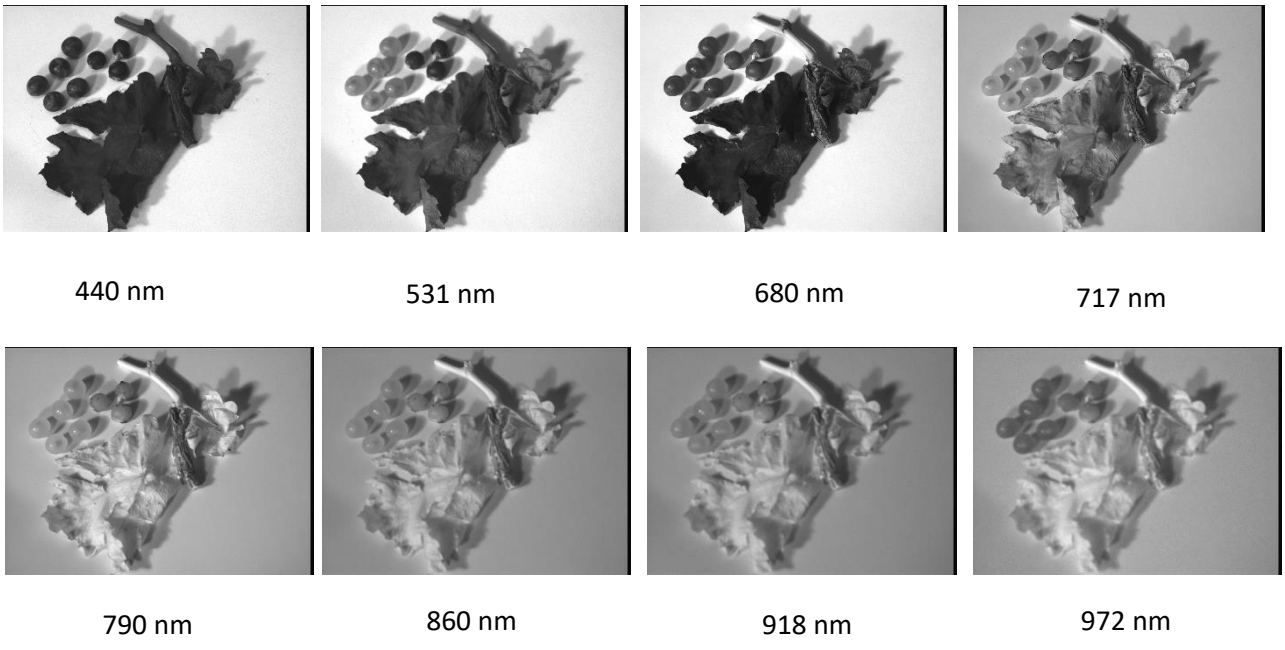


Figure 22. SpectroCam single band images under halogen lighting

Multispectral imaging, laboratory-based





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
petiole	21034	1.52
leaf	335721	24.27
background	815975	59.00
wood	36658	2.65
cane	17055	1.23
infected	80885	5.85
Clean	75768	5.48

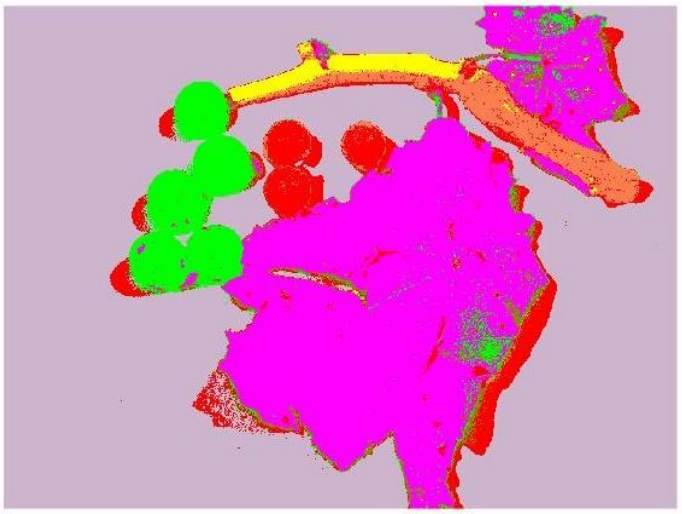
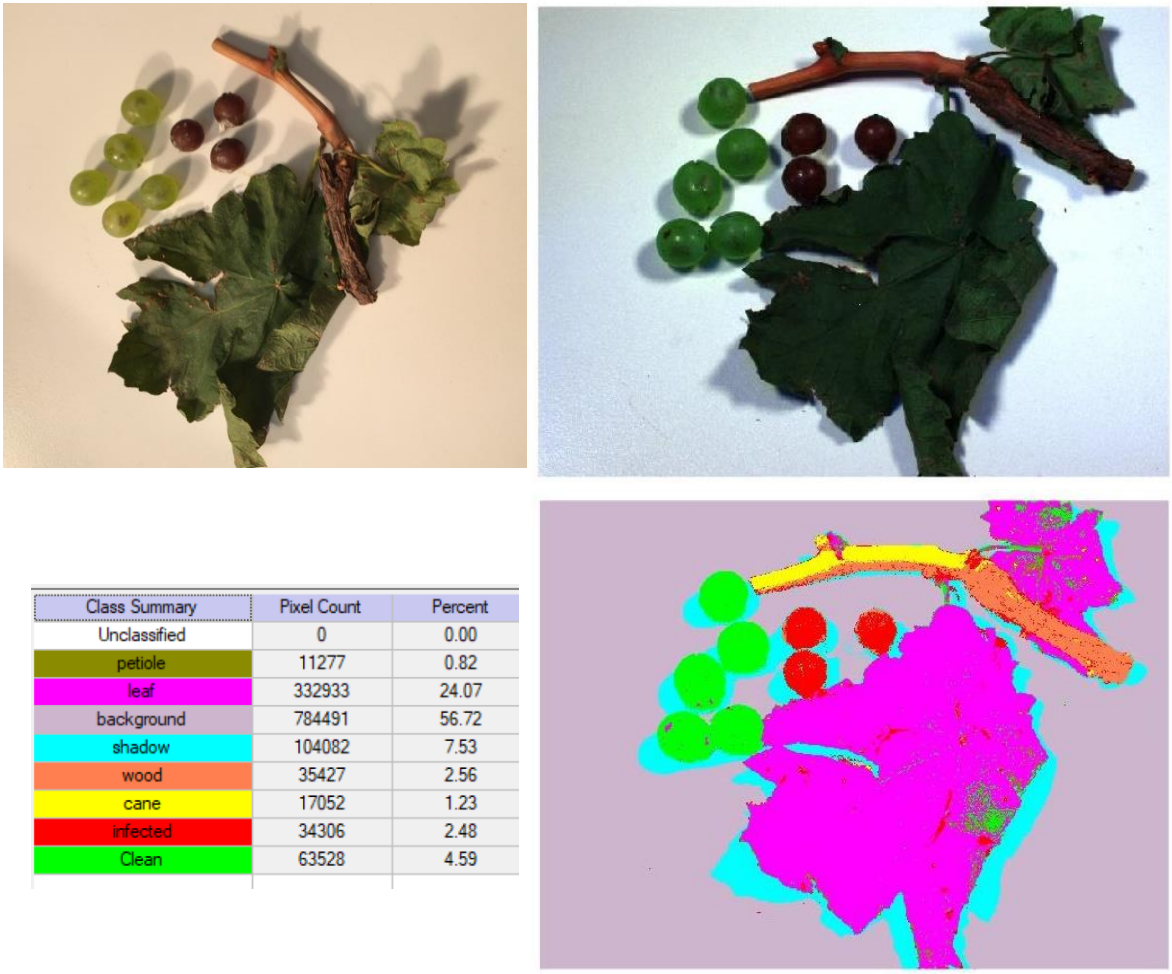
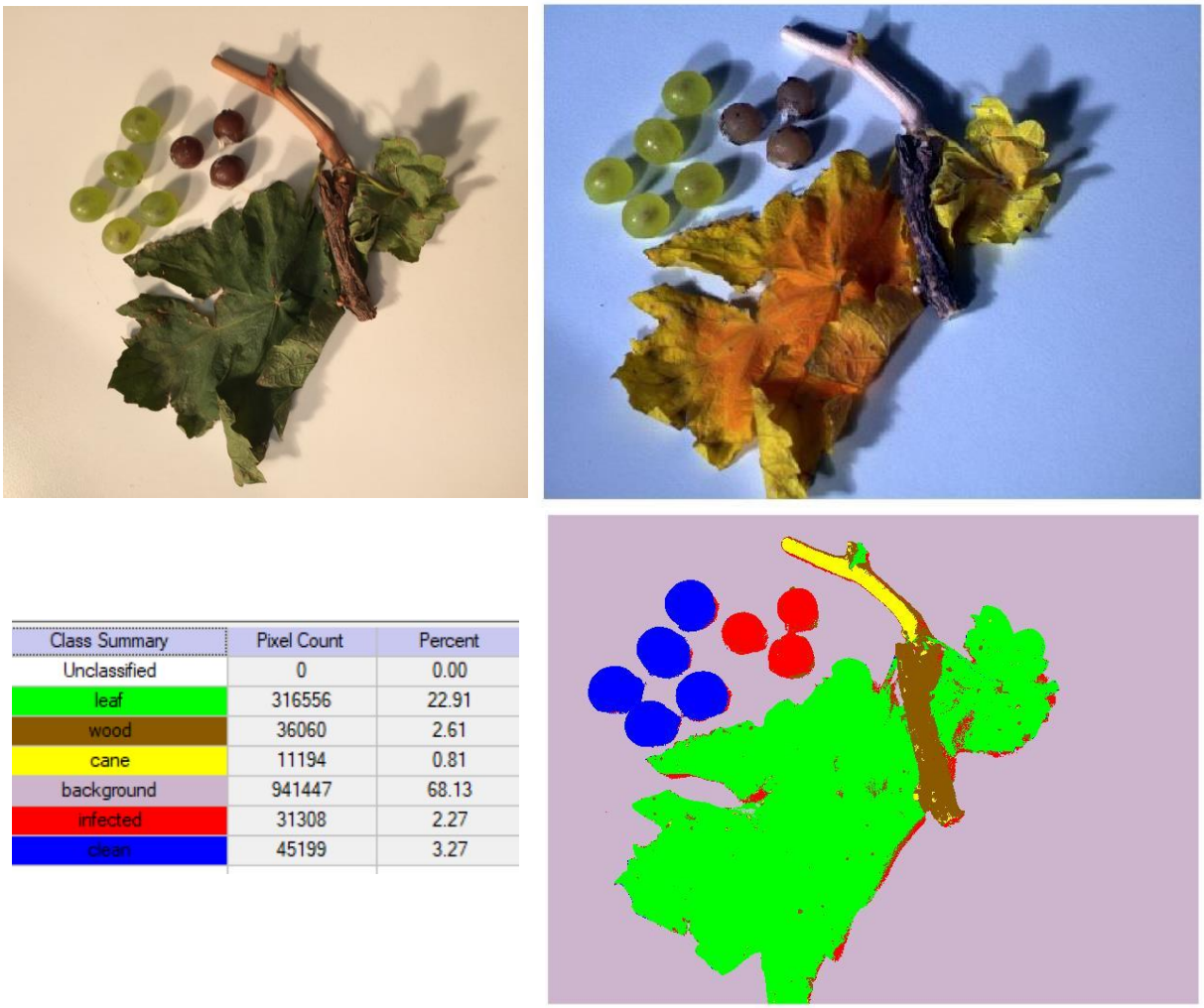


Figure 23. Laboratory-based multispectral imaging using LED lighting and only the first four SpectroCam filters. Clean and infected grapes, leaves, vine wood and vine cane. From top left, clockwise: standard RGB image; false RGB image using the first three SpectroCam filters; false colour image of SVM classification; pixel counts of classified regions. Note that dark shadows were classified as infected berries.



Class Summary	Pixel Count	Percent
Unclassified	0	0.00
petiole	11277	0.82
leaf	332933	24.07
background	784491	56.72
shadow	104082	7.53
wood	35427	2.56
cane	17052	1.23
infected	34306	2.48
Clean	63528	4.59

Figure 24. Laboratory-based multispectral imaging using LED lighting and only the first four SpectroCam filters. Clean and infected grapes, leaves, vine wood and vine cane. From top left, clockwise: standard RGB image; false RGB image using the first three SpectroCam filters; false colour image of SVM classification; pixel counts of classified regions. When spectral libraries were made for shadows they could be classified correctly but some small regions of leaves, cane and wood were classified as infected grapes. Small powdery mildew scars on grapes were classified as *Botrytis*.



Class Summary	Pixel Count	Percent
Unclassified	0	0.00
leaf	316556	22.91
wood	36060	2.61
cane	11194	0.81
background	941447	68.13
infected	31308	2.27
clean	45199	3.27

Figure 25. Laboratory-based multispectral imaging using halogen lighting and all SpectroCam filters. Clean and infected grapes, leaves, vine wood and vine cane. From top left, clockwise: standard RGB image; false SpectroCam RGB image using filters four to six; false colour image of SVM classification; pixel counts of classified regions. Dark shadows could be included in the background spectral library but there were small edge effects of mis-classification that may be related to mixed pixels on borders or shadowing.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
infected	247770	18.17
stem	8690	0.64
clean	441631	32.39
shadow	147390	10.81
background	517951	37.99

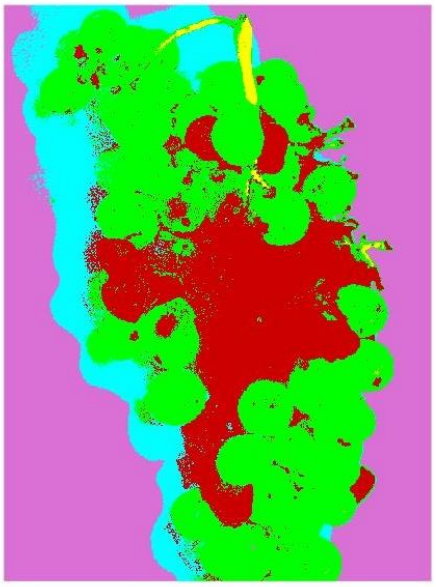
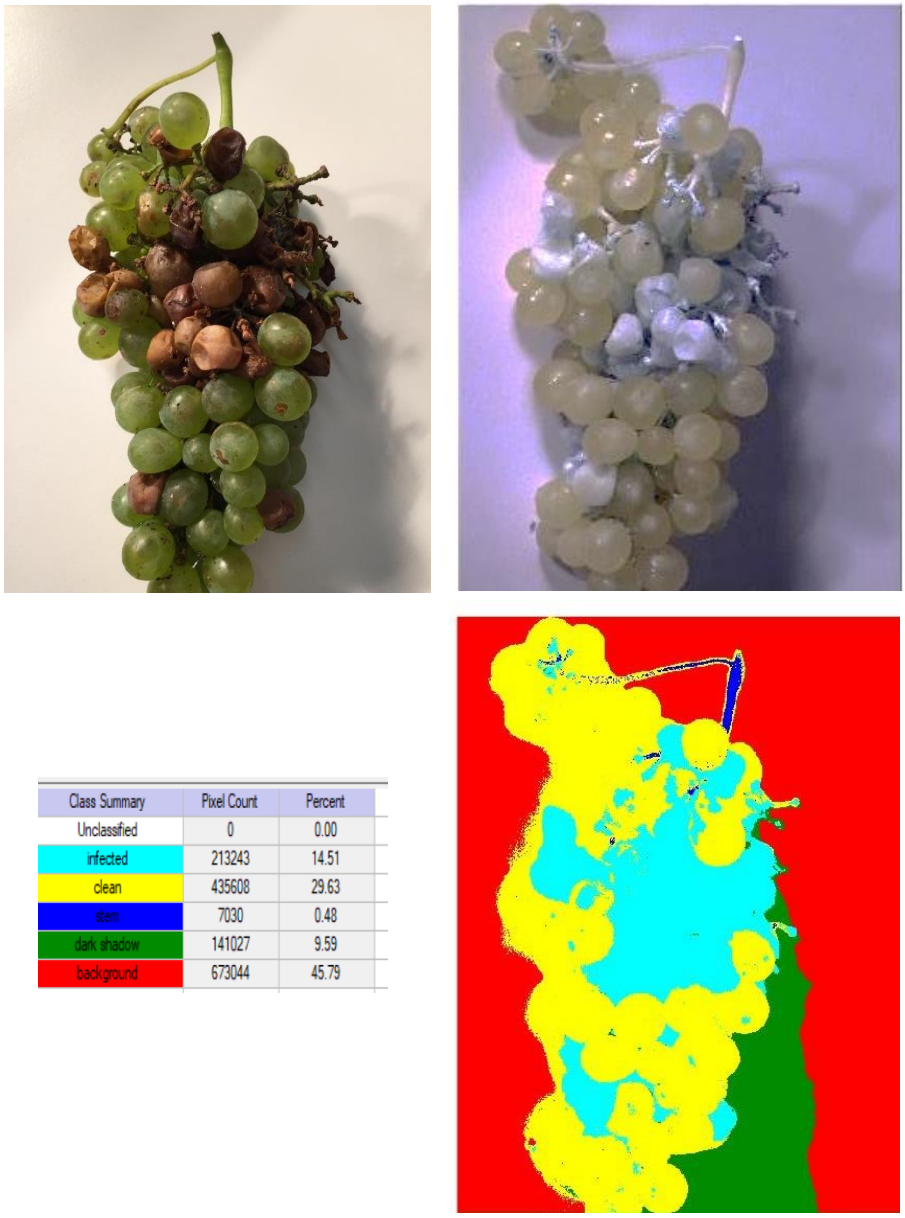


Figure 26. Laboratory-based multispectral imaging using LED lighting and only the first four SpectroCam filters. From top left, clockwise: standard RGB image; false RGB image using the first three SpectroCam filters; false colour image of SVM classification; pixel counts of classified regions. When spectral libraries were made for shadows they could be classified correctly but some pixels near the edges of clean grapes were classified as infected. Small powdery mildew scars on grapes were classified as *Botrytis*.



Class Summary	Pixel Count	Percent
Unclassified	0	0.00
infected	213243	14.51
clean	435608	29.63
stem	7030	0.48
dark shadow	141027	9.59
background	673044	45.79

Figure 27. Laboratory-based multispectral imaging using halogen lighting and all eight SpectroCam filters. From top left, clockwise: standard RGB image; false RGB image using SpectroCam filters four to six; false colour image of SVM classification; pixel counts of classified regions. Library made for dark shadows. Some pixels near the edges of clean grape were classified as background. Some parts of stems were classified as grapes. Small powdery mildew scars on grapes were classified as *Botrytis*.

Multispectral imaging at the winery grape intake weighbridge

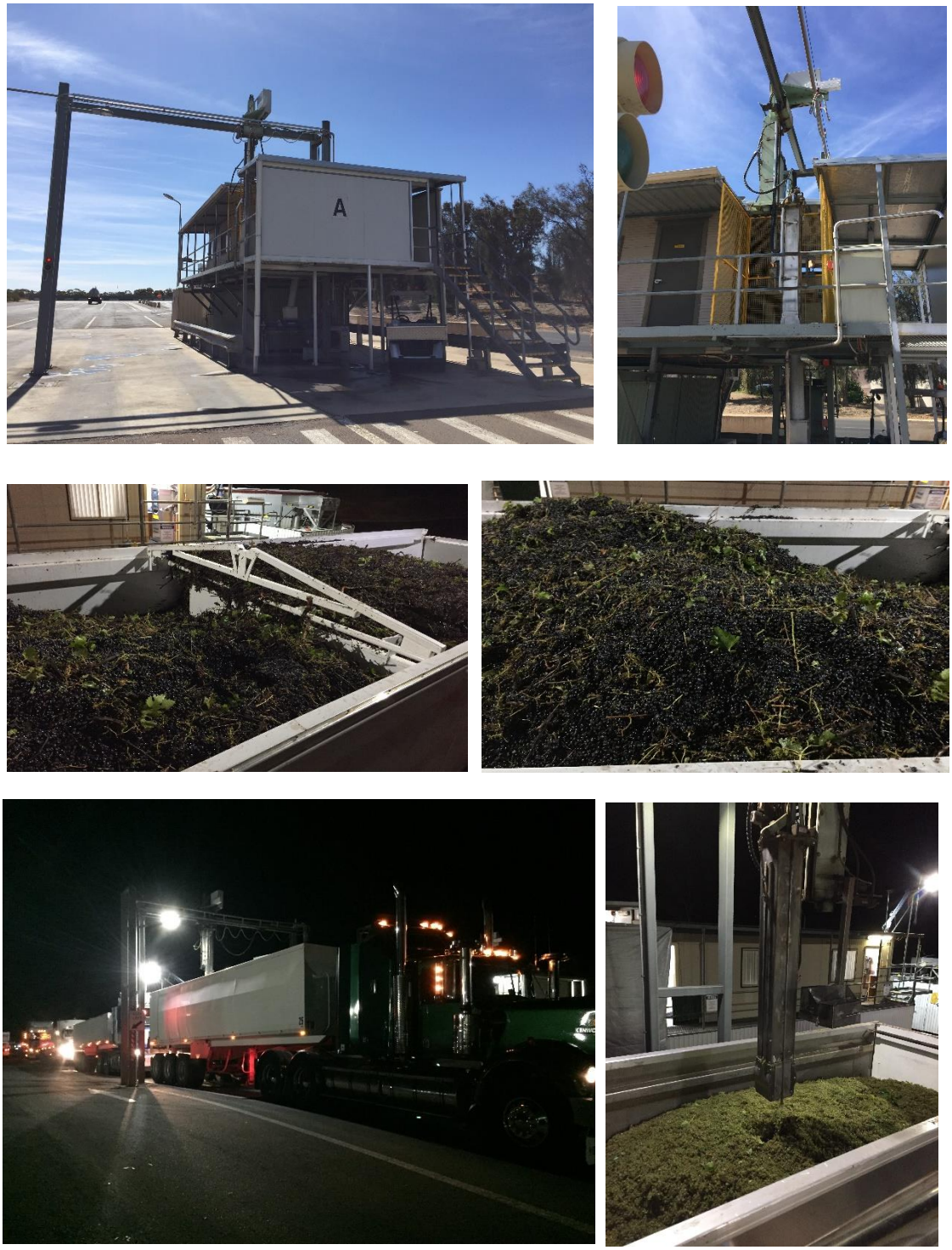


Figure 28. Weighbridge testing station at the Accolade winery, Glossop, South Australia – one of Australia's largest wineries, crushing up to 250,000 tonnes per year. The majority of the intake comes in large 30-tonne loads, difficult to access and difficult to image as fruit is not level in the back of the truck. To obtain a representative sample for testing, the loads are routinely sampled at multiple locations with a Yuba sampler (originally a tomato sampler from California), taking 20 kg top-to-bottom cross sections each time, then automatically subsampled to create a composite sample that is dumped on a sorting table and spread out.

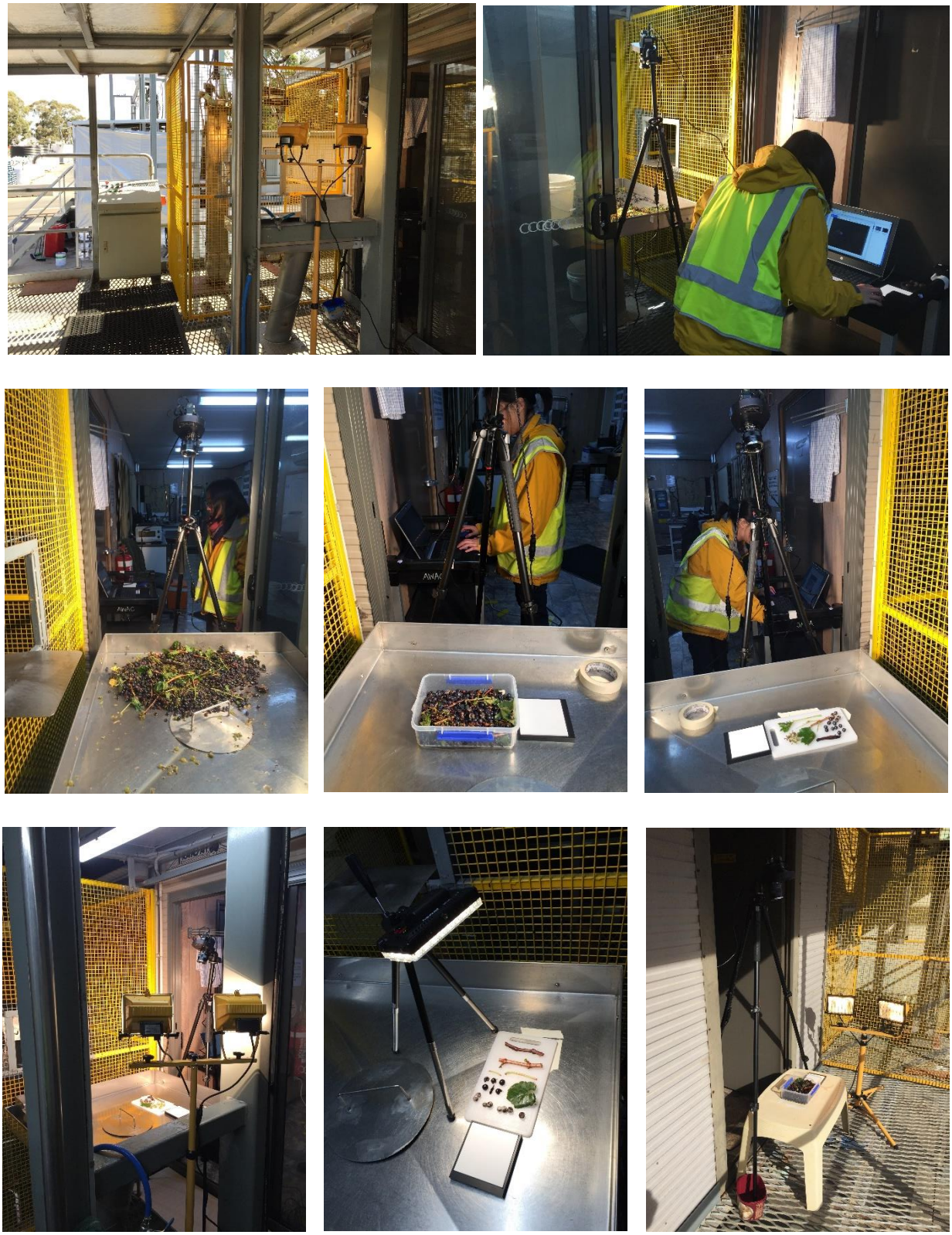
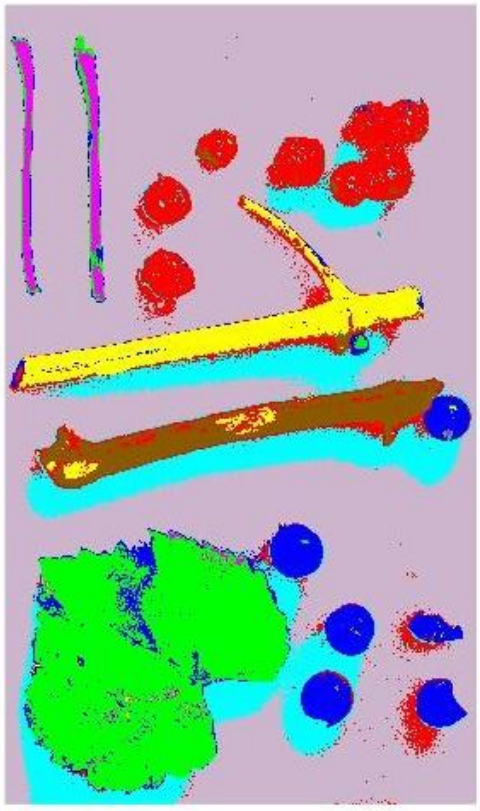


Figure 29. The samples were imaged under halogen or LED lighting as a mass, in a container that could also be scanned using the FX10 which was located inside the testing station, or on a board where each item could easily be visualised with less shadowing. The majority of the intake was at night, but some samples were imaged in daylight under the shaded alcove of the testing station, and in the full afternoon sun.







Class Summary	Pixel Count	Percent
Unclassified	0	0.00
petiole	6048	1.22
leaf	60762	12.30
wood	15160	3.07
cane	17174	3.48
infected	33773	6.84
clean	21320	4.31
shadow	52917	10.71
background	286946	58.07

Figure 30. Clean mechanically harvested Merlot, laboratory-infected Merlot and MOG imaged with SpectroCam under LED lighting at night (using the first four filters). From top left, clockwise: standard RGB image; false RGB using the first three SpectroCam filters; false colour image from SVM classification; pixel counts from SVM false colour image. Note: specular reflection due to juice coating on samples, some mis-classification at object edges, some shadows mis-classified.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
petiole	7433	1.43
leaf	62429	11.99
wood	15364	2.95
clean	19646	3.77
infected	27797	5.34
cane	16718	3.21
background	371463	71.32

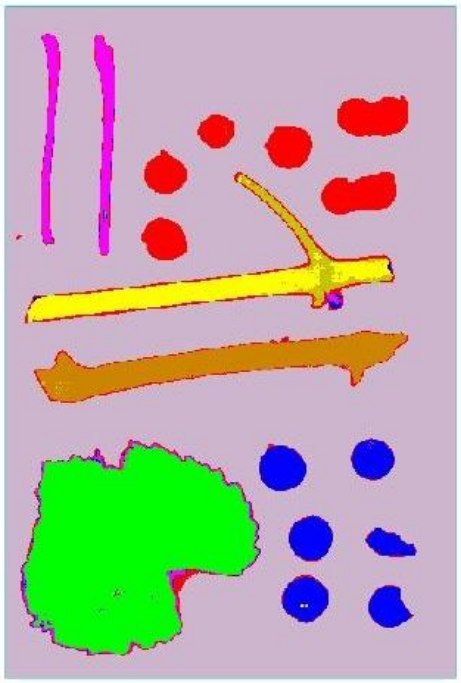


Figure 31. Clean mechanically harvested Merlot, laboratory-infected Merlot and MOG imaged with SpectroCam under halogen lighting at night (using all filters). From top left, clockwise: standard RGB image; false RGB using filters four to six; false colour image from SVM classification; pixel counts from SVM false colour image. Note: some mis-classification at object edges, mainly mis-classified as infected grapes.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
dead tendril	5601	0.67
petiole	14921	1.79
infected	41967	5.05
clean	24253	2.92
leaf	92422	11.11
wood	27863	3.35
cane	19656	2.36
background	605107	72.75



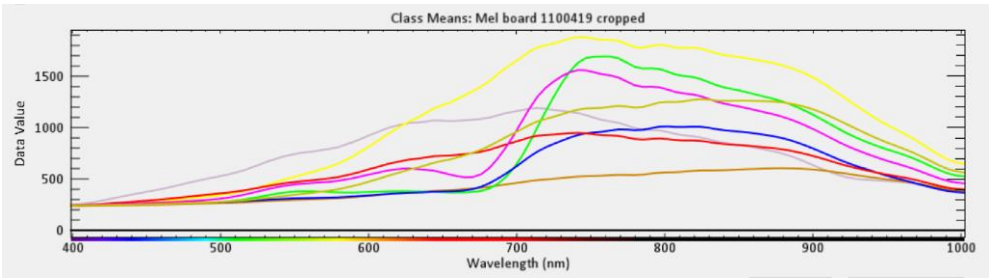


Figure 32. Clean mechanically harvested Merlot, laboratory-infected Merlot and MOG imaged with FX10 under halogen lighting. From top left, clockwise: standard RGB image; RGB image from FX10; false colour image from SVM classification; pixel counts from SVM false colour image. Bottom image shows mean spectra for classes. Note: some misclassification at object edges, mainly mis-classified as infected grapes.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
leaf	40845	8.35
infected	26225	5.36
clean	25945	5.30
shadow	9611	1.96
petiole	9721	1.99
cane	15926	3.25
wood	17564	3.59
background	343453	70.19

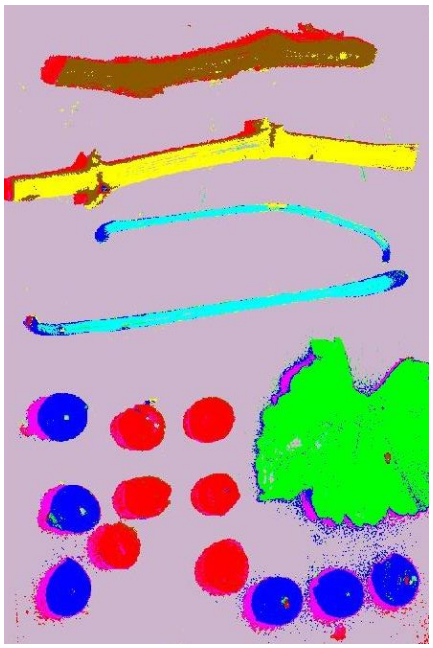
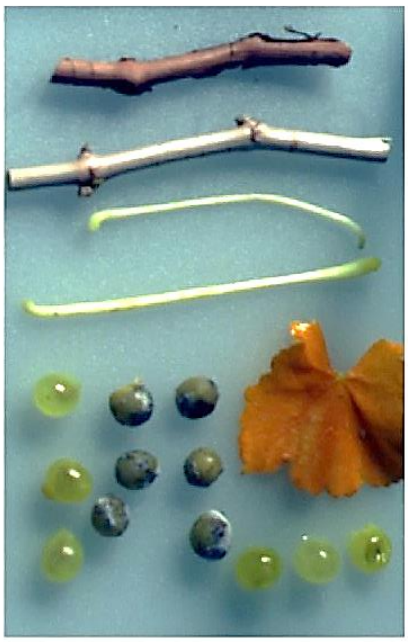


Figure 33. Clean mechanically harvested Colombard, laboratory-infected Colombard and MOG imaged with SpectroCam under LED lighting at night (using first four filters). From top left, clockwise: standard RGB image; false RGB using first three SpectroCam filters; false colour image from SVM classification; pixel counts from SVM false colour image. Note: some mis-classification at object edges and in regions of specular reflection.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
leaf	39308	8.07
petiole	11952	2.45
infected	23321	4.79
clean	22447	4.61
wood	15630	3.21
cane	17740	3.64
background	356658	73.23

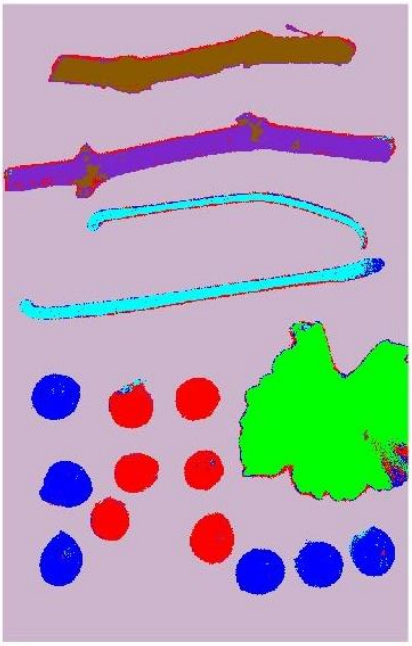
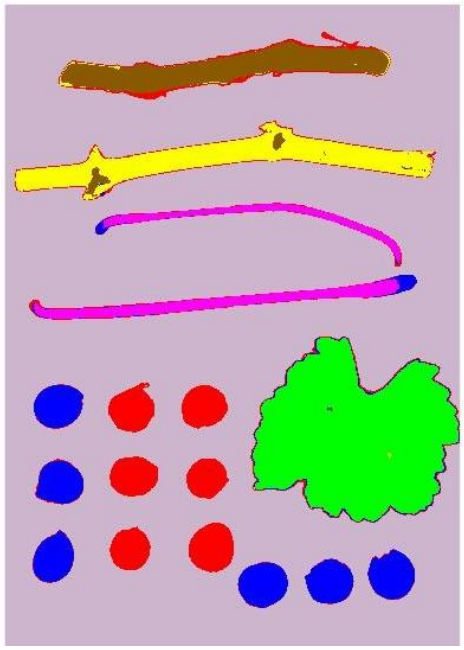


Figure 34. Clean mechanically harvested Colombard, laboratory-infected Colombard and MOG imaged with SpectroCam under halogen lighting at night (using all filters). From top left, clockwise: standard RGB image; false RGB using filters four to six; false colour image from SVM classification; pixel counts from SVM false colour image. Note: some mis-classification at object edges.



Class Summary	Pixel Count	Percent
Unclassified	0	0.00
background	592154	74.60
leaf	69416	8.74
infected	36839	4.64
clean	30468	3.84
petiole	16178	2.04
cane	26486	3.34
wood	22266	2.80



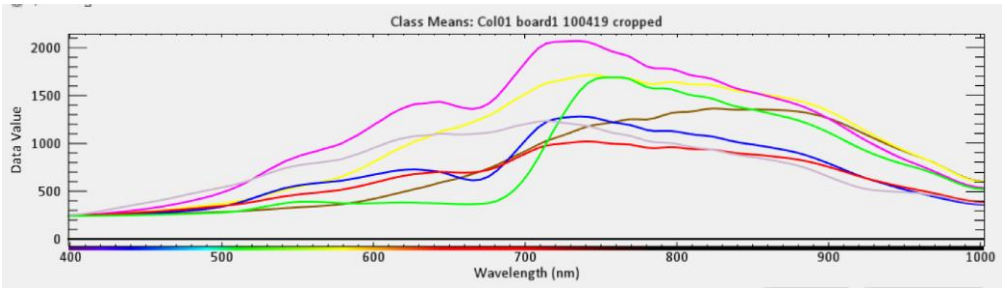


Figure 35. Clean mechanically harvested Colombard, laboratory-infected Colombard and MOG imaged with FX10 under halogen lighting. From top left, clockwise: standard RGB image; RGB image from FX10; false colour image from SVM classification; pixel counts from SVM false colour image. Bottom image shows mean spectra for classes. Note: some mis-classification at object edges.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
clean	14053	3.36
infected	17028	4.07
petiole	5533	1.32
wood	13498	3.23
cane	8823	2.11
leaf	27042	6.46
background	332419	79.45

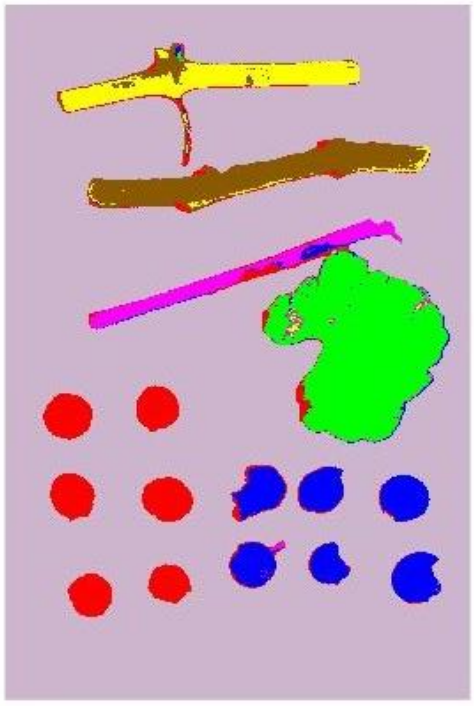


Figure 36. Clean mechanically harvested Merlot, laboratory-infected Merlot and MOG imaged with SpectroCam under afternoon sunlight with additional halogen lighting (using all filters). From top left, clockwise: standard RGB image; false RGB using filters four to six; false colour image from SVM classification; pixel counts from SVM false colour image. Note: some mis-classification at object edges.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
dead tendril	5606	1.04
leaf	59748	11.05
cane	13828	2.56
wood	17822	3.30
petiole	14393	2.66
stem	5606	1.04
infected	22948	4.24
clean	18171	3.36
background	382662	70.76

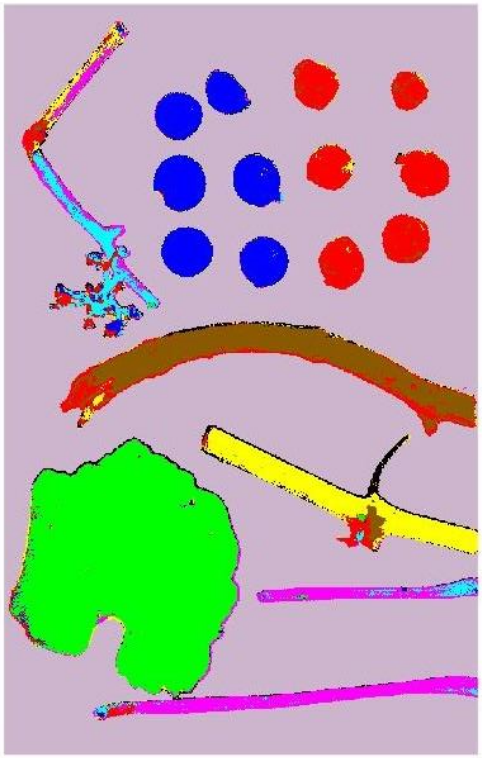
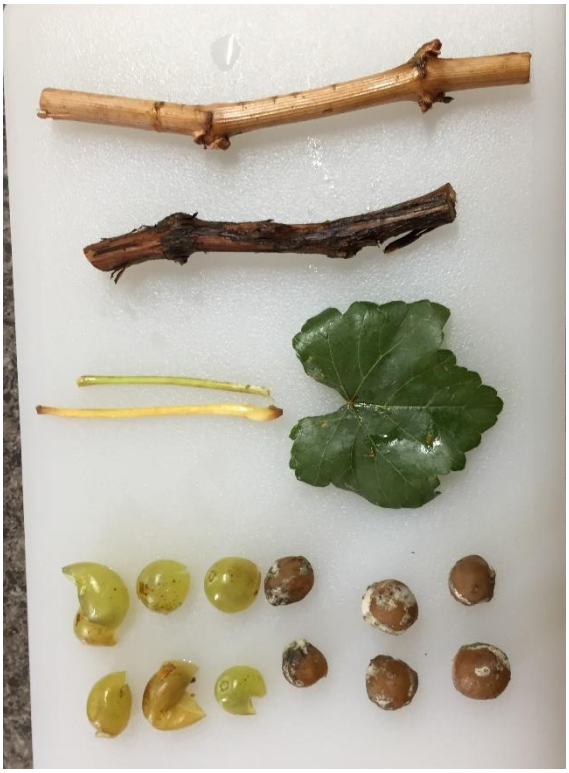


Figure 37. Clean mechanically harvested Merlot, laboratory-infected Merlot and MOG imaged with SpectroCam in testing station with shaded ambient sunlight and additional halogen lighting (using all filters). From top left, clockwise: standard RGB image; false RGB using filters four to six; false colour image from SVM classification; pixel counts from SVM false colour image. Note: some mis-classification at object edges.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
petiole	7840	1.45
infected	21087	3.89
sunburn	3092	0.57
clean	21578	3.98
wood	17324	3.20
cane	16951	3.13
leaf	38044	7.02
background	416294	76.78

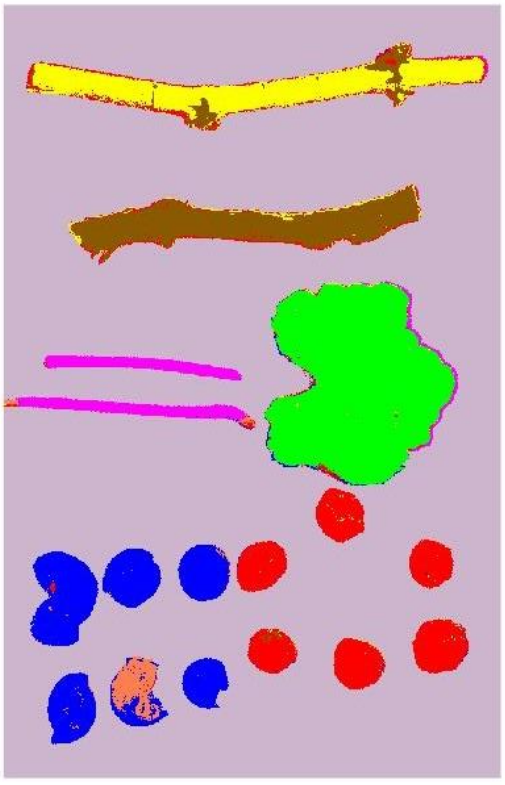
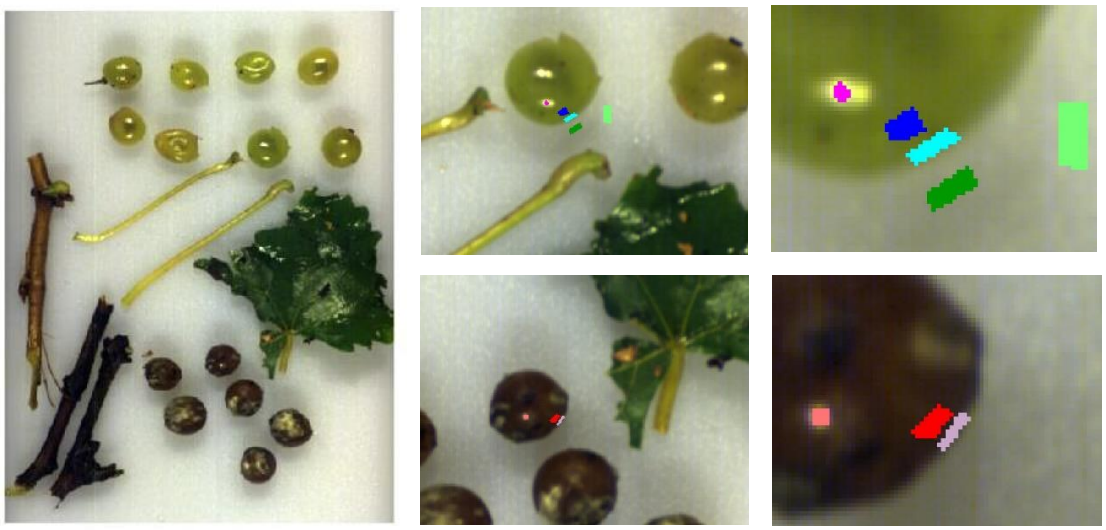


Figure 38. Clean mechanically harvested Merlot, laboratory-infected Colombard and MOG imaged with SpectroCam in testing station with shaded ambient sunlight and additional halogen lighting (using all filters). From top left, clockwise: standard RGB image; false RGB using filters four to six; false colour image from SVM classification; pixel counts from SVM false colour image. Note: some mis-classification at object edges.



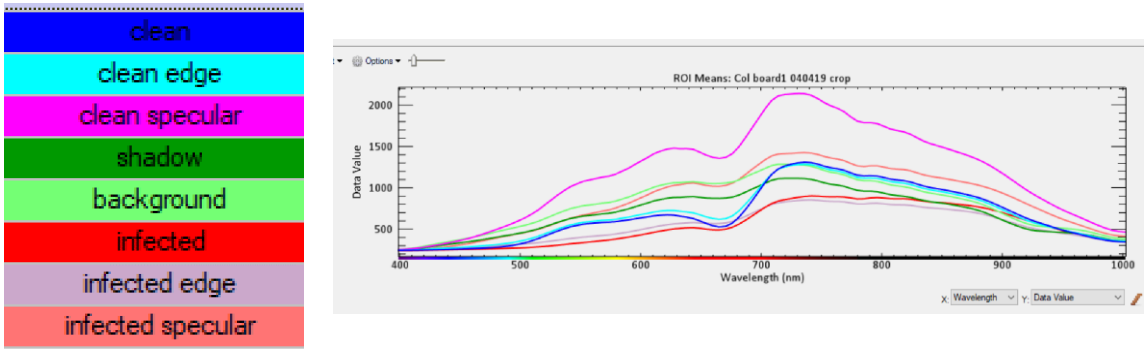
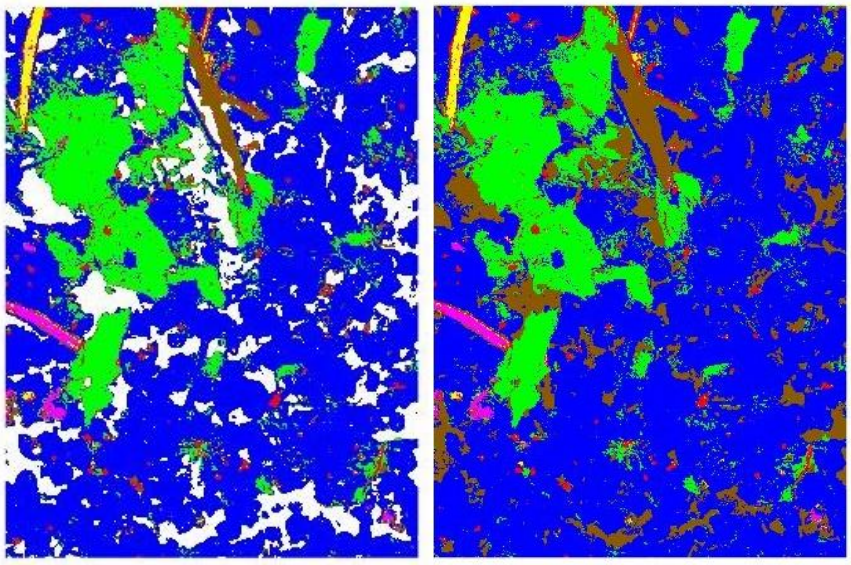


Figure 39. Top left is an RGB image scanned on the FX10 under ideal lighting conditions. Bottom right shows average spectra for regions marked in colour: clean grape, clean grape edge, clean grape specular reflection, shadow on background, clear background, infected grape, edge of infected grape, specular reflection on infected grape. Edges of grapes where there are mixed pixels and close shadows have different spectra to the main object image. Shadowed background has different spectra to clear background. Specular reflection on an object has different spectra to the main object. These differences could contribute to mis-classification.





Class Summary	Pixel Count	Percent
Unclassified	0	0.00
shadow	197811	14.74
wood	51987	3.87
petiole	10123	0.75
leaf	218331	16.27
cane	9426	0.70
grapes	829501	61.83
seed	24499	1.83

Class Summary	Pixel Count	Percent
Unclassified	0	0.00
wood	164526	12.26
petiole	10209	0.76
leaf	224690	16.75
cane	9424	0.70
grapes	908226	67.69
seed	24603	1.83

Figure 40. Imaging with SpectroCam using halogen lighting and all eight filters. Top left, clockwise: standard RGB image of mechanically harvested Colombard; close-up of previous image showing area imaged with SpectroCam; SpectroCam image (false RGB using filters four to six); SVM classification with no specific shadow spectral library; SVM classification including a spectral library for dark shadows. Both SVM false colour images include pixel counts below. Note: when no spectral library for dark shadows was included, the shadows were classified as wood.

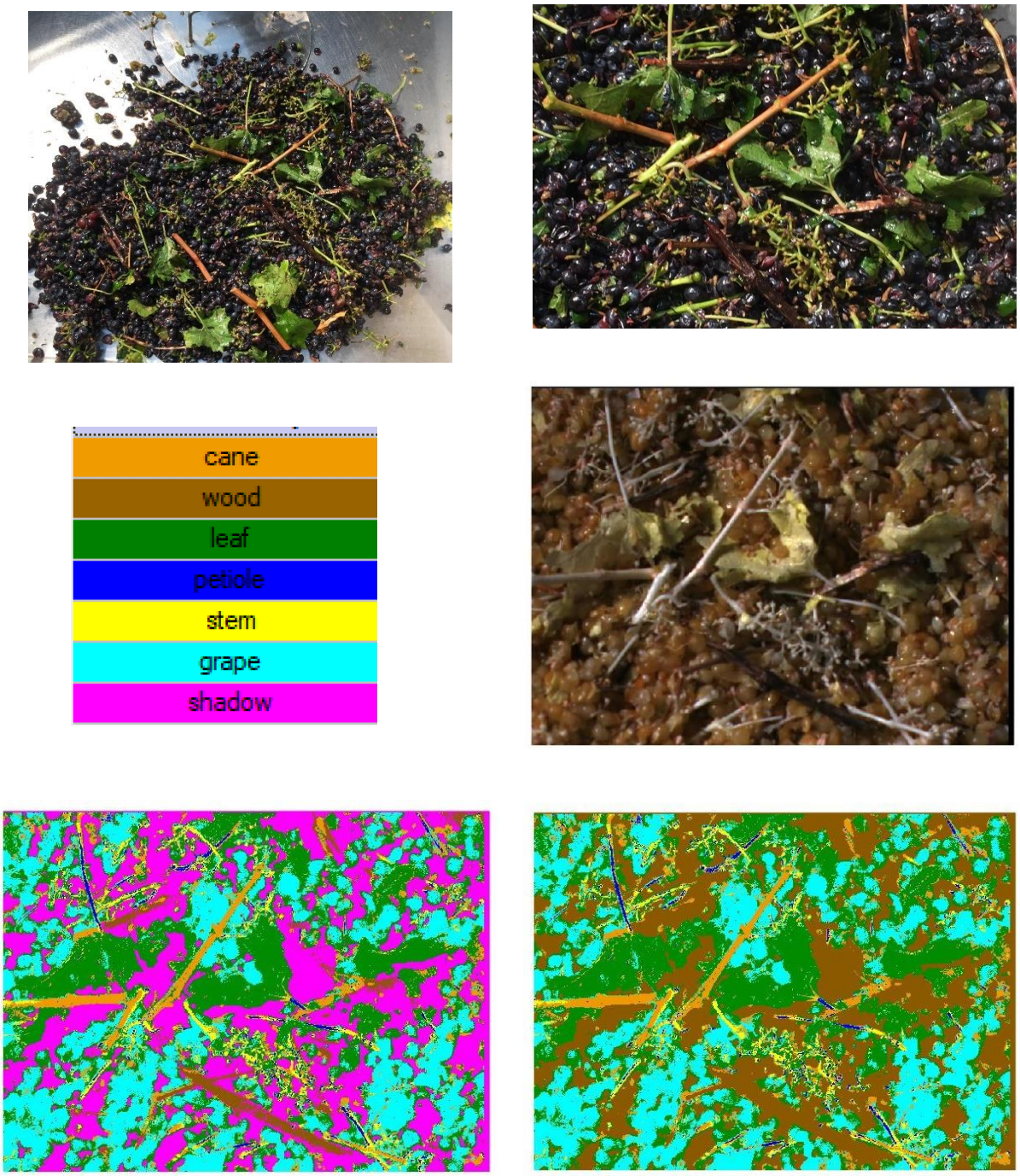
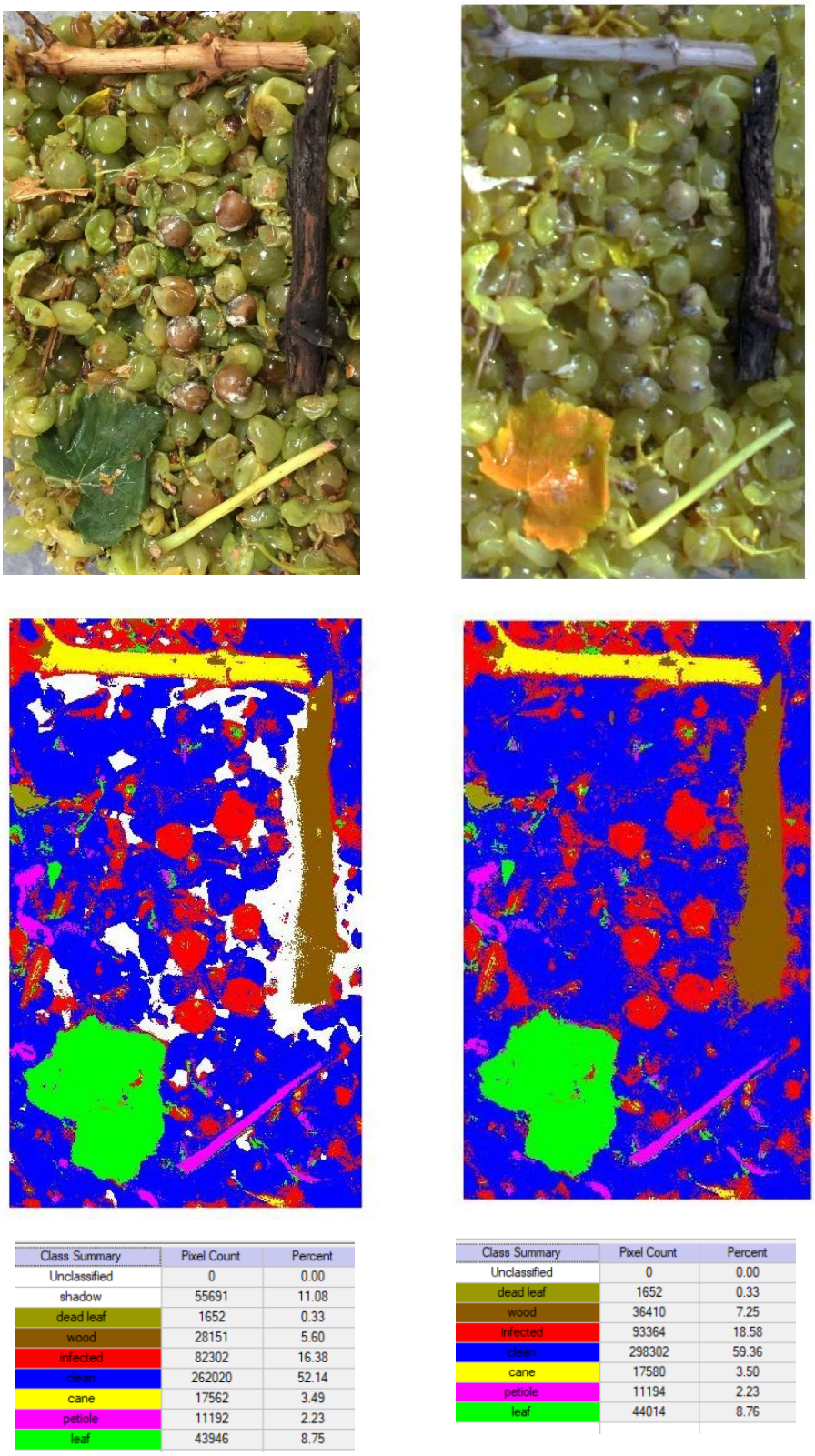


Figure 41. Imaging with SpectroCam using halogen lighting and all eight filters. Top left, clockwise: standard RGB image of mechanically harvested Merlot; close-up of previous image showing area imaged with SpectroCam; SpectroCam image (false RGB with filters four to six); SVM classification with no specific shadow spectral library; SVM classification including a spectral library for dark shadows. Note: when no spectral library for dark shadows was included, the shadows were classified as wood.



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

Class Summary	Pixel Count	Percent
Unclassified	0	0.00
dead leaf	1652	0.33
wood	36410	7.25
infected	93364	18.58
clean	298302	59.36
cane	17580	3.50
petiole	11194	2.23
leaf	44014	8.76

Figure 42. Imaging with SpectroCam using halogen lighting and all eight filters. Top left, clockwise: standard RGB image of mechanically harvested Colombard; SpectroCam image (false RGB using filters four to six); SVM classification with no specific shadow spectral library; SVM classification including a spectral library for dark shadows. Note: when no spectral library for dark shadows was included, some shadows were classified as infected grapes. When a spectral library for dark shadows was included, some grapes in shadow area were not classified, some wood in light shadow was classified as infected, some wood was classified as shadow, edge effects on objects remained. Some natural infection in the sample was identified.

Multispectral imaging and RotBot imaging in the vineyard

It was originally planned to run the SpectroCam in the vineyard with the camera filter wheel running with an internal lithium-ion battery and the laptop running from its battery. Unfortunately, the camera would not run correctly without the computer connected to mains power, possibly due to a critical stable voltage requirement for the filter wheel stepper motor to synchronise with the camera shutter operated by the computer. Instead, a generator was used to provide stable power, this also allowed the use of fill-in halogen lighting. RotBot requires a blue background and this also simplified preparation of spectral libraries with SpectroCam images.



Figure 43. Imaging with SpectroCam in the vineyard. The blue background ensures that the bunches are distinct and this is a requirement for the RotBot app. The yellow halogen light provided supplementary lighting to ensure that shadows were minimised.

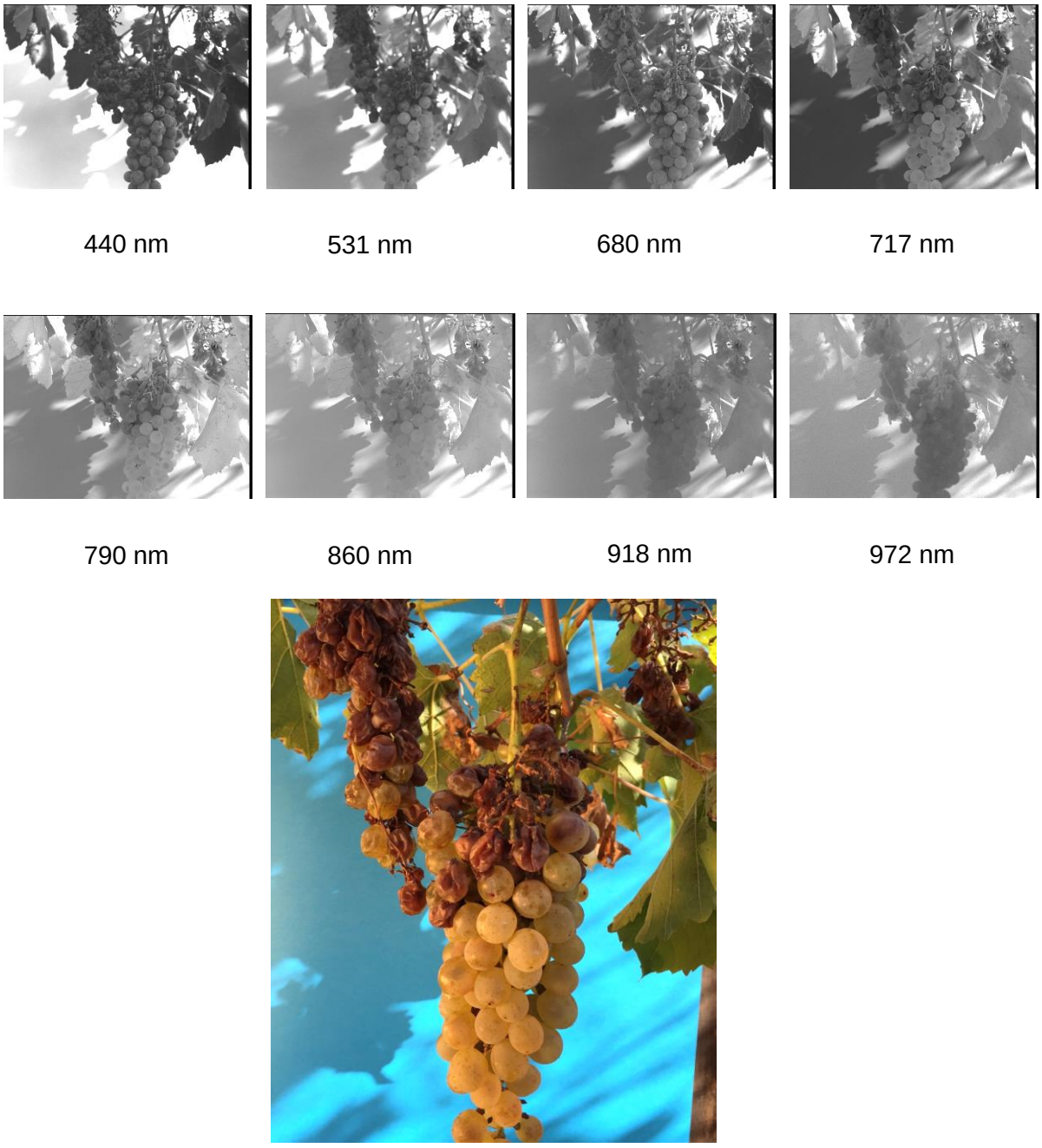


Figure 44. Single band images from the SpectroCam with a blue background board and halogen fill-in lighting. The sunlight came from a 45 degree angle at the right. With the single band images it dominated the lighting and the direction in which the shadows were cast. The strongest shadows were at the red-edge wavelength 717 nm. The eight single-band images must be perfectly registered with each other so that they can be combined into one multispectral image with the eight wavelengths in identical pixels or as close to each other as possible; the camera was held steady on a tripod but poor image registration occurred if there was even a slight breeze.

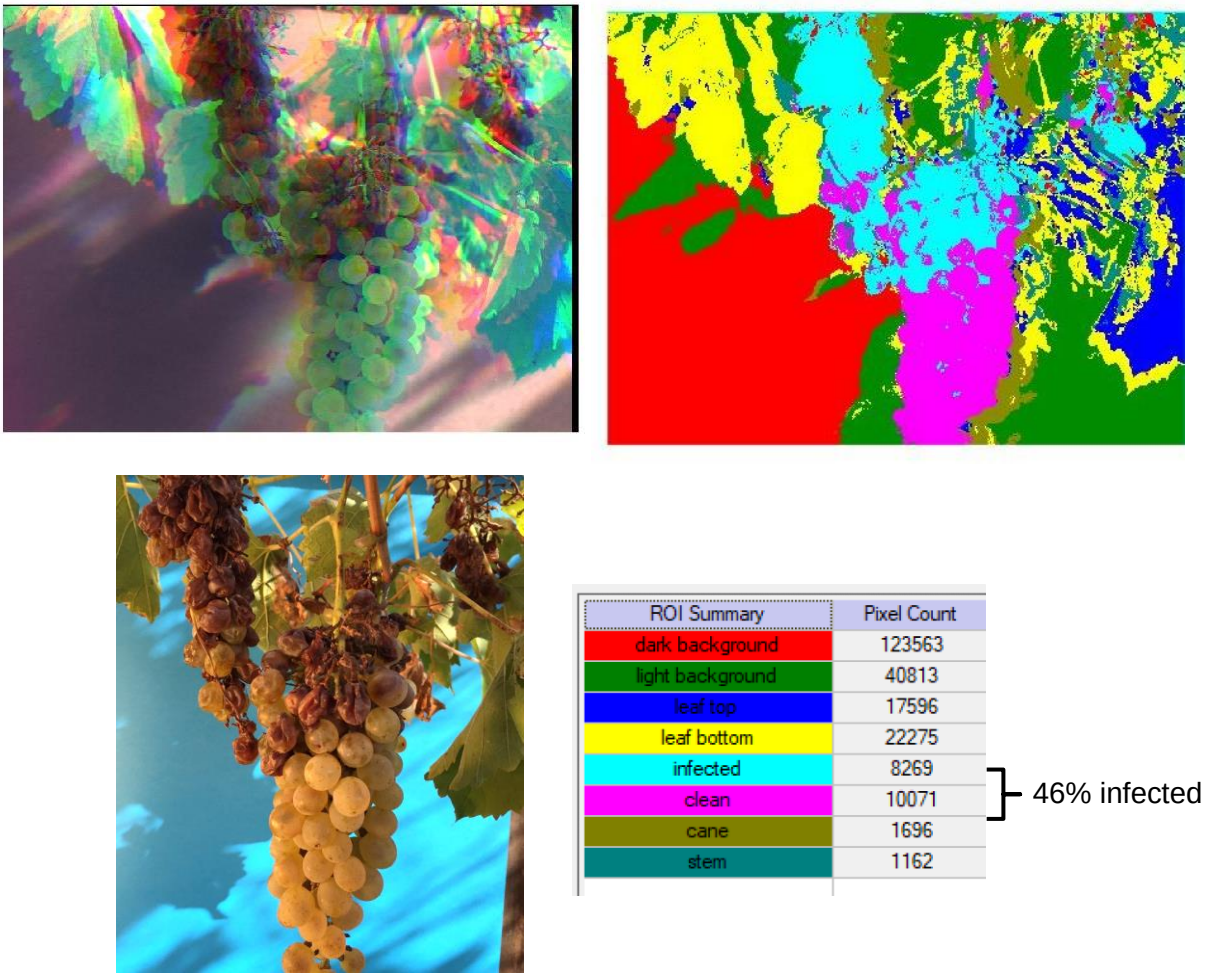


Figure 45. Multispectral imaging in the vineyard with SpectroCam. Images were taken with a blue background, and a combination of natural and halogen lighting. From top left, clockwise: SpectroCam false RGB image using filters three to five; false colour image of SVM classification; pixel count summary; and RGB image.

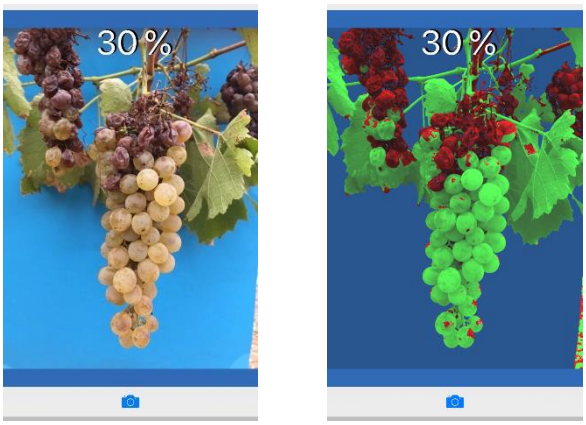


Figure 46. RotBot imaging of a similar scene shown in Figure 45. RotBot marks the background in blue, clean grapes in green and infected grapes in red. Note: RotBot classifies petioles, leaves and green canes as being clean grapes and classifies lignified canes, dead patches on leaves and blemishes on clean grapes caused by sun exposure as being infected grapes.

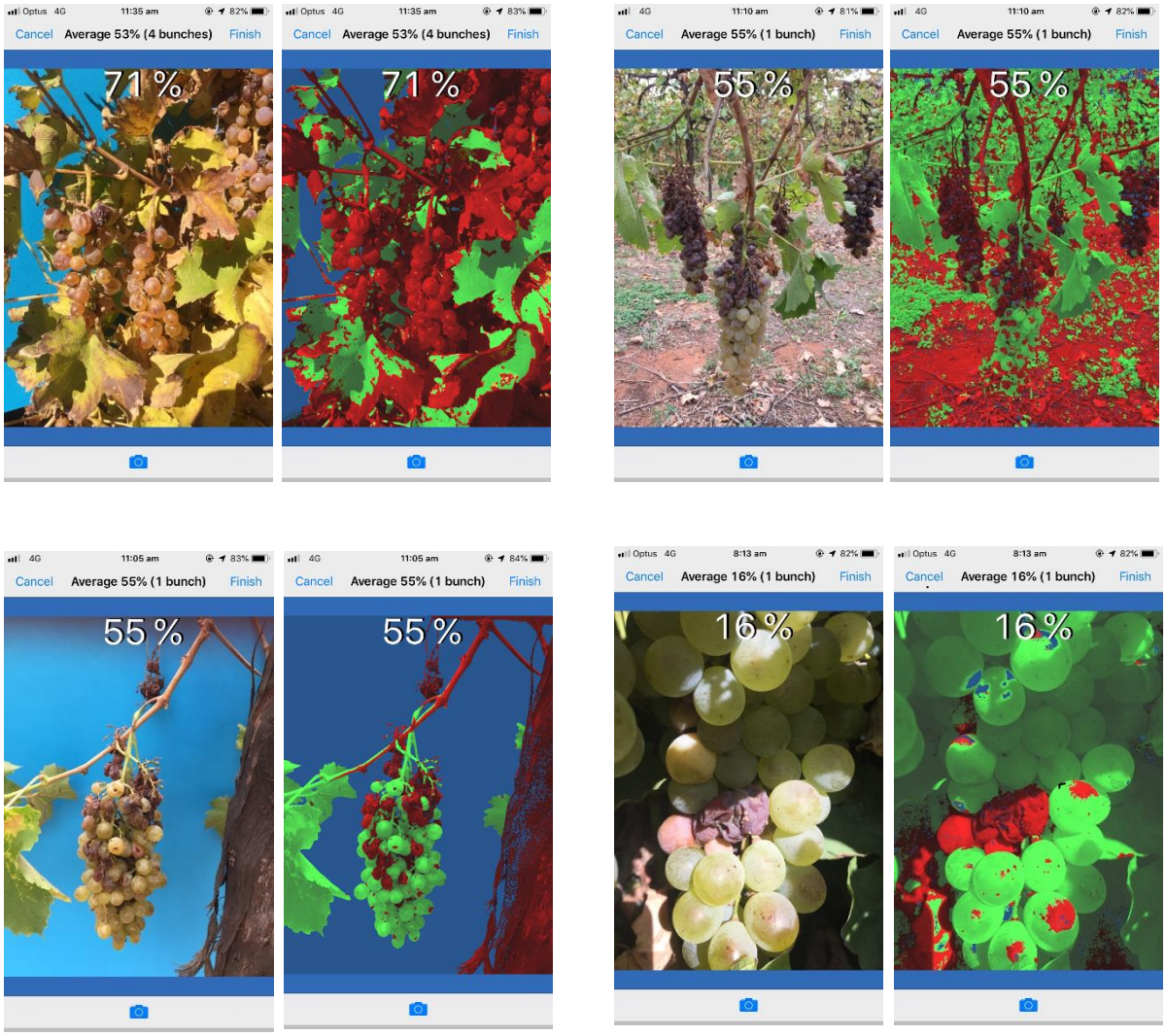


Figure 47. Examples of RotBot imaging in the vineyard: a series of image pairs, RGB and RotBot output. Top left: sun-bronzed grapes, scorched leaves, lignified canes and senescent petioles show up as infected berries. Top right: if no blue background is used, the background scene (in this case vineyard floor and canopy of next row of vines) is classified as clean or infected grapes, depending on the hue. Bottom left: if a blue background is used, clean and infected berries are clearly marked but lignified canes and bark are marked as infected grapes and leaves, green petioles and green canes are marked as clean grapes, while small blemishes on otherwise clean berries are marked as infected patches. Bottom right: if a mass of grapes filling the whole field is imaged, no blue background is needed but any leaves in the scene will be mis-classified. RotBot can handle shadows but over-exposed bright patches are marked as infected berries.

Conclusions

Hyperspectral imaging (HIS) using a full spectral linescan camera covering the 400-1000 nm wavelength range could discriminate clean and infected red and white grapes, with both laboratory infections and field samples. The calibrations were not dependent on growing region, grape variety and *Botrytis* strain. his could also discriminate *Botrytis* infection from sour rot (mixed fungal and bacterial infection of grapes). Washing sporulating berries with grape juice to simulate mechanical harvesting did not prevent identification and smashing berries to simulate mechanical harvesting also did not prevent identification of *Botrytis.* HSI could also identify sunburn in white grapes and shrivel in red and white grapes. HSI could discriminate other grapevine components that often form MOG in mechanically harvested grape loads (i.e. canes, wood, petioles, leaves and insects).

The spectra of materials to be classified were distinct and had broad peaks, enabling the selection of a small number of wavelengths for use in a multispectral camera operating in snapshot mode, without a requirement to move the sample under the camera as with the linescan camera. Using the multispectral camera to create separate single band images with each wavelength, images collected under LED lighting indicated insufficient output in NIR wavelengths (790, 860, 918, 972 nm) and only the first four filters (444, 531, 680, 717 nm) could be used for multispectral imaging (MSI). Halogen lighting produced well-exposed images over the whole wavelength range and was more suited to Vis-NIR imaging as it allowed the use of the NIR wavelengths that provide information on all organic material, whereas visible wavelengths only provide information on specific pigments. Until improvements are made with LED lighting systems, halogen lighting is the preferred system. Tests under field conditions at a winery intake testing station indicated that imaging could be performed with halogen lighting under varied ambient lighting conditions, but imaging in full sun required constant changes to camera exposure settings and daylight cast long shadows as the day progressed which made the images difficult to analyse.

Trials with mechanically harvested grapes indicated that the best sample presentation method was to spread the samples out on a standard backing material. When samples were imaged as a mass, shadows caused errors with material classification due to alterations in spectral profiles. With a bulk sample the composition under shadows is difficult to model, as the shadows fell on a variety of surfaces (other grapes, MOG etc.) as opposed a standard backing. If samples are scanned on a standard background and with some fine tuning of image analysis and lighting to remove the small errors at the edges of objects, this system has merit for commercial use in objective monitoring of *Botrytis* and MOG in mechanically harvested grapes. An important outcome is that although *Botrytis* in mechanically harvested red grapes is difficult to observe visually, it can be identified with multispectral imaging. The methods used for this study involved separate software systems for acquisition of images and image analysis; for commercial implementation the systems need to be combined in one software package for real-time analysis.

The SpectroCam multispectral camera could classify material on the vine but the system used was not practical in terms of field portability. The RotBot app is simple to use in the field with a standard smartphone, but it classified bunch stems, leaves and other vine material as clean or infected grapes, so would only be of use if the images contained only grapes.

4 Project level achievements

Four key project activities were addressed:

- Develop and trial sensors for level of disease in grapes.

The initial focus was on developing a proof of concept and establishing the critical wavelengths for the identification of disease-affected grapes. This research was laboratory-focused and used a hyperspectral camera (a pushbroom type camera where either the camera or the sample needed to be moved in order to collect an image). The linescan camera covered the 400-1000 nm wavelength range and could discriminate clean and infected red and white grapes, for both laboratory infections and field samples. The calibrations were not dependent on growing region, grape variety and *Botrytis* strain. Hyperspectral imaging could also discriminate *Botrytis* infection from sour rot (mixed fungal and bacterial infection of grapes). Washing sporulating berries with grape juice or smashing berries to simulate mechanical harvesting did not prevent identification of *Botrytis*. Hyperspectral imaging could also identify sunburn in white grapes and shrivel in red and white grapes.

- Conduct simulations to measure contaminants in harvested wine grapes.

Simulations were conducted both in the laboratory and in the grape receival area. Both hyperspectral and multispectral imaging could discriminate the components that often form mater other than grapes (MOG) in mechanically harvested grape loads (i.e. canes, wood, petioles, leaves, and insects).

- Develop prototype technologies and protocols for disease detection.

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

- Collect data from vineyards and harvested fruit loads and validate against disease levels.

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

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

The multispectral camera could classify material on the vine but the system used was not practical in terms of field portability. The RotBot app is simple to use in the field with a standard smartphone, but it classified bunch stems, leaves and other vine material as clean or infected grapes, so would only be of use if the images contained only grapes.

4.1 Contribution to programme objectives

- generating knowledge, technologies, products or processes that benefit primary producers.

This project demonstrated that multispectral imaging has merit for commercial use in objective monitoring of *Botrytis* and MOG in mechanically harvested grapes. This includes the demonstration of the proof of concept that hyperspectral imaging can delineate and quantify the levels of mater other than grapes (MOG), *Botrytis* and other defects in grape samples. It also includes the selection of critical wavelengths for the use of multispectral cameras to identify *Botrytis* and MOG, and the use of the selected filters in cameras at the grape receival area to identify defects. Care would be needed to ensure that samples are scanned on a standard background and with some fine tuning of image analysis and lighting to remove the small errors at the edges of objects. An important outcome is that although *Botrytis* in mechanically harvested red grapes is difficult to observe visually, it can be identified with multispectral imaging.

- strengthening pathways to extend the results of rural R&D, including understanding the barriers to adoption.

This project has garnered considerable interest from the wine industry and the wider agricultural community as demonstrated by a presentation at EvokeAg. Projects that span research and technology providers inherently require more engaged stakeholders than projects that target a simple practice change at the vineyard or winery level. By engaging equipment suppliers (i.e. Lastek and Adept Turnkey) during the project development, these companies are well placed to support the industry and provide turnkey solutions.

- establishing and fostering industry and research collaborations that form the basis for ongoing innovation and growth of Australian agriculture.

This project was a collaboration between Accolade Wines and the Australian Wine Research Institute. Accolade was critical to setting the research targets and provided grape samples and access to facilities (i.e. the grape receival station) to allow the analysis to be completed. The Australian Wine Research Institute will continue to work with Accolade on methods to assess disease incidence in the vineyard and at the weighbridge.

4.2 Productivity and profitability

Although it may be desirable in certain wine styles, infection of wine-grapes with *Botrytis cinerea* generally creates serious loss of quality and can promote growth of other spoilage organisms. *Botrytis* tends to be an ongoing problem in cool, wet climates but under adverse weather conditions it can also spread rapidly in regions that normally have a dry climate. An example of a challenging vintage was 2017, when many of the high-production inland areas experienced late summer rains at a time when the grapes were very susceptible to *Botrytis* infection. Most wineries inspect fruit in the field before harvesting, but when the conditions are very conducive to *Botrytis* growth the infection can expand exponentially in a matter of days. Fruit that has been assessed as 'clean' in the vineyard can quickly deteriorate prior to delivery to the winery. While it is easy to identify in the vineyard, the machine harvest of *Botrytis* affected fruit makes it very difficult to determine the detrimental effects of the disease at the weighbridge. *Botrytis* is also more difficult to detect visually in red grapes. If *Botrytis* is present in the load but not observed, the resultant wine may have a lower value (50-70% of potential).

Matter other than grapes (MOG) is often present in the mechanically harvested load when it arrives at the weighbridge. This can consist of items such as leaves, petioles, canes, grapevine wood, insects and vine trellis material. Excessive MOG can cause taints and other quality problems and large foreign objects can cause damage to processing equipment. Most wineries perform visual checks at the weighbridge and reference against photographic charts (Allan 1996) to determine the level of MOG, which may result in downgrading of the price paid for the load or outright rejection. This subjective assessment can cause mistrust in the grape supplier about the load assessment process.

The implementation of a hyperspectral system at the grape receival point as described in this report would allow effective screening of fruit for *Botrytis* and MOG at intake. It would allow the winery to identify and avoid or better manage disease-affected loads during processing and therefore prevent the production of *Botrytis*-affected wine, which can be virtually unsaleable. Likewise an objective system to measure MOG will provide greater transparency of the assessment process and more confidence than the current visual system.

5 Collaboration

This project was developed as a collaboration with Accolade Wines which was actively involved both with developing the project brief and providing access to grape samples and winery facilities (especially the weighbridge stations). During the course of the project the AWRI investigated other methods of assessing disease at the weighbridge on behalf of Accolade Wines and this relationship is likely to continue.

As with most 'agritech' research and development, the vendors that provide software and hardware were critical to its success. Adept Turnkey supplied the hyperspectral camera and provided advice on its implementation, especially lighting. Lastek supplied the multispectral camera and provided advice on its set-up and use. Software was also a critical component of this project; initially the Scyven package from Data61 was used and when a more integrated solution was required it was replaced with ENVI from ESRI. The hardware and software providers are now ideally placed to collaborate with wine companies to implement a solution.

The biannual project meetings were also an important opportunity to interact with projects that had a similar focus; especially 'new technologies for dynamic canopy and disease management' and 'new non-destructive technologies for simultaneous yield, crop condition and quality estimation' from the CSIRO and 'taking grapevine yield forecasting into the digital age' from the University of Tasmania.

Project collaborators:

Accolade Wines (Alex Sas, Warren Birchmore, Stephen Winnall, Jarrod Thorpe) vineyard samples, access to weighbridge station and advice on project application.

PIRSA/SARDI (Barbara Hall, Sue Pederick): *Botrytis* cultures

Adept Turnkey (Mark Fimieri): Hyperspectral camera and lighting advice

Lastek (Zhenfang Gong, Alex Stanco): Multispectral camera advice

ESRI (Dipak Paudyal): ENVI image analysis software advice

Data61(Nariman Habili): Scyven software advice

Plant and Food Research NZ (Gareth Hill): RotBot app advice

6 Extension and adoption activities

Hyperspectral imaging of *Botrytis* in grapes CRUSH 2017, 13-14 November, Adelaide. This is an important annual conference for viticulture and oenology researchers. It is an opportunity for peer review of research and to gain feedback. This presentation was awarded 'best snapshot presentation'.

Hyperspectral imaging of *Botrytis in grapes* *Wine & Viticulture Journal*, Vol. 33, No. 3, May/Jun 2018: 22-24. The *Wine and Viticulture Journal* is a trade publication so is an ideal forum to present information to potential end-users.

Monitoring grapevine pathology with hyperspectral imaging ASVO Seminar, Mildura 25-26 July 2018. This is one of the most important viticulture seminars held by the Australian Society of Viticulture and Oenology. It is attended by both researchers and practicing viticulturists and winemakers, so is the ideal forum to present this work to potential end-users.

Hyperspectral imaging of *Botrytis* in grapes CRUSH 2018, 25-26 September, Adelaide. This is an important annual conference for viticulture and oenology researchers. It is an opportunity for peer review of research and to gain feedback.

Digital solutions for grape quality measures at the weighbridge EvokeAG, Melbourne 19-20 February 2019. This is a new event hosted by Agrifutures and is set to become the premier event to showcase the use of digital technologies in agriculture. This presentation was chosen by Wine Australia and Agrifutures to be included in a comprehensive program with international speakers. The event brings together granting bodies, researchers, entrepreneurs, start-up companies and industry end-users, so is the ideal forum to encourage uptake of research. The format of the conference encourages one-on-one interaction to encourage product development.

The final outcomes of the project will be included in an extension article to be published in *Wine & Viticulture Journal*, so that industry is aware of the potential of this work. It is also likely to be included in the suite of presentations that can be made to the Australian wine industry as part of the AWRI's roadshow program. The implementation of this work will require an integrated solution to be developed between wine companies and the providers of imaging systems, and the acceptance of the results by grapegrowers.

7 Lessons learnt

There were significant delays (more than six months) to the contracting at the initiation of this project. This placed pressure on the project team, especially during the first year of the project when the lost time was being caught up. A more streamlined process between the Department of Agriculture, Wine Australia and the Australian Wine Research Institute would have allow the work to be initiated earlier and completed in a more timely and considered manner.

8 Recommendations

There is strong potential to further develop this research into a turnkey application for industry use. The current study involved exporting data into third-party software for data analysis. An important requirement is a software package that can control the camera and perform the classification in the background, then report the result. ENVI has potential capability to do these tasks, but it would require expert programming.

Edge effects on objects to be classified were an issue with this study, but this is likely to be corrected with improvements to the image analysis routines.

Shadowing is an issue and for this reason the most suitable procedure would be to have the samples spread out on a conveyor belt and use a linescan camera or to spread out samples on a static tray and use a snapshot camera. The FX10 hyperspectral camera used for this study can be reconfigured to run a limited number of chosen wavelengths in multispectral mode. This may be a good linescan option for routine use, but is not an option for use in the vineyard.

Lighting is a critical issue and with both a conveyor belt or static tray, lighting can be controlled well, but lighting is simplified with a linescan camera, as only one row of pixels at are time is imaged. This means the whole sample passes through the same lighting field. A snapshot camera images the whole view simultaneously, so the whole field must be evenly lit. LED lighting would ultimately be best due to its low power use allowing battery operation and low heat output, but currently LED systems with the appropriate wavelength range are not readily available. LED lights suitable for Vis-NIR imaging are coming onto the market but are expensive and designed for linescan camera use. Development of alternatives to halogen lighting is important as halogen is being phased out by regulation in Australia and this has already occurred in some European countries.

Multispectral imaging with a small number of wavelengths, as opposed to full spectral imaging, is the most practical solution. The fact that successful classification of images can be performed with as little as three wavelengths suggests that the future for imaging in the vineyard could rely on the development of sensors in a smartphone type device with sensitivity to wavelengths other than red, green and blue. Such a device could include software for infield analysis and GPS marking of vineyard samples. Cameras, computing power and imaging software are evolving quickly and reducing in cost, providing a promising future for this technology.

During the course of the project some potential new applications for the existing RotBot app were highlighted. With Australia's increasingly hot summers leaf scorching and grape berry sunburn and shrivel are becoming more prominent issues. RotBot appears to be capable of classifying these problems and there is potential for further work on the existing app, in addition to other multispectral work to monitor these quality issues.

9 Appendix – additional project information

9.1 Project, media and communications material and intellectual property

Going digital at the weighbridge Media Interview by Nick Carne: Wine Australia RD&E news. This is a monthly email bulletin profiling research funded by Wine Australia. https://www.wineaustralia.com/news/articles/going-digital-at-the-weighbridge

Hyperspectral imaging of *Botrytis* in grapes CRUSH 2017, 13-14 November, Adelaide. This is an important annual conference for viticulture and oenology researchers. It is an opportunity for peer review of research and to gain feedback. This presentation was awarded 'best snapshot presentation'.

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9.2 Equipment and assets

Specim FX10 hyperspectral camera

9.3 References

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Sun, D-W (ed.) 2010. *Hyperspectral imaging for food quality analysis and control*. Academic Press.

9.4 Staff

Paul Petrie

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Simon Nordestgaard

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9.5 Evaluation report

The key project outcome for this work was to reduce losses for grapegrowers through fewer quality downgrades due to disease. This included improved disease detection using digital technology during the growing season, allowing rapid mitigation strategies to be implemented, and rapid objective validation of disease status of grapes delivered to buyers.

This project has developed a system that has the potential to rapidly provide information to grapegrowers and winemakers on the level of disease present in loads of grapes when they are delivered to the winery (see section 3.1). Note that a commercial system was not implemented. If this technology is installed it will allow the winemaker to determine disease levels in a load of grapes and make an informed management decision for the fruit. This decision could range from accepting the fruit as fit for purpose, varying the winemaking process (e.g. addition of additional sulfur, reducing exposure to oxygen, pasteurisation) or rejecting the load. Implementation of this technology would greatly reduce the likelihood of the production of faulty wine. The knowledge that an objective system is in place to assess disease severity would also encourage grapegrowers to be more proactive about reporting and managing disease-affected fruit in the immediate lead-up to harvest. This would allow the winery to be better prepared to manage disease-affected blocks either prior to harvest or once they are received at the winery.

The trial of the multispectral system to assess disease in the vineyard was less successful as the system was not portable and needed additional lighting to collect appropriate images. If excessive bunch disease such as *Botrytis* is identified once the fruit has started to ripen, the key management option is to avoid the harvest of this fruit. This is managed either by dropping the disease-affected bunches or avoiding the worst affected portions of the block. Fungicide sprays may be used; however, these are generally recommended as protectants, to prevent the disease infection as opposed to eradicants which could cure infected bunches.

Period	Item	Budget	Actual Expenditure	Variance - overspend / (underspend)
2016/17 (1/8/2016 - 30/6/2017)	Salaries	71,315	58,444	-12,871
	Operating	93,500	1,132	-92,368
	Capital	11,500	3,181	-8,319
	Total	176,315	62,757	-113,558
2017/18 (1/7/2017 - 30/6/2018)	Salaries	146,196	159,287	13,091
	Operating	59,707	71,221	11,514
	Capital	40,293	40,293	0
	Total	246,196	270,801	24,605
2018/19 YTD (1/7/2018 - 30/6/2019)	Salaries	74,925	178,439	103,514
	Operating	42,500	2,463	-40,037
	Capital	0	0	0
	Total	117,425	180,902	63,477
Total Project	Salaries	292,436	396,170	103,734
	Operating	195,707	74,816	-120,891
	Capital	51,793	43,474	-8,319
	Total	539,936	514,460	-25,476

Reconciliation to AGWA clearing:					
Carried fwd income		88,952.53	as reported to Wine Australia / recorded in our accounts		
FY19 invoices recd		36,434.60			
Less: FY19 expenditure	-	180,901.77	per above		
(receivable)	-	55,514.64	final receivable amount		
Recorded in AGWA clearing:	-	55,514.64			
Variance:		-	balances		