Mitigation of climate change impacts on the national wine industry by reduction in losses from controlled burns and wildfires and improvement in public land management

FINAL REPORT TO WINE AUSTRALIA

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Title: Mitigation of Climate Change Impacts on the National Wine Industry by Reduction in Losses from Controlled Burns and Wildfires and Improvement in Public Land Management

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Abstract

This project's objectives were to mitigate the impacts of climate change on the national wine industry by reducing losses to smoke taint from bushfires and controlled burns and improve public land management. An early warning remote sensing network of smoke detectors was established and, using correlations between smoke, grape and wine measurements taken around controlled burns and bushfires, has enabled early stage predictions of the risk of smoke taint from smoke events in vineyards. Additionally, a chitosan coating was found to reduce the uptake of smoke taint by grapes in controlled smoking experiments, whereas other coatings generally increased uptake.

Executive summary

The exposure of vineyards and grapes to smoke from bushfires and/or controlled burn events may result in 'smoke tainted' wine, that can cause serious economic losses to industry. Since 2003, major fire events have affected over $400M worth of grapes and wine that were either rejected commercially or downgraded as a result of smoke taint. The frequency of bushfires and controlled burns is expected to increase under various climate change scenarios, thus it is important that the Australian wine industry develop cost effective remediation tools to manage smoke affected grapes and wine. This collaborative DJPR and La Trobe University project was part of a larger program funded by DAWR and Wine Australia, and focussed on providing the industry with an early warning system and mitigation tools in the vineyard, while the Australian Wine Research Institute focussed on mitigation of smoke taint in wine.

This DJPR/La Trobe University project focussed on:

(i) Setting up a network of smoke detectors in wine regions prone to smoke,
(ii) Testing the smoke detector network to predict the risk of sensory smoke taint in wines produced from smoke affected vineyards
(iii) Determination of how smoke dose and composition linked to grape and wine levels of phenolic smoke taint compounds and sensory outcomes in wine.

A state-wide network of 7 remotely accessible aspirating smoke detectors was set up and operational from the 2017 autumn controlled burning period onwards. Commercially available Very Early Smoke Detection Apparatus (VESDA®, Xtralis P/L) units were modified to suit the purpose of the study. This network consisted of three VESDA®'s in the Ovens and King Valleys in north east Victoria, three VESDA®'s in the Yarra Valley, and one VESDA® in the Otways region. In addition, roving VESDA®'s were used to take smoke measurements at and around controlled burns, along with measurements of smoke composition and, where possible, grape uptake of smoke taint compounds. Wines were produced from smoke exposed grapes, both from bushfire affected vineyards and from grapes deliberately smoked at controlled burns.

Our in-field measurements allowed the establishment of some key relationships to be developed between smoke measurements and levels of smoke taint compounds in wine. When combined with wine sensory analysis results, these relationships will allow the development of a smoke taint risk assessment tool which can be used by industry to guide their decision-making process following smoke events.

The early warning network of smoke detectors proved to be effective for monitoring widespread smoke events during the growing season and quickly providing industry with objective measurement results. The current static VESDA® network was of limited value for monitoring the impact of smoke from small bushfires and controlled burns, which impacted a much smaller area than large bushfires, and was often found to be very localized. Accurate measurement of the impacts of these smaller fires would require a much more extensive network of smoke detectors because of highly variable smoke concentrations in the atmosphere.

It is recommended that a more extensive statewide and national network of smoke detectors and smoke composition monitoring be developed and that this be made readily accessible to industry, such as via a mobile phone app, which could provide interpretation of smoke exposure levels in terms of smoke taint risk.

An effective coating to reduce the uptake of smoke taint compounds was found — chitosan — which is a biopolymer that was applied to grapes as an aqueous solution and found to reduce the uptake of smoke taint compounds by 30 – 60% during controlled experiments. Further research is required to develop a product which could be practically and economically applied in the field. Another important finding of this work was that coating products such as commercially available liquid anti-transpirants and sunburn protectants have the effect of increasing, in some cases by greater than 50%, the uptake of smoke taint compounds by grapes, and thus some products should be avoided when there is the risk of smoke exposure. Investigations also showed that absorption of smoke taint compounds by grapes is rapid, generally complete within a day of smoking, meaning any attempt to wash the compounds from the grapes after this time would be unlikely to have any significant effect.

This project was funded by the Commonwealth Department of Department of Agriculture, Water and the Environment Rural R&D for Profit program through Wine Australia with co-investment from La Trobe University and the Department of Jobs, Precincts and Regions.

1 Project rationale and objectives

The exposure of vineyards and grapes to smoke from bushfires and/or controlled burn events may result in 'smoke tainted' wine, that can cause serious economic losses to industry. Since 2003, major fire events have affected over $400M worth of grapes and wine that were either rejected commercially or downgraded as a result of smoke taint. The frequency of bushfires and controlled burns is expected to increase under various climate change scenarios, thus it is important that the Australian wine industry develop cost effective remediation tools to manage smoke affected grapes and wine. This collaborative component of the project (DJPR, La Trobe University) aimed to evaluate a range of possible remedial management options and tools for dealing with smoke affected grapes in the vineyard. The results were related to critical sensory thresholds for the key smoke taint volatile phenols and their associated glycosides in Chardonnay, Pinot Noir and Shiraz (oaked and unoaked). Once these critical chemical threshold concentrations were determined for each variety and style, other studies by AWRI trialled options to remove smoke related free volatile phenols and their associated glycosides from affected wines, or treatments that facilitate the degradation of these free volatile phenols and their glycosides in wines. The benefit/cost of these remediation and mitigation treatments was evaluated and reported to help industry implement cost-effective solutions in their business.

The objectives of the broader smoke taint project were to:

1. Establish wine quality ratings, sensory thresholds, compositional and flavour profiles and consumer preferences for smoke affected Chardonnay, Pinot Noir and Shiraz wines (oaked and unoaked) using dilution techniques.

2. Evaluate a range of remediation strategies for managing smoke affected fruit and wines in the winery. This objective aims to examine processing options and materials to remediate wines and minimise the loss to final wine quality.

3. Investigate vineyard mitigation options and strategies to identify vineyards at risk from smoke exposure, in addition providing options to decrease uptake of smoke taint compounds in the vine and grapes. This objective aimed to explore options viticulturists could implement at short notice to protect fruit from becoming smoke tainted. The work linked with work by AWRI to explore other options to limit the conversion of free volatile phenols into their more difficult to remove glycosidic/bound forms, however no products were found to be effective enough to be further evaluated in laboratory and/or in-field evaluation in this project. Additional options to those found effective by this project (e.g. chitosan) included the use of anti-transpirants and modulation of glycosidase enzymes (AWRI). This objective was funded through DJPR/La Trobe University co-investment.

4. Evaluate the economics of remediation activities undertaken under objectives 2 and 3 above. Assess (by an economist and a process engineer) cost data for the various remediation treatments trialled in objectives 2 and 3 to determine cost effective treatments for implementation.

2 Method and project locations

2.1 Smoke measurement

Our methods involved the measurement of smoke density (particulates) and smoke chemical composition (concentrations of each smoke taint compound within the smoke) and relating these to the uptake of smoke taint compounds by grapes, the concentrations of the smoke taint compounds in wine, and the degree of sensory smoke taint in those wines. This allowed smoke measurements from an early warning network of smoke detectors to be used to predict the risk of smoke taint, thus giving producers the ability to make informed decisions regarding their crop from a much earlier stage than if they had to wait for grape testing results.

2.1.1 Particulates

Smoke intensity was measured using Very Early Smoke Detection Apparatus (VESDA®) — aspirated smoke detectors based on a nephelometer (which measures the deflection of a laser beam by smoke particles). Commercially available VESDA®'s (VLF-300, Xtralis P/L, Victoria, Australia) were modified to allow data collection at suitable sampling rates for our purposes. These VESDA®'s recorded the smoke particulate matter concentration as obscuration values in units of percentage obscuration per metre (% obs/m).

Smoke dose

The smoke 'dose' at each measurement site was calculated as the area under the VESDA® plot, which is the cumulative total of each measurement multiplied by the duration of that measurement. Thus, the smoke 'dose' was a cumulative measure of the smoke each measurement site had been exposed to. To exclude the effect of the background reading of the smoke detector and the contribution of low-level smoke haze from old smoke, which was found not to contain significant levels of smoke taint compounds, the smoke dose was calculated using only smoke measurement above a specific obscuration reading (0.04% obs/m). Further work is required to determine if a different limit should be set for this parameter.

Static VESDA® network

A state-wide network of 7 VESDA® smoke detectors was set up and operational from the 2017 autumn controlled burning period onwards. This network consisted of three smoke detectors in the Ovens and King Valleys in north east Victoria, three in the Yarra Valley, and one in the Otways region, as shown in Figure 1. The smoke detectors were located in vineyards and encompassed the breadth of each region, enabling a broad picture of the smoke experienced across a region from any particular fire. Each smoke detector was connected to a cellular IP gateway device, allowing remote communication with the smoke detector and download of the data to a server via the Telstra cellular network.

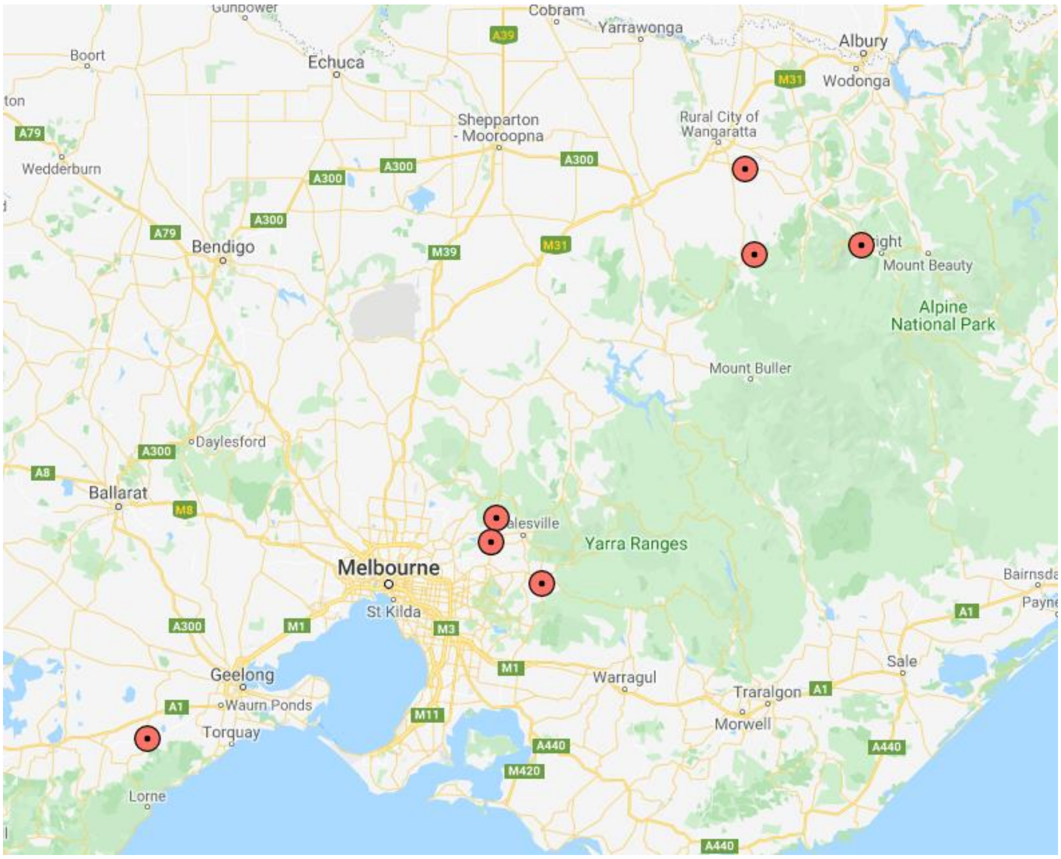

Figure 1: Locations of the remotely accessible Vesda® smoke detectors.

Roving VESDA® units

Roving VESDA®'s were used to take smoke measurements directly above the fire at controlled burns (fresh smoke) and at various distances from controlled burns and bushfires. These were the same as the static smoke detectors, but with battery power and no telemetry, and were housed in a tool tote for easy transport in burns as shown in figure 2, enabling smoke sampling to be performed anywhere. The smoke was drawn into the smoke detector through a 1 metre length of PVC pipe, placing the smoke inlet approximately 1.2 m above the ground, which is approximately the height of grape bunches on a vine. Where necessary, a 4.9 m telescopic pole was used when sampling smoke directly above a fire, and the smoke conveyed to the smoke detector via a suitable length of 20 mm diameter flexible PVC electrical conduit. Smoke measurements were conducted for variable lengths of time, governed by the duration of smoke at a particular site, the smoke concentration and prevailing weather conditions.

Figure 2: Roving VESDAs® placed near a controlled burn of pasture grass near Derrimut in 2018 and Lethbridge (bottom right) in 2019.

2.1.2 Smoke chemical composition

The smoke chemical composition was determined at all roving VESDA® sites, and whenever possible during smoke events at static VESDA® sites, using sampling tubes containing Tenax® resin. These tubes enabled the measurement of the smoke chemical composition by capturing the smoke taint compounds from the air, which was drawn through the tube at 100 ml/min using a calibrated vacuum pump. The tubes were subsequently returned to the laboratory, where the phenols were desorbed from the resin with ethyl acetate, derivatised with bis-silyltrifluoroacetamide/1 % trimethylchlorosilane (BSTFA/1 % TMCS) and analysed using an Agilent 7890A GC coupled to an Agilent 5975C mass selective detector (GC-MS).

Given the complexity of trying to deploy the sampling tubes remotely at the static VESDA® sites, the Tenax® tubes were generally deployed by the vineyard manager at each location.

2.1.3 Smoke uptake by sentinel grapes

In most cases, roving smoke measurements were accompanied by 'sentinel' grape bunches — excised bunches of grapes exposed to the exact same smoke as was measured by the smoke detector and sampled on Tenax® tube. The use of these sentinel bunches was to provide a mechanism which would simulate similar uptake by grapes in a vineyard. Previous work (Porter et al, 2015) has shown that excised bunches were able to take up smoke taint compounds similarly to bunches on-vine. Grapes used as sentinels were harvested from the phylloxera exclusion zone (PEZ) of Victoria so they could be used in all experiments throughout Victoria. Similarly, Shiraz grapes were purchased from a vineyard in Great Western, Victoria, Chardonnay grapes were purchased from vineyards in Drysdale, Victoria and Faraday, Victoria and Pinot Noir grapes were purchased from a vineyard in Faraday, Victoria. All grapes were stored at 4°C and allowed to come to room temperature before smoke exposure. Where measurements were made at a site within the PEZ, local grapes were sourced to avoid biosecurity issues.

Where possible, grapes samples were also taken from vines within vineyards exposed to smoke from controlled burns or bushfires. After treatment, grapes were sealed in zip-lock plastic bags prior to transport to the laboratory for chemical analysis. Where measurements took place in a phylloxera infested zone (PIZ), grapes were frozen and permits obtained prior to removal of the grapes from the PIZ.

Where practical, 20 kg each of Shiraz and Chardonnay grape bunches were placed on racks in close proximity to the VESDA® smoke sensor, so that we could compare the smoke dose and composition being measured to the grapes and wine made. Bunches were placed at varying distances from the controlled burns and following smoke exposure, these grapes were made into wine.

2.1.4 Sampling locations

Smoke and grape sampling was performed in wine regions across Victoria and Tasmania, as shown in figures 3 – 5. Measurements encompassed bushfire and controlled burn smoke, and results are expected to be applicable to all wine regions across Australia.

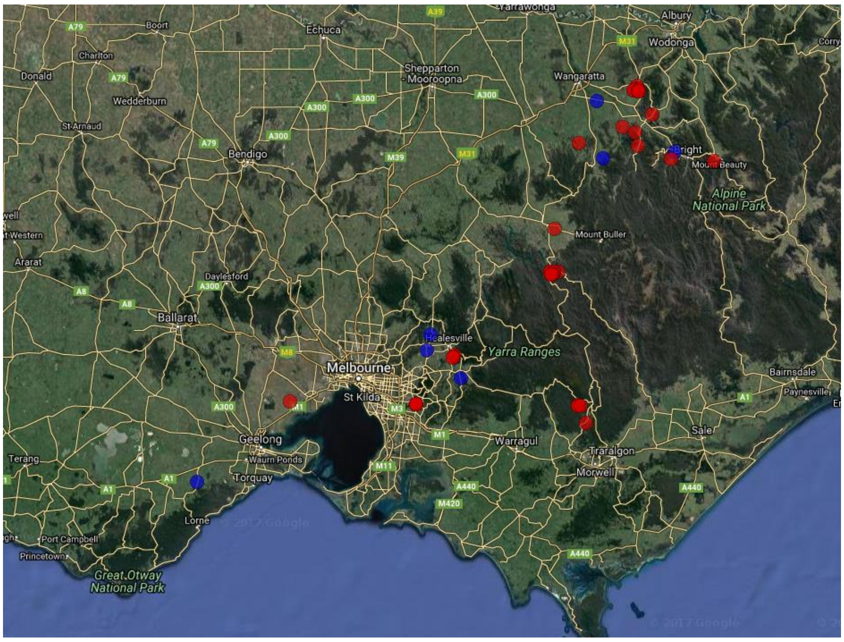

Figure 3: Locations of sampling sites across Victoria in the 2017 vintage season. Blue sites represent the location of static smoke detectors recording continuous smoke measurements and red sites represent additional sampling sites using roving smoke detectors.

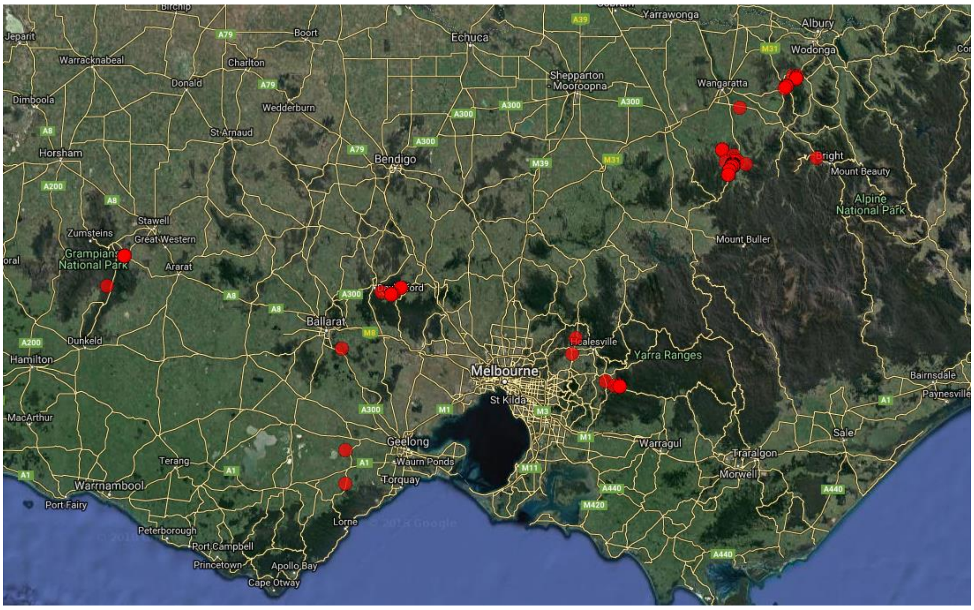

Figure 4: Sampling locations for the autumn 2018 bushfire and autumn controlled burn season.

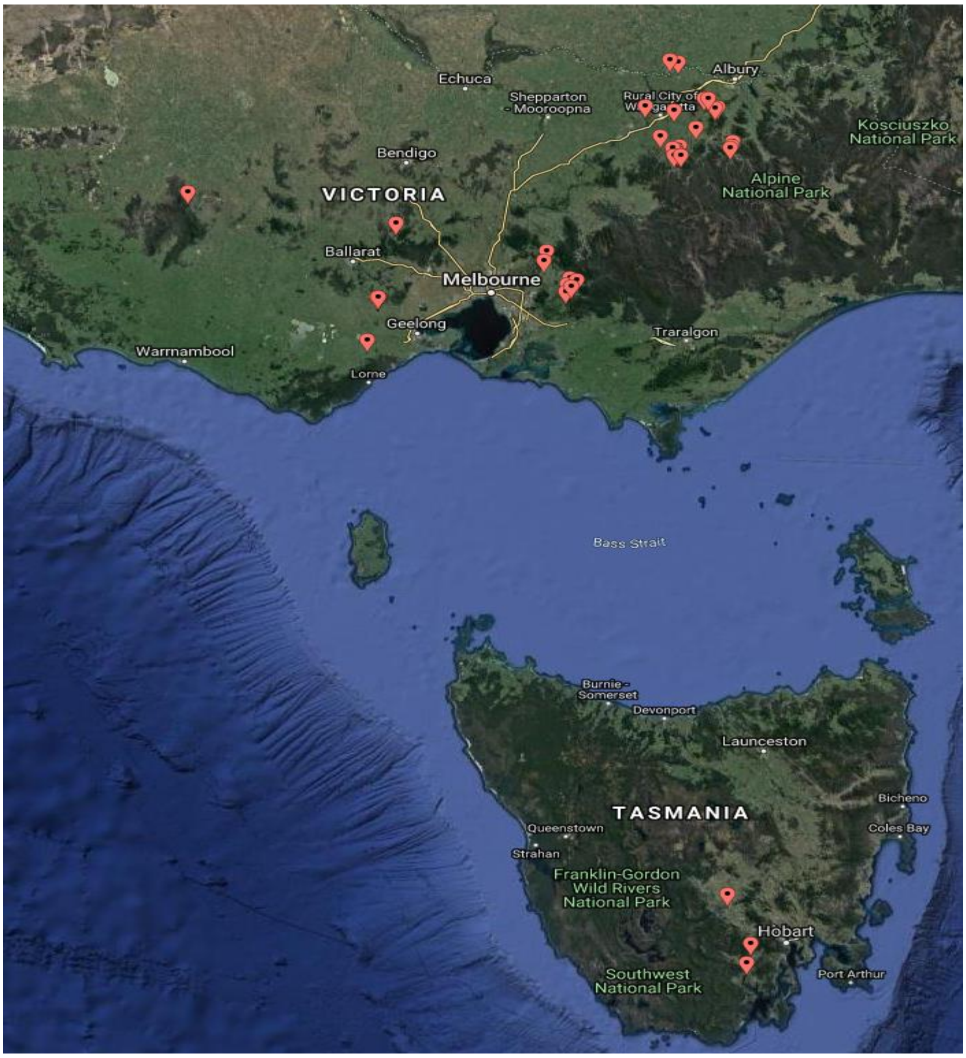

Figure 5: Smoke and grape sampling locations for the 2019 bushfires and autumn-controlled burn season.

2.2 Barrier compounds to prevent the uptake of smoke taint compounds by grapes

The methodology for this work is detailed in the technical report attached in the Appendix, section 8.1. Briefly, grape bunches were coated with some commercially available fruit coating products, as well as some solutions of biopolymers, then hung up and allowed to dry. Coated and uncoated bunches were then smoked for one hour at 20% obs/m in a purpose-built smoking chamber, or a smoking tent, using wheat or barley straw as the smoke source. The grapes were then extracted and analysed for smoke taint compounds as detailed in section 2.4.

2.3 Winemaking

Unsmoked and smoked grapes from both bushfires, controlled burns and controlled smoking experiments were made into wines at a commercial winery (Chrismont, Cheshunt) in the King Valley. Wines were made using a standardized method without any exposure to oak barrels or chips to avoid artificially raising the levels of some taint compounds in the wine.

2.4 Grape and wine analysis

Grapes and wines were analysed for 23 phenols in both free and bound (glycoconjugated) forms using the method described by Allen, et al (2013). Briefly, the phenols were extracted from the grapes by homogenisation and centrifugation, followed by re-extraction of the tissue pellet with methanol. The grape extract or wine was then subjected to solid phase extraction to separate the free and bound phenols and clean up these fractions ready for derivatisation with BSTFA/1 % TMCS and GC-MS analysis. Grapes were sampled from pea size (GS 3.1) through to harvest (GS 3.5) and wine was sampled from juice extracts through to final bottling (2-6 months later). Some wines were resampled approximately 12 months after bottling.

2.5 Sensory analysis

This testing was delayed due to the late availability of our 2019 small scale wines, and the high workload of professional panels at AWRI. Informal testing of wines has been performed by DJPR and La Trobe University researchers, however, this was intended to guide our research and to allow selection of suitable wines for professional sensory testing after the completion of the project. Results of this sensory testing will be part of proposed follow-up projects which will include detailed sensory studies of wines from the 2020 bushfire season together with reference wines from this project.

3 Project results and discussion

3.1 Project level achievements

3.1.1 Early warning remote sensing network (Output B4)

The VESDA® network proved to be effective for monitoring widespread smoke events during the growing season and quickly providing industry with objective measurement results. The current static network was of limited value for monitoring the impact of smoke from small bushfires and controlled burns, which impacted a much smaller area than large bushfires, were often found to be very localized, and depended on wind direction and speed, topography, fire dynamics and proximity to the fire. Accurate measurement of the impacts of these smaller fires was determined by our roving VESDA®'s, however to monitor these broadly across a viticultural region or state would require a much more extensive network of smoke detectors.

Our in-field measurements allowed the establishment of some key relationships to be developed, most notably the relationship between smoke and wine compositional measurements, and the relationship between smoke dose and wine composition. Future sensory analysis of these wines will enable the relationship continuum between smoke and sensory outcomes to be determined and this will enable development of a smoke taint risk assessment tool which can be used by industry to guide their decision-making process following smoke events. At present, predictions have been made by comparison of grape and wine chemical composition with those of professionally sensory assessed wines produced during the previous CESTR project (Porter et al, 2015).

Relationship between smoke dose and smoke chemical composition

Our data show a linear correlation between the total dose recorded by VESDA®'s with the total phenols recovered from Tenax® tubes, for samples taken greater than 500 metres from fires, as shown in Figure 6. This suggests that VESDA® measurements provide a good estimate of the total smoke concentrations of the key smoke taint compounds. Samples taken less than 500 metres from a fire, as shown in Figure 7, correlated less well due to high smoke variability and there were numerous samples with significantly elevated levels of smoke taint compounds relative to the VESDA® measurement of obscuration. This may be due to the presence of much higher proportions of gaseous smoke taint compounds in fresh smoke, relative to the amount of particulate matter present. These gaseous compounds are not detected by the smoke detector but are known to rapidly react and coalesce into secondary aerosol particles (Yee, 2013), which would be detected, and this may explain the better correlations for measurements taken greater than 500 m from fires. The data indicates that vineyards within 500m of a burn may experience much higher concentrations of smoke taint compounds than would be predicted from VESDA® measurements.

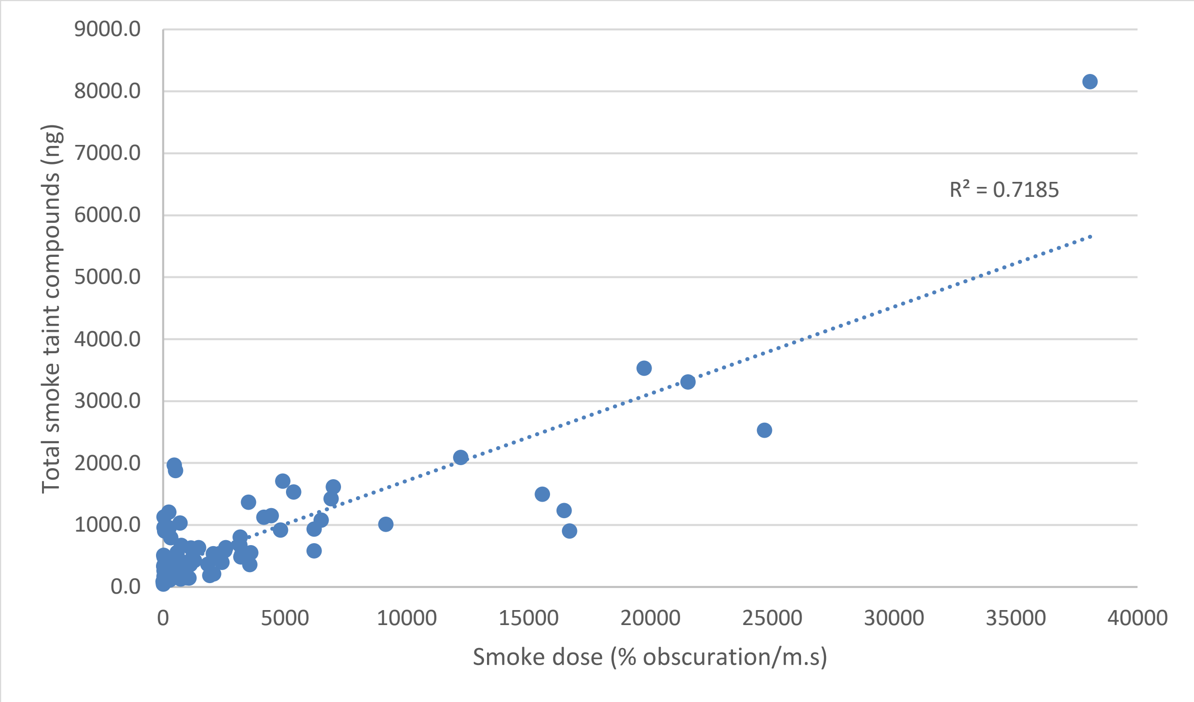

Figure 6: Total smoke taint compounds (sum of amounts of phenol, o-cresol, m-cresol, p-cresol, guaiacol, 4-methylguaiacol, syringol and 4-methylsyringol recovered from Tenax® tubes) versus area under curve of VESDA® measurements during sampling period. Measurements taken less than 500 m from fires have been excluded.

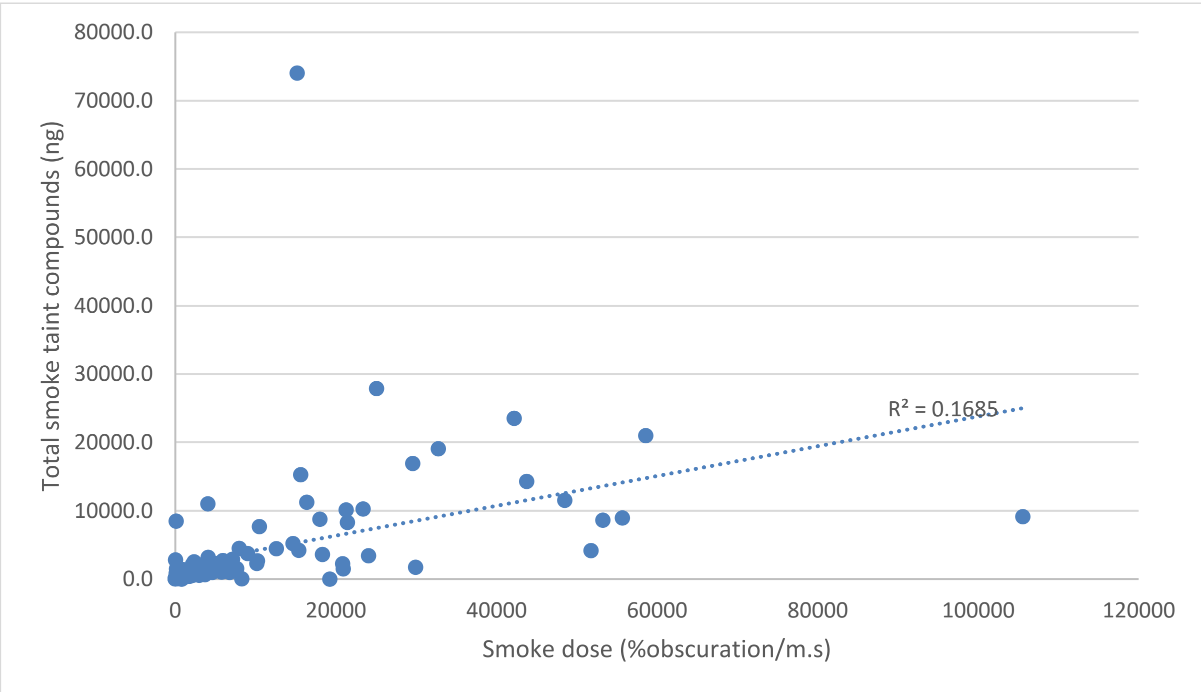

Figure 7: Total smoke taint compounds (sum of amounts of phenol, o-cresol, m-cresol, p-cresol, guaiacol, 4-methylguaiacol, syringol and 4-methylsyringol recovered from Tenax® tubes) versus area under curve of VESDA® measurements during sampling period for measurements taken less than 500 m from fires.

Relationship between smoke and grape chemical compositions

Our results showed the concentrations of individual smoke taint compounds in grapes were correlated with the amount of each compound captured on Tenax® tubes, as shown in Figure 8 and Table 1. Similar relationships were found for the uptake of each smoke taint compound by Chardonnay and Shiraz grapes, suggesting that uptake is more influenced by the concentration of the smoke in the atmosphere than the grape variety. Further research is needed to see how varietal differences may affect grape levels. Shiraz showed higher levels of guaiacol than Chardonnay due to the natural levels found in Shiraz grapes. These correlations were less significant than the correlations found between smoke and wine chemical composition below. This greater variability may be due to the smaller sample size of the sentinel bunches compared to the wines, which were made from 20 kg of excised grapes. The much larger sample size used for wine making would reduce the variability caused by differences in uptake between individual bunches and bunch position on a vine in a vineyard.

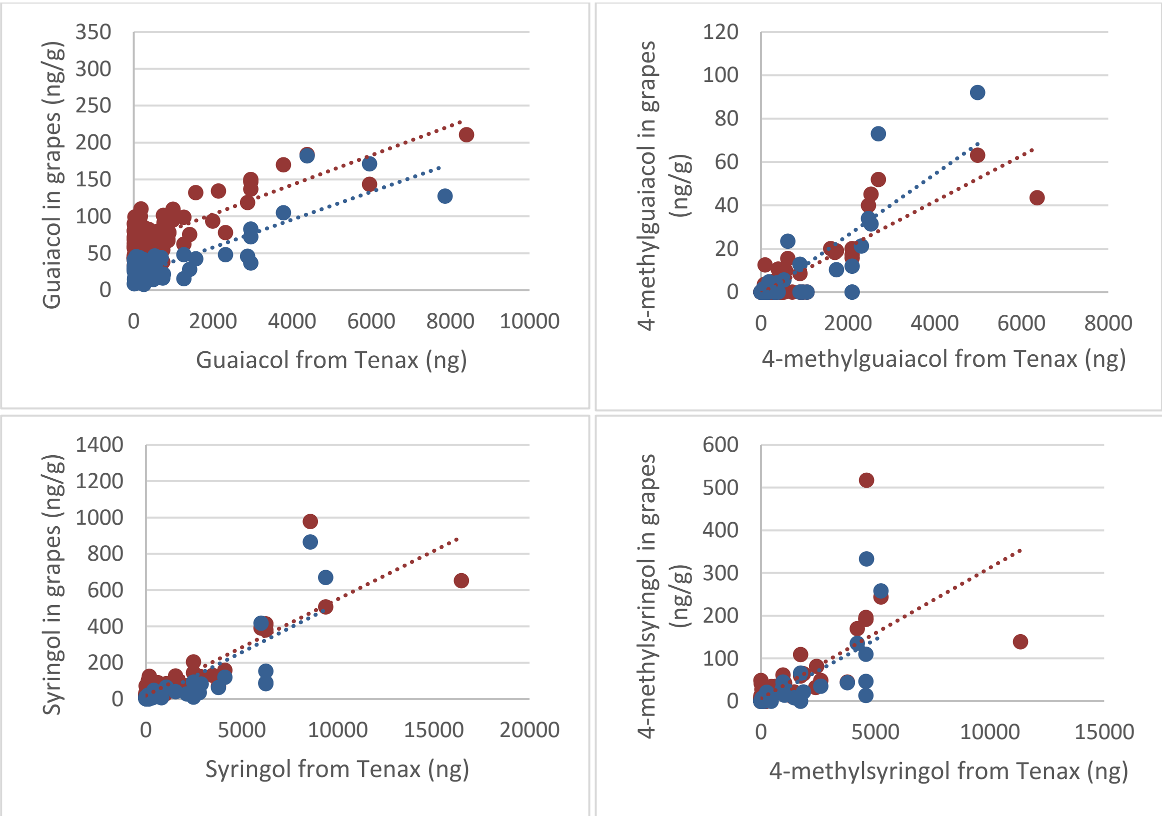

Figure 8: Relationship between the concentration of smoke taint compounds in grapes (ng/g) and the amount of compound captured on Tenax® tubes (ng). Linear regression lines for Chardonnay (blue) and Shiraz (orange) shown.

Table 1: Relationship between the concentration of smoke taint compounds in grapes (ng/g) and the amount of compound captured on Tenax® tubes (ng) for Chardonnay and Shiraz.

	Chardonnay		**Shiraz**	
Compound	**Equation**	**R^2**	**Equation**	**R^2**
Guaiacol	y=0.0189x+19	0.710	y=0.02x+63	0.611
4-Methyguaiacol	y=0.0141x-2	0.696	y=0.0106x-0.5	0.799
Syringol	y=0.0537x-11	0.669	y=0.0531x+19	0.803
4-Methylsyringol	y=0.0292x-2	0.566	y=0.0306x+6	0.536

Relationship between smoke and wine chemical compositions

Our results showed the concentrations of individual smoke taint compounds in wine were highly correlated with the amount of each compound captured on Tenax® tubes, as shown in Figure 9 and Table 2. The coefficient of determination for guaiacol in Shiraz was lower than for Chardonnay due to the naturally higher, and more variable, levels of guaiacol in Shiraz. These results show that measurement of the cumulative amount of smoke taint compounds to which the grapes are exposed can allow an accurate prediction of the concentrations of these compounds in the resulting wine.

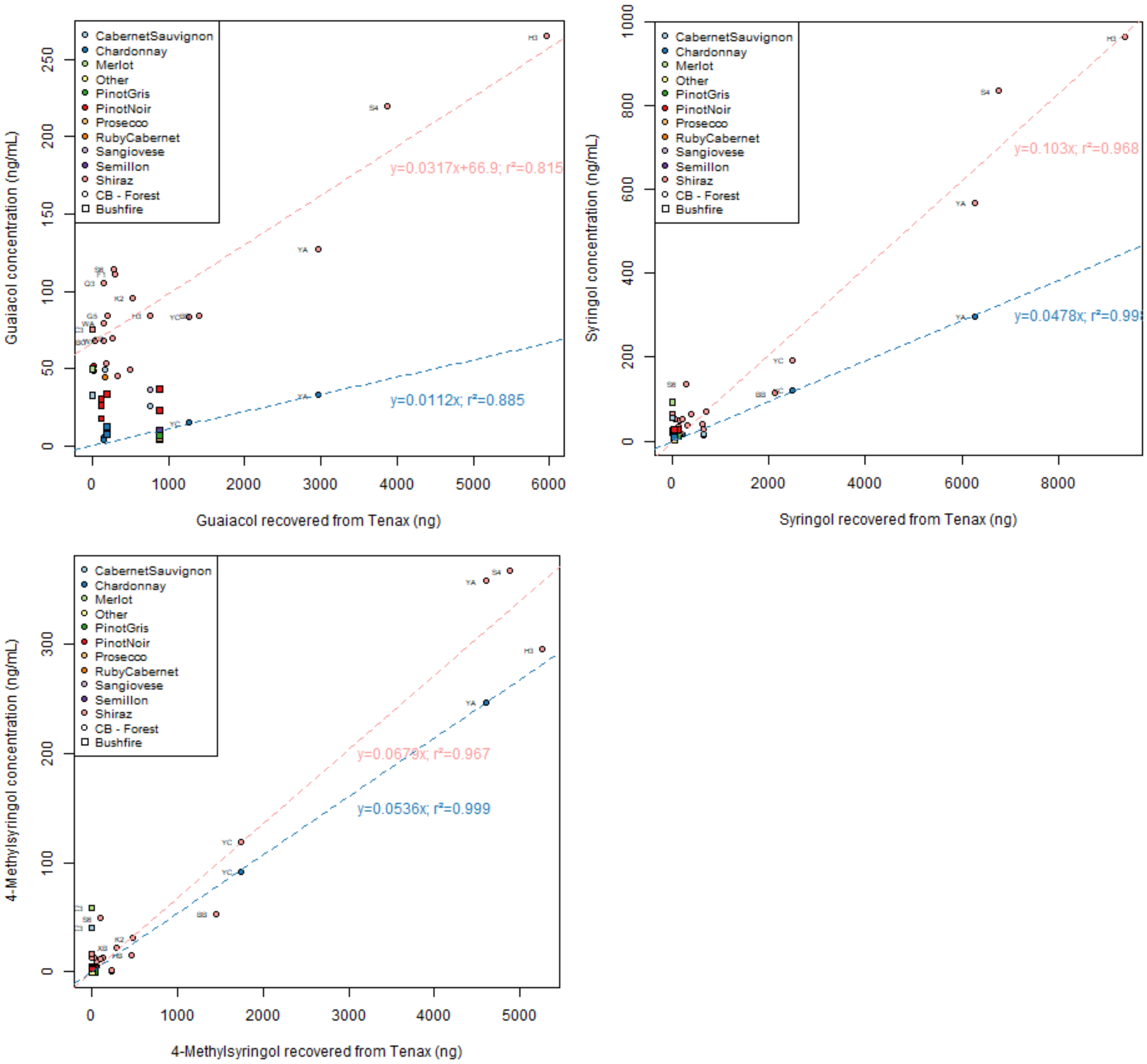

Figure 9: Relationship between the concentration of three smoke taint compounds in wine (ng/ml) and the amount of compound captured on Tenax® tubes (ng) for all wines. Linear regression lines for Chardonnay (blue) and Shiraz (orange) shown.

Table 2: Relationship between the concentration of smoke taint compounds in wine (ng/ml) and the amount of compound captured on Tenax® tubes (ng) for Chardonnay and Shiraz.

	Chardonnay		**Shiraz**	
Compound	**Equation**	**R^2**	**Equation**	**R^2**
Guaiacol	y=0.0112x	0.885	y=0.0317x+66.9	0.815
4-Methyguaiacol	y=0.00652x	0.948	y=0.0127x	0.84
Syringol	y=0.0478x	0.99	y=0.103x	0.968
4-Methylsyringol	y=0.0536x	0.999	y=0.0679x	0.967

Relationship between smoke dose and wine chemical composition

Our results showed the concentrations of individual smoke taint compounds in Chardonnay wines were highly correlated with the smoke dose, as shown in Figure 10 and Table 3. Shiraz wines did not correlate as well, perhaps due to these wines being made 'on-skins' and the extra variability introduced through extraction of smoke taint compounds from the skins during fermentation. The naturally higher and more variable levels of guaiacol may be an additional factor causing the lower correlation for guaiacol in Shiraz. These results show that measurement of the smoke dose to which the grapes are exposed can allow an accurate prediction of the concentrations of smoke taint compounds in Chardonnay wine, and a reasonable prediction for some smoke taint compounds in Shiraz wine. The lower correlation between some phenols and smoke dose may be influenced by background levels of some phenols in wine (e.g. Shiraz) and also the lower molecular weight of some phenols (e.g. guaiacol) which disperse more easily in the atmosphere.

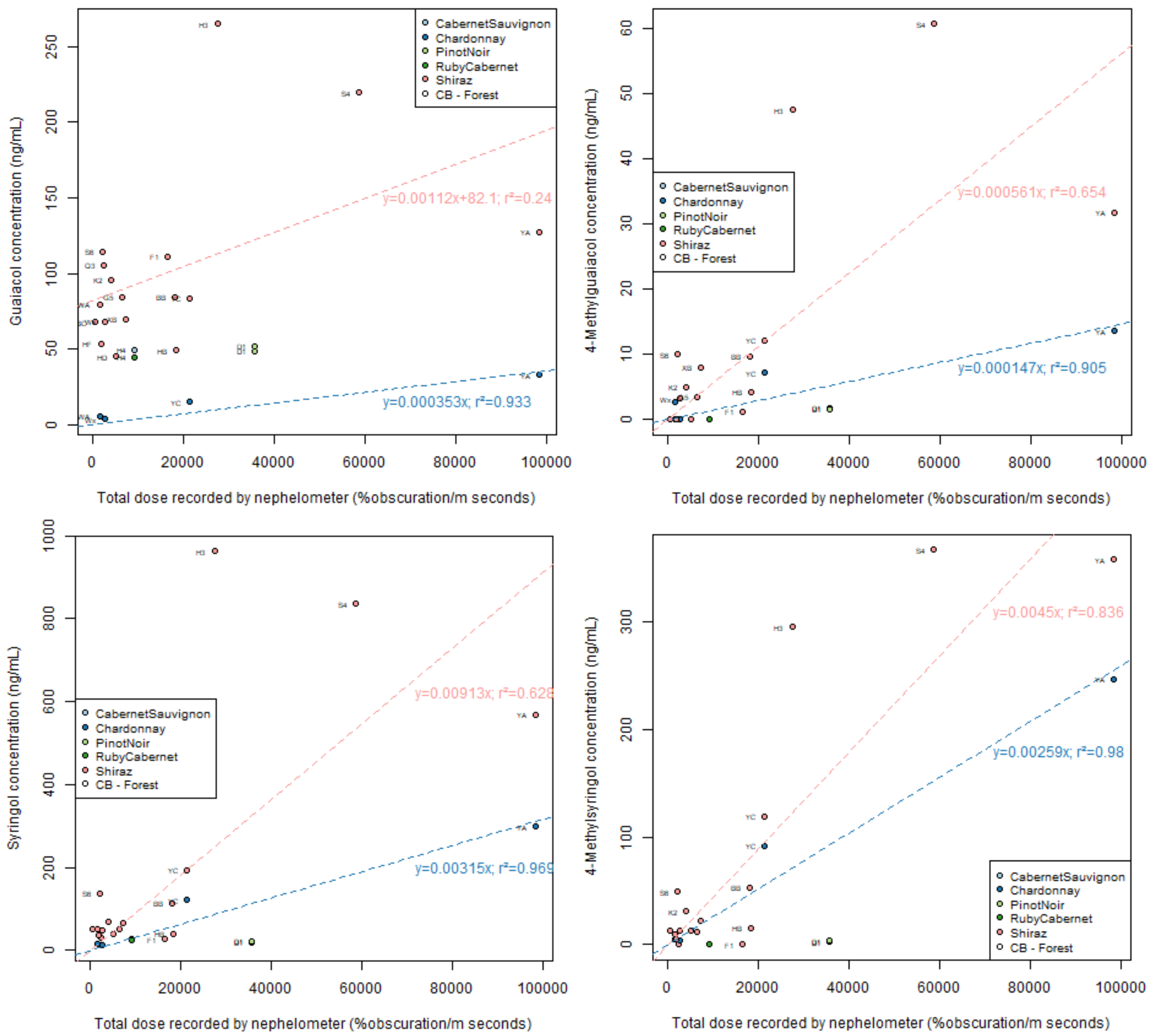

Figure 10: Relationship between the concentration of smoke taint compounds in wines (ng/ml) and the smoke dose (measured by VESDA®) applied to grapes at controlled burns. Linear regression lines for Chardonnay (blue) and Shiraz (orange) shown.

Table 3: Relationship between the concentration of smoke taint compounds in wine (ng/ml) and the smoke dose (measured by VESDA®) applied to Chardonnay and Shiraz grapes at controlled burns.

	Chardonnay		Shiraz	
Compound	**Equation**	**R^2**	**Equation**	**R^2**
Guaiacol	y=0.000353x	0.933	y=0.00112x + 82	0.24
4-Methyguaiacol	y=0.000147x	0.905	y=0.000561x	0.654
Syringol	y=0.00315x	0.969	y=0.00913x	0.628
4-Methylsyringol	y=0.00259x	0.98	y=0.0045x	0.836

Linking smoke dose, smoke composition, grape, wine and sensory data with climatic information to develop thresholds for each parameter

As described above, data collection during the project generated several large databases (Figures 11 and 12) to enable linkage of smoke information with wine levels of phenols and smoke taint, but further sensory data is required to tighten the threshold values. Strong correlations are described in the above sections for linking cumulative smoke dose with phenol levels in wine. This has been made possible by use of an acid hydrolysis method which consistently measures the total phenol levels of the key smoke taint compounds at all stages from smoke through to wine.

Owing to this method, the project was able to establish good correlations in the free forms of the phenols and their bound glycosidic form throughout each stage from smoke, grapes and wine. It is now well-established that in smoke, all phenols exist in a free form (Figure 13) but within 24 hours of entering the grape they are converted to their bound glycosidic forms, as shown below for Shiraz and Chardonnay (Figure 14) and confirmed in this project (Section 3.1.2). Similar trends have been observed for other varieties, showing that grapes are able to convert the majority of free phenols rapidly into the bound glycosidic form and that only low levels of the free form of phenols exist in smoke-affected grapes.

Analysis of wines made from smoke affected grapes showed that fermentation naturally cleaves the bound forms of phenols in grapes and that the level of conversion from bound to free form varies with the type of phenol and the grape variety. For instance, the relative concentration of free to bound guaiacol in wines from a controlled smoking trial conducted over a four-year period was 1:2 for Chardonnay, 1:1 for Shiraz and 2:1 for Cabernet Sauvignon (Allen *et al*, unpublished). This information is important for sensory outcomes and the relationships need to be further clarified with the addition of sensory data collected in future. The same study by Allen et al also showed that after some initial stabilisation of the compounds in wine in the first six months, the bound forms of phenols remained very stable in wines over a four-year period (Allen *et al*, unpublished) and this will assist the development of robust threshold values from smoke, grape and wine data as well as having implications for storage of potentially smoke-affected wines. Recent data from bushfires suggests in young wines this ratio may vary more widely from 1:2 to 1:10 (free to unbound phenol ratio) for recently made vintages depending on variety (Porter *et al.*, unpublished).

ire type	Wind	Distance from burn (km)	Downwind	Grape sample	Grape reading	Variety	Type	Grape chemical composition	Wine made	Wine chemical composition	Wine sensory testing	Taste score (0–5 scale)	Comment
Bushfire	Still - Inversion	0.47	Yes	Yes	Yes	Semillon	On-vine	Yes	Small-scale	Yes	Basic	1	Low taint
Bushfire	Still - Inversion	0.51	Yes	Yes	Yes	Pinot Noir	On-vine	Yes	Small-scale	Yes	Basic	1	Low taint
Bushfire	Still - Inversion	0.63	Yes	Yes	Yes	Prosecco	On-vine	Yes	Small-scale	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.57	Yes	Nearby	Nearby	Chardonnay	On-vine	Yes	Small-scale	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.58	Yes	Nearby	Nearby	Pinot Gris	On-vine	Yes	Small-scale	Yes	Basic	0	No taint
Bushfire	Still - Inversion	1.07	Yes	No	No	Pinot Noir	On-vine	Yes	Small-scale	Yes	Basic	0	No taint
Bushfire	Still - Inversion	1.40	Yes	No	No	Pinot Gris	On-vine	Yes	Small-scale	Yes	Basic	0	No taint
Bushfire	Still - Inversion	1.39	Yes	No	No	Prosecco	On-vine	Yes	Small-scale	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.55	Yes	Yes	Yes	[illegible]	On-vine	No	Commercial	Yes	Basic	1	Slight taint
Bushfire	Still - Inversion	0.79	No	No	No	Riesling	On-vine	No	Commercial	Yes	Basic	<1	Very slight taint
Bushfire	Still - Inversion	0.76	Yes	No	No	Sauvignon Blanc	On-vine	No	Commercial	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.72	Yes?	Nearby	Nearby	Chardonnay	On-vine	No	Commercial	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.93	No	Nearby	Nearby	Pinot Gris	On-vine	No	Commercial	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.72	Yes	Nearby	Nearby	Pinot Gris	On-vine	No	Commercial	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.58	Yes	Yes?	Yes?	Prosecco	On-vine	No	Commercial	Yes	Basic	0	No taint
Bushfire	Still - Inversion	0.53	Yes?	Yes?	Yes?	Pinot Noir	On-vine	No	Commercial	Yes	Basic	<1	Very slight taint
Controlled burn	Low	0.01	Yes	Yes	Yes	Shiraz	Excised bunches	Yes	Small-scale	Yes	Basic	1	Slight taint
Controlled burn	Low	0.15	Yes	Yes	Yes	Shiraz	Excised bunches	Yes	Small-scale	Yes	Basic	2	Low taint
Controlled burn	Low	0.15	Yes	Yes	Yes	Chardonnay	Excised bunches	Yes	Small-scale	Yes	Basic	1	Slight taint
Controlled burn	Low	0.01	Yes	Yes	Yes	Shiraz	Excised bunches	Yes	Small-scale	Yes	Basic	3	Medium taint
Controlled burn	Low	0.01	Yes	Yes	Yes	Chardonnay	Excised bunches	Yes	Small-scale	Yes	Basic	2	Low taint
Controlled burn	Moderate	0.01	Yes	Yes	Yes	Shiraz	Excised bunches	Yes	Small-scale	Yes	Basic	1	Slight taint
Controlled burn	Moderate	0.01	Yes	Yes	Yes	Chardonnay	Excised bunches	Yes	Small-scale	Yes	Basic	<1	Very slight taint
Controlled burn	Moderate	0.09	Yes	Yes	Yes	Shiraz	Excised bunches	Yes	Small-scale	Yes	Basic	0	No taint

Figure 11: Example of data collection: parameters related to wines made from smoke-exposed grapes in autumn 2018

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Trip	Type	Site	Label	Location	Matrix	Variety	Sample_Number	Latitude	Longitude	Vesda	Pump	AvgFlo	Deployed	Retrieved	Duration	Distance	Dosegt01 D
2	Lysterfield	Controlled burn	L3	A3a	Lysterfield, 50m from burn area, north side of Wellington RD	Tenax	None	17-00645-0001	-37.93889785	145.315356	NEW1	AES1	99.4	2017-03-10 14:00:11	2017-03-10 16:01:11	2.02	0.05	1.440
3	Lysterfield	Controlled burn	L4	A4a	Lysterfield, 100m from burn area, north side of Wellington RD	Tenax	None	17-00645-0002	-37.93858948	145.3158177	NEW2	S/N 10	105.3	2017-03-10 13:48:23	2017-03-10 16:00:23	2.20	0.1	1.200
4	Lysterfield	Controlled burn	L5	A5a	Lysterfield, 200m from burn area, north side of Wellington RD	Tenax	None	17-00645-0003	-37.93816234	145.3168173	NEW3	S/N 10	101.7	2017-03-10 14:01:24	2017-03-10 16:00:11	1.98	0.2	13.470
5	Lysterfield	Controlled burn	L2	A2a	Lysterfield, 25m from burn area, South side of Wellington RD	Tenax	None	17-00645-0004	-37.93912819	145.3150884	NEW4	B	105.9	2017-03-10 14:23:25	2017-03-10 16:00:14	1.61	0.025	0.000
6	Lysterfield	Controlled burn	L1	A1a	Lysterfield, in the burn area	Tenax	None	17-00645-0005	-37.940961	145.317743	B	$6 pur	370.2	2017-03-10 15:04:02	2017-03-10 15:29:40	0.43	0.01	4055.31
7	Erica	Bushfire	MorganHill	B3a	Erica. Morgan Hill RD. West of fire. 0.5-1km from fire	Tenax	None	17-00645-0006	-37.94554411	146.3091437	NEW4	T7 anc	100	2017-03-16 18:53:00	2017-03-17 13:14:00	12.83333333	0.75	409.18
8	Erica	Bushfire	BucklesRd	B2a	Erica. Buckles Rd. 0.5-1 km from fire	Tenax	None	17-00645-0007	-37.94892672	146.3269679	NEW3	T6	100	2017-03-16 19:27:00	2017-03-17 07:05:00	11.63333333	0.75	1169.22
9	Erica	Bushfire	LOG	B1a	Erica. next to Smouldering LOG. 1-1.5 m away from fire	Tenax	None	17-00645-0008	-37.94754135	146.3130217	NEW2	T2	100	2017-03-17 11:04:24	2017-03-17 12:58:13	1.896944443	0.001	2360.14
10	Little River	Controlled burn	LR1	C1a	Little River, Bulban Rd, Approx 15 min, directly at fire (smouldering bull grass or sticks)	Tenax	None	17-00645-0009	NA	NA	B	T7	100	2017-03-24 13:16:20	2017-03-24 13:28:51	0.20861111	0.005	2163.41
11	Little River	Controlled burn	LR2	C2a	Little River, Bulban Rd, Approx 40 min, 2 to 10m downwind of fire	Tenax	None	17-00645-0010	-37.927849	144.543216	NEW1	E	100	2017-03-24 11:14:21	2017-03-24 11:54:21	0.666666667	0.005	6779.92
12	Little River	Controlled burn	LR1	C1b	Little River, Bulban Rd, Approx 15 min, directly at fire (smouldering bull grass or sticks)	Tenax	None	17-00645-0011	NA	NA	B	T7	100	2017-03-24 13:39:00	2017-03-24 13:54:54	0.265000001	0.005	5915.01
13	Little River	Controlled burn	LR3	C3a	Little River, Bulban Rd, Approx 2.5 hours, 5 to 30m downwind of fire	Tenax	None	17-00645-0012	NA	NA	NEW1	E	100	2017-03-24 12:00:21	2017-03-24 14:20:02	2.328055555	0.01	5791.53
14	Little River	Controlled burn	LR4	C4a	Little River, Bulban Rd, Approx 3.0 hours, 30 to 100m downwind of fire (which had movec	Tenax	None	17-00645-0013	NA	NA	NEW4	T6	100	2017-03-24 11:33:01	2017-03-24 14:49:50	3.280277777	0.05	3005.44
15	Little River	Controlled burn	LR5	C5a	Little River, Bulban Rd, Approx 3.5 hours, 50 to 200m downwind of fire (which had moved	Tenax	None	17-00645-0014	NA	NA	NEW3	D	100	2017-03-24 11:08:48	2017-03-24 14:56:37	3.796944447	0.1	300.36
16	Little River	Controlled burn	LR6	C6a	Little River, Bulban Rd, Approx 3.5 hours, 100 to 250m downwind of fire (which had move	Tenax	None	17-00645-0015	NA	NA	NEW2	G	100	2017-03-24 11:09:55	2017-03-24 14:57:44	3.796944444	0.2	612.37
17	Jamieson	Controlled burn	Mt Terrible	D1a	Mt Terrible Vineyard at school hill started 11:15am on 1/04/2017 for 24hr	Tenax	None	17-00645-0016	-37.294176	146.161398	E	CH-D	104	2017-03-29 16:00:00	2017-04-01 11:10:00	67.16666667	1.8	561
18	Jamieson	Controlled burn	Mt Terrible	D1b	Mt Terrible Vineyard 8:55am to 11:15am on 2/04/2017	Tenax	None	17-00645-0017	-37.294176	146.161398	E dayli	CH-D	104	2017-04-01 11:10:00	2017-04-02 08:50:00	21.66666667	2.5	3631.63
19	Jamieson	Controlled burn	Mt Terrible	D1c	Mt Terrible vineyard 9:05am 2/04/2017 to 17:00 5/04/2017	Tenax	None	17-00645-0018	-37.294176	146.161398	E	CH-D	100	2017-04-02 09:00:00	2017-04-05 17:00:00	80.000	2.5	18422.1
20	GDRbushfires	Bushfire	EdiUpper	E1a	EDI Upper 30/03/2017 to 14/04/2017	Tenax	None	17-00645-0019	-36.740523	146.466472	Edi Upper		100	2017-03-30 00:00:00	2017-04-14 00:00:00	360.000	53	289.07
21	GDRbushfires	Bushfire	EdiUpper	E1b	EDI Upper 14/04/2017 to 20/04/2017	Tenax	None	17-00645-0020	-36.740523	146.466472	Edi Upper		100	2017-04-14 00:00:00	2017-04-20 00:00:00	144.000	28	2942.4
22	Jamieson	Controlled burn	PointB	D2a	Jamieson burn Point B from 4:25pm 1/04/2017 to 7:50am 2/04/2017	Tenax	None	17-00645-0021	-37.308203	146.15126	NEW2		112	2017-04-01 16:21:00	2017-04-02 07:53:00	15.53333333	0.65	4615.08
23	Jamieson	Controlled burn	FireFront	D3a	Jamieson burn at fire front 6:50pm to 7:05pm 1/04/2017	Tenax	None	17-00645-0022	-37.310932	146.143474	NEW4		99.9	2017-04-01 18:50:53	2017-04-01 19:06:44	0.264166666	0.001	3565.3
24	Jamieson	Controlled burn	FireFront	D3b	Jamieson burn at fire front 7:10pm to 7:25pm 1/04/2017	Tenax	None	17-00645-0023	-37.310932	146.143474	NEW4		99.9	2017-04-01 19:10:35	2017-04-01 19:20:35	0.166666665	0.001	15611.2
25	Jamieson	Controlled burn	C	D4a	Jamieson burn 1-1.5km from fire 50 minute ???, 1/04/2017	Tenax	None	17-00645-0024	-37.297357	146.16086	NEW5		103.1	2017-04-01 21:51:19	2017-04-02 08:39:09	10.79722222	1.25	1451.92
26	Jamieson	Controlled burn	D	D5a	Jamieson burn 1km from fire 11hr 42min (21:50-8:35am), 1/04/2017	Tenax	None	17-00645-0025	-37.303907	146.15401	NEW4		99.9	2017-04-01 21:35:09	2017-04-02 08:12:07	10.61611111	1	2238.16
27	Jamieson	Controlled burn	SchoolHill	D6a	Jamieson burn School Hill second day 13:12-22:15, 1/04/2017	Tenax	None	17-00645-0026	-37.295441	146.140291	B		100.9	2017-04-01 20:03:02	2017-04-01 22:14:50	2.196666667	0.001	15222.4
28	Jamieson	Controlled burn	SchoolHill	D7a	Jamieson burn School Hill fresh smoke 14:30-22:45, 1/04/2017	Tenax	None	17-00645-0027	-37.294895	146.137778	NEW6		114.8	2017-04-01 14:30:45	2017-04-01 22:42:44	8.199722222	0.03	10653.1
29	Jamieson	Controlled burn	Will	D8a	Jamieson burn Malcolm Will property at 512 Licola Road from 3:40pm to 7:00am, 1/04/2(	Tenax	None	17-00645-0028	-37.294509	146.1876	NEW3		102.8	2017-04-01 15:27:35	2017-04-02 06:46:22	15.31305556	1.7	3919.43
30	GDRbushfires	Bushfire	EdiUpper	E1c	EDI Upper 20/04/2017 to 27/04/2017	Tenax	None	17-00645-0029	-36.740523	146.466472	Edi Upper		100	2017-04-20 00:00:00	2017-04-27 00:00:00	168.000	19	595.79
31	GDRbushfires	Bushfire	EdiUpper	E1d	EDI Upper 27/04/2017 to 17/05/2017	Tenax	None	17-00645-0030	-36.740523	146.466472	Edi Upper		100	2017-04-27 00:00:00	2017-05-17 00:00:00	480.000	NA	1688.23
32	Tawonga South	Controlled burn	Annapurna	F1b	Annapurna Estate 7:15pm on 4/04/2017 to 9:15am 7/04/2017 VESDA-New3, CH-A (62h*60=:	Tenax	None	17-00645-0032	-36.7525	147.1477777	NEW3	CH-A	110	2017-04-04 19:15:19	2017-04-07 09:15:50	62.00861111	2	17359.3
33	Beechworth	Controlled burn	Fighting Gully Roac	H1a	Beechworth Fighting Gully 12:06pm 5/04/2017 to 11:35am 6/04/2017 NEW1 CH-I (1409min)	Tenax	None	17-00645-0033	-36.4058333	146.6769444	NEW1	CH-I	118.9	2017-04-05 12:06:51	2017-04-06 11:35:46	23.48194445	0.8	992.27
34	Beechworth	Controlled burn	Smith	H6a	Smith Smith 13:05pm 5/04/2017 to 10:00am 6/04/2017 NEW2 CH-J (1255min)	Tenax	None	17-00645-0034	-36.3802777	146.6705555	NEW2	CH-J	107.2	2017-04-05 13:05:41	2017-04-06 10:00:38	20.91583333	3.3	266.089
35	Beechworth	Controlled burn	Library Rd Gate	H5a	Beechworth Library Rd front gate drive way 15:29pm 5/04/2017 to 11:00am 6/04/2017 NEW	Tenax	None	17-00645-0035	-36.3963888	146.6794444	NEW4	CH-K	104.3	2017-04-05 15:29:13	2017-04-06 11:00:10	19.51583333	0.5	185.04
36	Beechworth	Controlled burn	Library Rd House	H4a	Beechworth Library Rd front house 16:06pm 5/04/2017 to 10:40am 6/04/2017 NEW5 CHT-1(	Tenax	None	17-00645-0036	-36.3977777	146.6802777	NEW5	CHT-1	94.85	2017-04-05 16:06:48	2017-04-06 10:40:45	18.56583333	0.03	9285.68
37	Beechworth	Controlled burn	Baarmutha	H2a	Beechworth Baarmutha from 17:55pm on 5/04/2017 to 9:47am 6/04/2017 NEW6 T7 (952mir	Tenax	None	17-00645-0038	-36.4019444	146.6516666	NEW6	T7	122	2017-04-05 17:55:09	2017-04-06 09:47:06	15.86583333	2.5	677.968
38	Beechworth	Controlled burn	B.Wine Estate	H3a	Beechworth Wine estate at 19:45pm on 5/04/2017 to 8:50am 6/04/2017 V-B T-6(1min on tv	Tenax	None	17-00645-0039	-36.3977777	146.6541666	B	T6	**33.53**	2017-04-05 21:56:08	2017-04-06 07:35:13	9.651388889	2.4	4942.55
39	Beechworth	Controlled burn	B.Wine Estate	H3b	Beechworth Wine estate at 9:05am 6/04/2017 to 10:16am 7/04/2017V-B T-6(1min on 3 mir	Tenax	None	17-00645-0040	-36.3977777	146.6541666	B	T1	**25.15**	2017-04-06 09:05:10	2017-04-07 10:16:22	25.18666667	2.4	734.689
40	Beechworth	Controlled burn	Baarmutha	H2b	Beechworth Baarmutha from 9:47am 6/04/2017 to13:46pm 7/04/2017 NEW6 T7 (1679min)	Tenax	None	17-00645-0041	-36.4019444	146.6516666	NEW6	T7	122	2017-04-06 09:47:06	2017-04-07 17:32:55	31.76361111	2.5	0.66
41	Beechworth	Controlled burn	Smith	H6b	Smith Smith 10:00am 6/04/2017 to 13:00pm 7/04/2017 NEW2 CH-J (1620min)	Tenax	None	17-00645-0042	-36.3802777	146.6705555	NEW2	CH-J	107.2	2017-04-06 10:00:38	2017-04-07 13:00:34	26.99888889	3.3	0
42	Beechworth	Controlled burn	Library Rd House	H4b	Beechworth Library Rd front house 10:45am 6/04/2017 to 14:17pm 7/04/2017 NEW5 CHT-1(	Tenax	None	17-00645-0043	-36.3977777	146.6802777	NEW5	CHT-1	94.85	2017-04-06 10:45:45	2017-04-07 17:24:46	30.65027778	0.03	3446.94
43	Beechworth	Controlled burn	Library Rd Gate	H5b	Beechworth Library Rd front gate drive way 11:00am 6/04/2017 to 14:30pm 7/04/2017 NEW	Tenax	None	17-00645-0045	-36.3963888	146.6794444	NEW4	CH-K	104.3	2017-04-06 11:01:10	2017-04-07 14:30:05	27.48194444	0.5	57.18
44	Beechworth	Controlled burn	Fighting Gully Roac	H1b	Beechworth Fighting Gully 11:40am 6/04/2017 to 14:04pm 7/04/2017 NEW1 CH-I (1584min)	Tenax	None	17-00645-0046	-36.4058333	146.6769444	NEW1	CH-I	134.2	2017-04-06 11:40:46	2017-04-07 14:04:04	26.38833333	0.8	181.114
45	GDRbushfires	Bushfire	Porepunkah	P1a	Dalbosca's shed started 30/03/2017?? to 16:00pm 6/04/2017	Tenax	None	17-00645-0047	-36.708095	146.902521			95.6	2017-03-30 00:00:00	2017-04-06 16:00:00	184	5	280
46	GDRbushfires	Bushfire	Porepunkah	P1b	Dalbosca's shed started 16:00pm 6/04/2017 to 8:50am 19/04/2017	Tenax	None	17-00645-0048	-36.708095	146.902521			95.6	2017-04-06 16:00:00	2017-04-19 08:50:00	305	24	1164.7
47	Tawonga South	Controlled burn	Annapurna	F1c	Annapurna Estate 9:20am on 7/04/2017 to 10:06pm 8/04/2017	Tenax	None	17-00645-0049	-36.7525	147.1477777	NEW3	CH-A	100	2017-04-07 09:20:50	2017-04-08 22:06:45	36.76527778	2	24963.9
48	Tawonga South	Controlled burn	Annapurna	F1a	Annapurna Estate?? 2/04/2017 to 7:15pm 4/04/2017 VESDA NEW3 CH-A	Tenax	None	17-00645-0050	-36.7525	147.1477777	NEW3	CH-A	100	2017-04-02 11:23:00	2017-04-04 17:15:00	53.86666667	3	431.88

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Figure 12: Example of data collection: extract from a database linking smoke grape and wine parameters from four years of studies on controlled burns and bushfires (i.e. type of burn,

distance from fire, location, smoke dose as determined by Tenax® , grape and wine concentration of phenols (data not shown)).

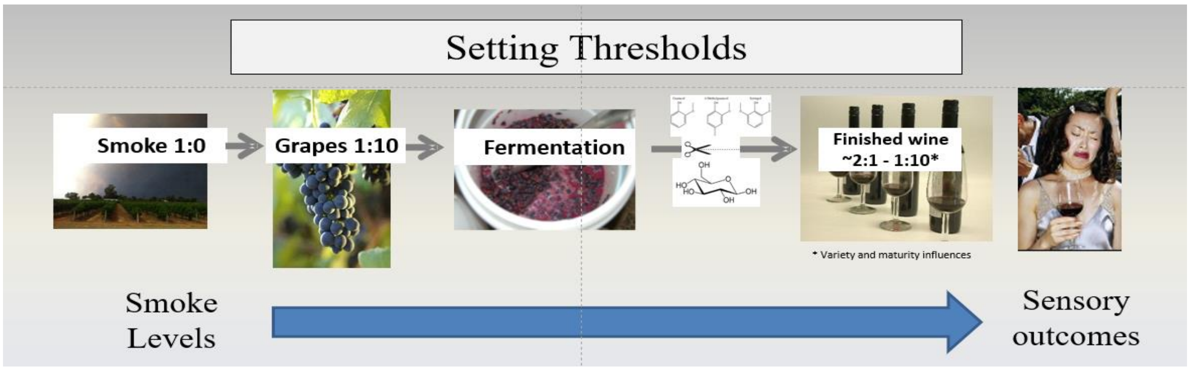

Figure 13: Relative relationship of free to bound forms of phenols extracted using acid hydrolysis methods to measure total phenols in smoke, grapes and wine.

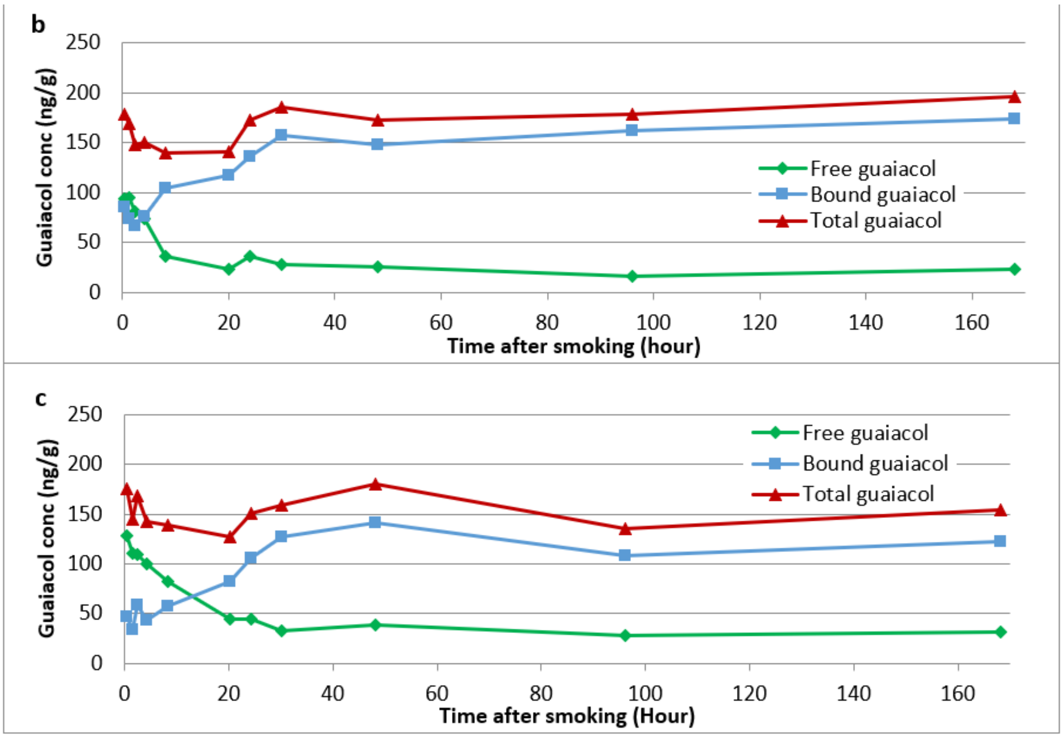

Figure 14: Conversion of free to bound forms of guaiacol (a key smoke taint phenol) in b) Shiraz and c) Chardonnay, extracted using acid hydrolysis (Allen et al, 2013)

Effect of fuel type

The effect of fuel type on the composition of smoke emitted from controlled burns is documented in the Technical Report, *Impact of distance and fuel source on the profile of smoke taint compounds*, attached in the Appendix, section 8.1. Briefly, the profile of the smoke taint compounds emitted from a fire reflects the chemical composition of the lignin contained within the fuel. Grasses emitted higher levels of phenol derivatives followed by guaiacyl derivatives and low levels of syringyl derivatives, whereas hardwood tree species emitted high levels of syringyl derivatives, followed by guaiacol derivatives and low levels of phenol derivatives. The levels of these compounds in wines was shown to follow a similar pattern to smoke levels.

Effect of distance from a fire

The Technical Report, *Impact of distance and fuel source on the profile of smoke taint compounds*, also shows the effect of distance on the profile of these compounds, with the concentration of all compounds decreasing exponentially with distance from fires, as would be expected due to dilution of the smoke with the surrounding clean air. The relative rate of decline in the concentration of the smoke taint compounds also indicated that degradation processes were occurring, with the larger, more heavily substituted compounds such as syringol and 4-methylsyringol reducing in concentration more quickly than the less heavily substituted compounds such as phenol and guaiacol. These findings are consistent with the work of Lauraguais et al. (2015) and Lauraguais et al. (2016) whose studies showed syringol to degrade more quickly than guaiacol in controlled experiments simulating the atmospheric degradation of methoxylated phenols.

Principal component analysis of the smoke compositional data from our in-field smoke measurements, shown in Figure 15, shows the effect of both fuel type and distance on the percentage composition of the major smoke taint compounds in smoke. Grass burns were shown to generally produce smoke of a distinctly different chemical composition from forest burns and bushfires, primarily due to lower levels of syringyl derivatives. Smoke measurements within 500 m of controlled burns and bushfires generally showed greater proportions of syringyl derivatives, and measurements greater than 500 m from controlled burns and bushfires generally showed a predominance of phenol and to a lesser extent, cresols and guaiacol, as the syringyl derivatives had degraded in the time taken for the smoke to travel that distance.

These results indicate that the risk of smoke taint decreases rapidly as the smoke ages (has travelled further from a fire) and that the profile of smoke taint compounds taken up by grapes would be expected to contain less syringyl derivatives at greater distances from fires.

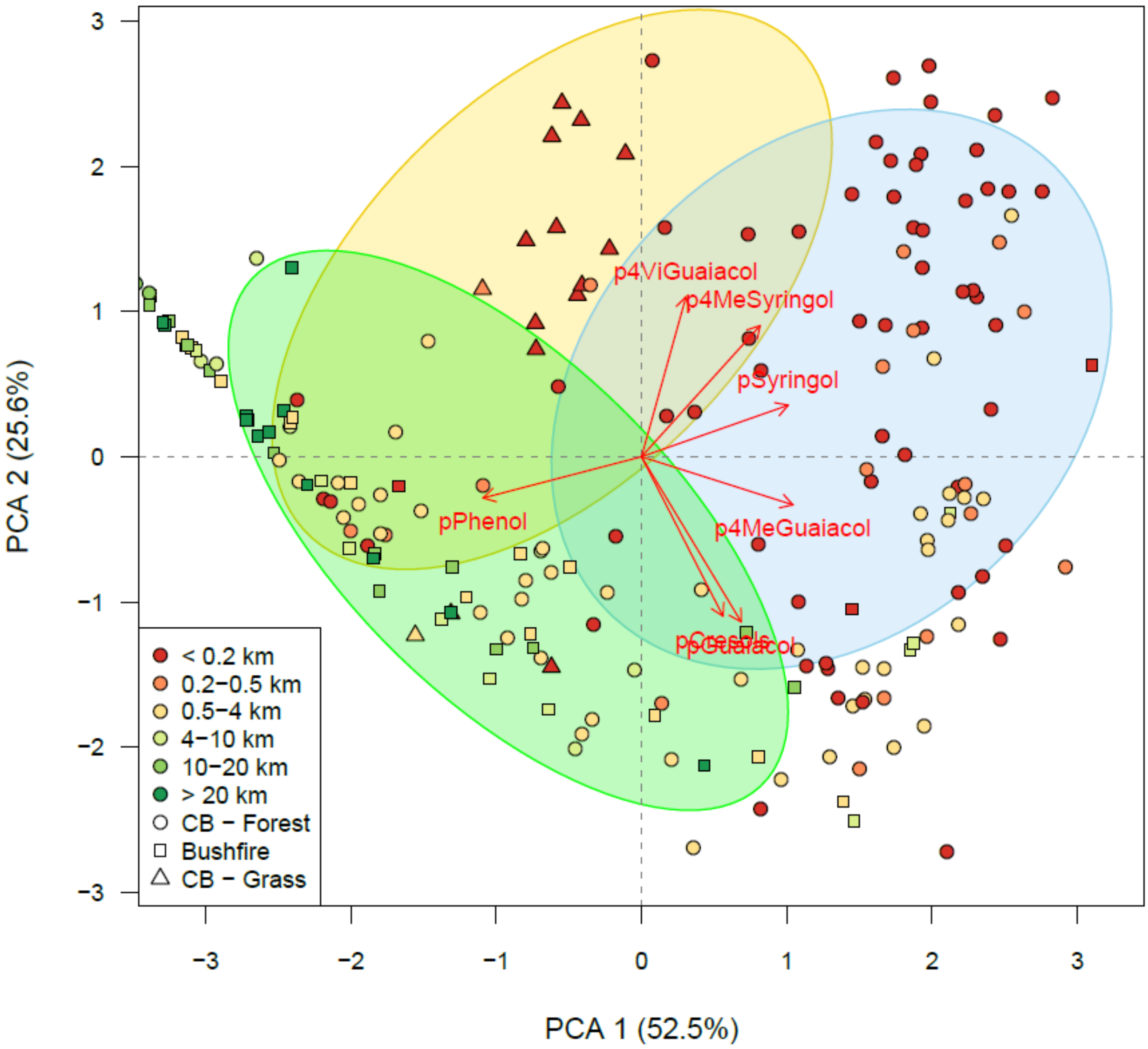

Figure 15: Biplot from principal components analysis of percentage of individual phenolic components (phenol, sum of cresol isomers, guaiacol, 4-methylguaiacol, syringol, 4-methylsyringol and 4-vinylguaiacol) recovered from Tenax® tubes. Ellipses are 90% confidence intervals for i) Forest burn sampled at < 500 m in blue, ii) Grass burn sampled at < 500 m in yellow and iii) Burns sampled at ≥ 500 m in green.

3.1.2 Vineyard mitigation options (output B5)

These results have been documented in the technical report, *Barrier compounds to prevent the uptake of smoke taint compounds by grapes,* attached in the Appendix, section 8.1.

An effective coating for grapes was found — chitosan — which is a biopolymer sourced from fungi or the shells of crustaceans. Chitosan was applied to grapes as an aqueous solution and was found to reduce the uptake of smoke taint compounds by 30 – 60% during controlled experiments where grapes were exposed to very high concentrations of smoke for a period of one hour in a smoking chamber. A field experiment was conducted in March 2019 in collaboration with AWRI using excised bunches of Shiraz grapes. Both uncoated and chitosan-coated bunches were smoked in duplicate, and the grapes were made into wine by AWRI. A similar reduction in the uptake of the smoke taint compounds was achieved as in smoking chamber experiments, and informal tasting of the wines has shown a noticeable decrease in the perception of taint in the wine made from chitosan-coated grapes.

Chitosan sourced from the fungus, *Aspergillus niger*, is currently an allowed product for use in winemaking in Australia. It is important to note that not all chitosan products displayed the same efficacy, some did not work at all, and we do not know at this stage which properties of the chitosan polymer enable its ability to prevent the uptake of smoke taint compounds.

Another important finding of this work is that other coating products such as commercially available anti-transpirants and sunburn protectants had the effect of increasing, in some cases by greater than 50%, the uptake of smoke taint compounds by grapes, so it is very important that growers avoid using these products when there is the risk of smoke exposure.

Investigations also showed that grapes are able to rapidly convert the smoke taint compounds to their glycoconjugates, with this process generally complete within a day of smoking. Since the compounds must first be absorbed by the grapes before glycoconjugation can take place, this implies the bulk of the smoke taint compounds have been absorbed within a day. Therefore, any attempt to wash the compounds from the grapes after this time would be unlikely to have any significant effect, and this was confirmed in laboratory experiments.

3.1.3 Other relevant studies

Effect of grape maturity on smoke taint uptake

Excised bunches of Chardonnay and Merlot grapes were harvested from a vineyard in the Yarra Valley approximately every 2 – 3 weeks from 18 December 2018 until 14 March 2019. Each harvest of excised bunches was smoked the day after harvest, except for the first harvest which was smoked 4 days after harvest. Analysis of the grapes showed the younger Chardonnay berries (E-L 27-34) to absorb up to 5 times the amount of smoke taint compounds per berry, relative to smoke concentrations, than more mature grapes (E-L ≥ 35) whereas Merlot showed a more uniform uptake per berry as they matured, as shown in Figure 16. It should be noted that these younger grapes had very little extractable juice, so our extraction procedure was modified to accommodate this, and it is unclear at present whether this contributed to the higher results for these samples or if the skins of the younger grapes are more permeable to smoke taint compounds.

A significant reduction in uptake at veraison (E-L 35) for both varieties suggests a physiological change in the grapes may have reduced their susceptibility to smoke taint compounds at this point, after which there appeared to be a general increase in uptake until harvest, which could be due to the grape skins becoming thinner and therefore more permeable. Our findings are in opposition to those of Kennison et al. (2011), who found the smoke taint susceptibility of Merlot grapes to peak seven days after veraison and then stay relatively constant until harvest. It is worth noting that Kennison's work did not measure the concentration of smoke taint compounds in the smoke applied to the grapes, and our past work has shown that the concentration can vary significantly due to changes in air temperature and fire intensity (Porter et al., 2015). Further, the 2011 study only analysed the wine for free guaiacol and 4-methylguaiacol, as analytical methods for the other smoke taint compounds, and their glycosylated forms, had not yet been developed. This means the bound smoke taint compounds, which can be a significant pool of smoke taint compounds within a wine, were not accounted for. Our results, and the advances in grape and wine analysis since Kennison's work was undertaken, suggest that the effect of grape maturity on the relative uptake of smoke taint compounds should be reassessed.

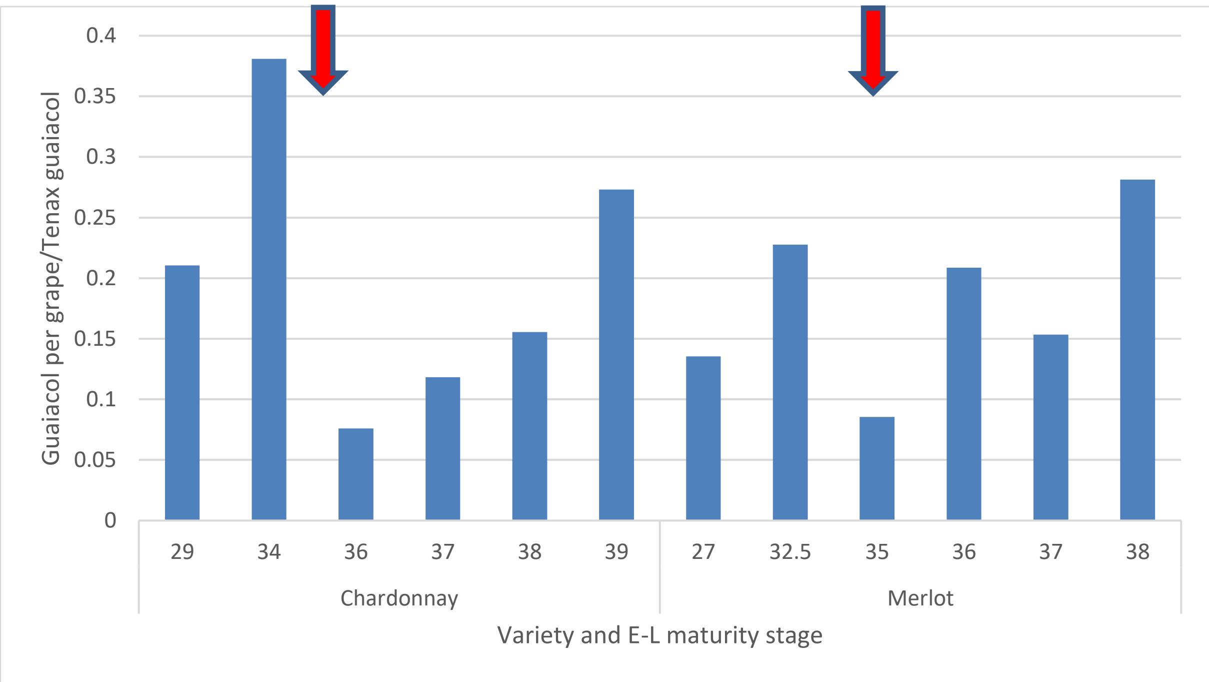

Figure 16: Plot of grape total guaiacol (ng) per grape, relative to grape guaiacol exposure (ng of guaiacol captured on Tenax® tube) for Chardonnay and Merlot grapes at varying E-L maturity stages. Arrows indicate stage 3.5 or veraison.

3.2 Contribution to program objectives

Our project achievements contribute to the achievement of the overall program by generating knowledge, technologies and products which benefit primary producers through reductions in losses and down-grading of grapes following smoke events. Our in-field smoke measurements along with corresponding grape and wine measurements have shown the utility of smoke measurements for the identification of smoke taint risk in wine. The established relationships between measurements of smoke dose and smoke composition with the levels of smoke taint compounds in wines will benefit industry once a more comprehensive network of smoke detectors is established, or if producers choose to install their own smoke detectors. This will enable growers to quickly make informed decisions following smoke events, will make marketing of grapes from areas where low level (insignificant) smoke events have occurred easier and more objective, and will enable informed decisions by winemakers at harvest, where the smoke taint status of grapes may be pending the results from grape analysis. Such a network may also benefit producers by allowing land managers such as Forest Fire Management Victoria to monitor the spread of smoke and risk of smoke taint from controlled burns in real-time.

Our work identified the biopolymer chitosan that can be coated on grapes to reduce the uptake of smoke taint compounds. With further development, chitosan may enable producers to protect their vineyards from smoke taint during smoke events.

3.3 Productivity and profitability

An analysis was performed by a DJPR economist, estimating the benefit/cost ratio of implementing an industry-wide smoke detector network, with the implementation of a protective spray where smoke levels pose a sufficiently high risk of smoke taint. The benefit/cost analysis has been calculated for the farm-gate value of premium wine grapes, over a 30-year period, with results expressed in present value terms. The benefit/cost analysis (spreadsheet) appears in the attachments, and indicates a potential benefit/cost ratio of 3.6. In other words, for every $1.00 invested, this component of the project would return $3.60 of value to the sector by reducing the incidence of smoke taint. The analysis demonstrates the outcomes and benefits that have emerged or are likely to emerge from investment in this project and that outcomes of this project, if implemented by producers, would have a significant long-term benefit.

This analysis has assumed that the protective grape coating tested in this project could be further developed to enable effective implementation by spraying in-field. All other assumptions were documented in the report.

4 Collaboration

La Trobe University (via Dr Ian Porter) was our major collaborator during this project as Dr Porter shifted employment from DJPR (then DEDJTR) to La Trobe University during the project but maintained his role as project leader. This collaboration covered all aspects of project delivery, except for personal management of DJPR staff and laboratory activities. Dr Porter performed the vast majority of extension duties, with significant input from DJPR in terms of analytical results and interpretation of results.

AWRI was the other formal collaborator during this project, via yearly project update meetings, reference group meetings and industry forums. In particular, Dr Krstic's facilitation skills and stature within the wine industry have made him a valuable collaborator throughout this project, particularly in extension.

It was also planned within the project for AWRI to evaluate and provide additional suitable grape coatings from their own experiments to prevent or reduce the uptake of smoke taint compounds, which DJPR/La Trobe would then trial in-field. AWRI screened a large number of commercially available coating products, with similar results to DJPR/La Trobe, in that an effective commercially available coating product could not be found. A suggestion to DJPR/La Trobe from Melbourne University then led to evaluation of biopolymers and we subsequently identified chitosan as an effective coating compound.

This project also relied heavily on collaboration with Forest Fire Management Victoria right throughout Victoria. The project networked with staff in all key controlled burn regions daily during the season. Incident controllers at burns were always notified and kindly allowed us into controlled burn sites so that we could conduct our measurements. All project staff attending burns had the appropriate PPE and had been trained in all safety and operational aspects of dealing with burns.

5 Extension and adoption activities

Media, communication, extension and other activities were:

- Porter, I. Presentation to the Statewide Stakeholders for Fire and Land Management, 2 June 2016.
- Ian Porter, Meetings with CSIRO re modelling (Dr Martin Cope and Team).
- Ian Porter, Presentation to Yarra Valley Growers, 15 September 2016.
- Ian Porter, Presentation to the North East Growers, 29 November 2016.
- Ian Porter, Tim Plozza, Pei Zhang, Joanne Bui. Presentation of results at a national DAWR project planning meeting, 13 December 2016.
- Ian Porter, Porter, I. Statewide Industry Forum Presentation, 14 December 2016.
- Smoke Taint Team, Project Review Meeting with AWRI researchers and AGWA Program Managers (Keith Hayes and Sharon Harvey).
- Ian Porter, Presentation to the Victorian Wine Industry and Fire Planning Officers at Brown Brothers, Milawa Vineyard, 9th February 2017.
- Ian Porter, Interview by Mansfield Press, 14 April 2017.
- Tim Plozza, Overview of the smoke taint program to DEDJTR Deputy Secretary, Macleod, March 2017.
- Ian Porter and Tim Plozza - Video on industry engagement with Grigg media and DELWP Fire Managers.
- Ian Porter and Tim Plozza, Smoke Taint Project Team Meeting with AWRI researchers and AGWA Program Manager (Sharon Harvey), Adelaide, 13 Sep 2017.
- Ian Porter, Presentation to DELWP senior management including Deputy Chief Fire Officer, Nicholson St, Melbourne, 4 Dec 2017.
- Ian Porter, Presentation to Wine Victoria and DELWP Bushfire Management Forum 2017, Collins St, Melbourne, 14 Dec 2017.
- Ian Porter and Tim Plozza, Presentation and discussions with DELWP Forest Fire Management north east Victoria Senior Fuel Management officers, Benalla, 26 Feb 2018.
- Ian Porter, Media interview at bushfire control centre (all main TV channels), 2 March, 2018.
- Ian Porter, DELWP internal communication about the project, June 2018.
- Ian Porter, Ad hoc presentations to regional DELWP staff at controlled burns, autumn 2018.
- Ian Porter, Macedon Ranges Vignerons Association Forum, Lancefield, 27 June 2018.
- Tim Plozza, AgriBio seminar, DEDJTR Bundoora, 29 June 2018.
- Ian Porter and Tim Plozza, Smoke Taint Project Team Meeting with AWRI researchers, Adelaide, 22 October 2018.
- Ian Porter, Victorian Fire Management and Wine Industry Forum, Lonsdale St, Melbourne, 31 October 2018.
- Ian Porter, Information session for EPA air monitoring group, Macleod, 22 November 2018.
- Mark Smith, Smoke taint a hot topic for vineyards, Tasmanian Times, 13 Feb 2019.
- Ian Porter, Interview with ABC Radio Hobart, 5 Feb 2019.
- Ian Porter, Presentation to DELWP Fuel Management Steering Committee, 8 Nicholson St, Melbourne, 9 May 2019.

- Ian Porter, Tim Plozza, Pei Zhang, Joanne Bui, David Allen. New early warning system and vineyard mitigation of smoke taint in wine. Poster presentation, Australian Wine Industry Technical Conference, Adelaide, 21-24 July 2019.
- Ian Porter, DELWP/Wine Victoria Planned Burn Forum, Victoria St, Melbourne, 17 October 2019.
- Ian Porter, Overcoming smoke taint, the biggest threat to the Australian wine industry, AgriBio Science Conference, DJPR Bundoora, 19 November 2019.
- Ian Porter, Presentation to Hunter Valley vignerons, Pokolbin, 19 November 2019.
- Ian Porter, Presentation to North East vignerons, 15 January 2020
- Ian Porter, Presentation to the Mornington vignerons, 17 January 2020

6 Lessons learnt

Linking smoke dose and composition to grape and wine data was very effective, however obtaining wines which exhibited suitable levels of sensory taint was challenging. This was because it took much more smoke from controlled burns and bushfires than we initially thought to cause sensory detectable smoke taint in wines. The elevation in smoke taint compounds in these wines was easily detectable by chemical analysis, however it became apparent that a much greater smoke dose was required to cause sensory smoke taint.

The first season's wines were made from grapes exposed to smoke from controlled burns up to several kilometres away, as the effect of distance on the concentration of smoke taint compounds in smoke was not fully understood at that stage. These experiments were very successful at showing how low smoke dose, combined with distance from the fire, duration of exposure and the dynamic nature of the smoke plume, does not produce taint. The early resultant wines therefore had little or no smoke taint. In subsequent seasons, we became more adept at choosing locations to smoke grapes, which were in general very close to burns or at bushfires in order to ensure a sufficient dose of smoke to cause sensory taint and provide useful data.

Issues with storing excised bunches for longer periods than anticipated, i.e. up to two months prior to smoking meant that, even though the grapes were still able to take up taint compounds after this period, they had often begun to degrade, resulting in inferior quality wine which made the wines unsuitable for sensory testing.

There were also considerable logistical issues throughout the project relating to the need to be sampling at fires in several places concurrently, and the often large distances between sampling locations. Obtaining smoke data to match with samples of grapes and wine from bushfire affected vineyards was also a difficult task due to the delay between a fire starting and the time we could respond to be on site, resulting in the early smoke being missed in some cases. These issues would be resolved or reduced with the implementation of a more extensive smoke detector network, which may reduce the need to always attend such unplanned smoke events.

7 Recommendations

It is recommended that the outcomes of this research be implemented in the form of a smoke taint risk assessment tool for the wine industry. The best way for this to be taken up by industry would be through the development of a publicly available internet website and smartphone app which would inform growers of the smoke taint risk associated with smoke events in their area. This would require the commissioning of a much more comprehensive network of smoke detectors and smoke modelling to predict the smoke levels in-between smoke detectors. Benefits of such an app would include quick access to objective data to help growers make informed decisions following smoke events, easier marketing of grapes from areas where low level (insignificant) smoke events have occurred, and informed decisions by winemakers where the smoke taint status of grapes may be delayed pending the results of grape analysis. Land managers such as Forest Fire Management Victoria would also benefit by being able to access real-time data to monitor the spread of smoke from controlled burns.

The development of technology to allow the real-time measurement of the concentration of smoke taint compounds in air at each smoke detector site would be a useful addition to the smoke detector network described above. We have shown that the composition of smoke changes dramatically as smoke ages, and at present our smoke detector network relies on the measurement of smoke composition using Tenax® tubes to obtain a more accurate estimation of the smoke taint risk posed by the smoke. This requires someone to be present to install a sampling tube, which then needs to be analysed in the laboratory, taking considerable time and expense. The development of a sensor, such as a low-cost electronic nose, to estimate the levels of smoke taint compounds during smoke events could alleviate the need for sampling with Tenax® tubes and allow an instantaneous estimate of smoke composition.

A comprehensive study of the sensory characteristics of smoke affected wines is necessary to assess the effect of differing smoke taint compound profiles within the smoke, grapes and wine, as would be expected from differing fuel sources and at varying distances from fires. This may enable the development of a standardized, objective assessment method for winemakers, who at present rely on their own ability to assess the suitability of smoke affected wines for sale.

Sensorially people vary considerably in their ability to taste smoke taint, and future projects need to place heavy emphasis on sensory testing to link all data collected from smoke events to smoke taint. This also means being able to interpret how grape and wine levels from commercial laboratories relate to smoke taint in wine, as presently the laboratories use different assessment methods, which creates confusion for the grower. Also, owing to the variability in data from commercial laboratories, the difference in wine making techniques and varieties and the liability for incorrect recommendations, it is at present difficult for commercial laboratories to provide accurate interpretation of test results. Providing a system which standardizes results from commercial laboratories and identifies risk on a traffic light system on a public database could improve the prediction of taint throughout the industry.

Further screening of chitosan products and analysis of their chemical properties would allow the identification or development of a chitosan product with optimum properties for the prevention of uptake of smoke taint compounds by grapes. This could also lead to the identification of other coating materials which could have better efficacy, easier application or lower cost than chitosan coatings.

Further work with chitosan application in-field would allow the development of an effective product and application technique which can be used by viticulturists to protect their crops in the event of high risk of smoke exposure of their vineyard. Considerations which need to be taken into account include the ability to apply the product in time (which may depend on notification from the early warning system), a suitable application technique which gives high levels of grape surface coverage with the coating product, and an assessment of the impact of the product on the winemaking process.

A reassessment of the effect of the stage of grape maturity on the relative uptake of smoke taint compounds should also be undertaken, as our results indicate that the uptake of smoke taint compounds pre-veraison may be higher than indicated in previous studies and may be variety dependent. The advances in grape and wine analysis techniques since previous studies, in particular the analysis of bound compounds, would allow a much better understanding of the total amount of smoke taint compounds taken up by the grapes. The DJPR analytical method enables the total uptake of smoke taint compounds to be accurately determined at any stage of maturity, which makes it suitable for this type of study.

8 Appendix - additional project information

8.1 Project, media and communications material and intellectual property

See Section 5 for a list of media, communication, extension and other activities. Additional communications material includes:

- Article: "Where there's smoke there's not necessarily taint". Wine Australia Research Newsletter, March 2017 https://www.wineaustralia.com/news/articles/where-there%e2%80%99s-smoke-there%e2%80%99s-not-necessarily-taint
- Video: "Smoke taint", Grigg Media and DELWP as part of community engagement for the controlled burning program (content relates primarily to a previous project on smoke composition, but Dr Ian Porter and Tim Plozza provided input on the current project). June 2017 https://youtu.be/j0tv67OtLo0
- Article: "Addressing knowledge gaps in smoke taint – the AWRI's new collaborative Rural R&D for Profit project", AWRI Technical Note, April 2017. Technical Review No. 227
- Article: "Looking at smoke is making things clearer", Wine Australia RD&E Newsletter, November 2017 https://www.wineaustralia.com/news/articles/looking-at-smoke-is-making-things-clearer
- Article: "Providing clarity on when smoke can cause taint", Ian Porter, Australian and New Zealand Grapegrower and Winemaker, April 2019
- Article: "Smoke taint concerns spark new smoke research in Tasmania", Australian and New Zealand Grapegrower and Winemaker 663: 43-48, April 2019
- Poster: New early warning system and vineyard mitigation of smoke taint in wine. Ian Porter, Tim Plozza, Pei Zhang, Joanne Bui, David Allen. 17th Australian Wine Industry Technical Conference, Adelaide, 21-24 July 2019
- Fact sheet: "Protocols for fire managers to minimise smoke taint in wine" February 2020 http://www.hin.com.au/__data/assets/pdf_file/0003/164631/Protocols-for-Fire-managers.pdf
- Fact sheet: "Protocols for vineyard managers to minimise smoke taint from prescribed burns" February 2020 http://www.hin.com.au/__data/assets/pdf_file/0020/164630/Protocols-for-Vineyard-managers.pdf

8.2 Equipment and assets

List of all equipment or assets created or acquired during the period covered by the project:

- 5 x SKC AirChek TOUCH air sampling pumps with low flow adaptors
- 6 x Xtralis VESDA® VLF-250 smoke detectors

8.3 References

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Porter, I., R. Kilmister, D. Allen, R. James, T. Plozza, K. M. Pitt, P. Zhang, A. D. Bui, P. Rogers and F. Hancock (2015). Centre for expertise in smoke taint research final report, Department of Economic Development, Jobs, Transport and Resources, Victoria.

Yee, L., K. Kautzman, C. Loza, K. Schilling, M. Coggon, P. Chhabra, M. Chan, A. Chan, S. Hersey and J. Crounse (2013). "Secondary organic aerosol formation from biomass burning intermediates: phenol and methoxyphenols." Atmospheric Chemistry and Physics **13**(16): 8019-8043.

8.4 Staff

La Trobe University: Professor Ian Porter

DJPR: Mr Tim Plozza, Mrs Pei Zhang, Mrs Joanne Bui, Mr David Allen

8.5 Attachments

8.5.1 Technical report: Barrier compounds to prevent the uptake of smoke taint compounds by grapes

8.5.2 Technical report: Impact of distance and fuel source on the profile of smoke taint compounds

8.5.3 Planning and management protocols for land/fire managers to minimise impact on vineyards

8.5.4 Planning and management protocols for vineyard managers to minimise smoke taint from prescribed burns

8.5.5 Cost/benefit analysis of early warning system and application of protective spray

Barrier compounds to prevent the uptake of smoke taint compounds by grapes

Agriculture Victoria Research Technical Report

Author: Tim Plozza, Pei Zhang, Joanne Bui, Ian Porter

Project RDC Number: RRD4P 15-02-033

Project CMI Number: 105639

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Contents

EXECUTIVE SUMMARY

The exposure of vineyards and grapes to smoke from bushfires and/or controlled burn events may result in 'smoke tainted' wine, that can cause serious economic losses to industry. Since 2003, major fire events have affected over $400M worth of grapes and wine that were either rejected commercially or downgraded as a result of smoke taint. The frequency of bushfires and controlled burns is expected to increase under various climate change scenarios, thus it is important that the Australian wine industry develop cost effective remediation tools to manage smoke affected grapes and wine. This collaborative DEDJTR, La Trobe University and AWRI project funded by DAWR and Wine Australia evaluated a range of possible remedial management options and tools for dealing with smoke affected grapes and wine. This Technical Report investigates possible vineyard mitigations strategies, specifically grape coatings to prevent the uptake of smoke taint compounds by grapes.

An effective coating for grapes was found – chitosan – which is a biopolymer sourced from fungi or the shells of crustaceans. Chitosan was applied to grapes as an aqueous solution and was found to reduce the uptake of smoke taint compounds by 30-60% during controlled experiments where grapes were exposed to very high concentrations of smoke for a period of one hour in a smoking chamber. Chitosan sourced from the fungus, *Aspergillus niger*, is currently an allowed product for use as a fining agent in winemaking in Australia, although it is unknown at this stage what effect it has on the winemaking process when used as a grape coating. It is important to note that not all chitosan products displayed the same efficacy, some did not work at all, and we do not know at this stage which parameters of the chitosan polymer confer its ability to prevent the uptake of smoke taint compounds.

Another important finding of this work is that other coating products such as commercially available anti-transpirants and sunburn protectants have the effect of increasing, in some cases by greater than 50%, the uptake of smoke taint compounds by grapes, so it is very important that growers avoid using these products when there is the risk of smoke exposure.

Investigations also showed that absorption of smoke taint compounds by grapes is rapid, generally complete within a day of smoking, meaning any attempt to wash the compounds from the grapes after this time would be unlikely to have any significant effect.

The identification of an effective grape coating to reduce the uptake of smoke taint compounds is an important step in helping grape growers to mitigate the risk of smoke taint damage due to increased frequency of bushfires and controlled burns, providing it can be used cost effectively in the vineyards. Further screening of chitosan products and analysis of their properties would allow the identification or development of a chitosan product with optimum properties for the prevention of uptake of smoke taint compounds by grapes and thus minimize the amount of chemical required. This could also lead to the identification of other coating materials which could have better efficacy, easier application or lower cost than chitosan coatings. Further work with chitosan application in-field could enable the development of an effective product and application technique which can be used by viticulturists to protect their crops in the event of high risk of smoke exposure of their vineyard.

INTRODUCTION

This technical report is a deliverable for the project Mitigation of Climate Change Impacts on the National Wine Industry by Reduction in Losses from Controlled Burns and Wildfires and Improvement in Public Land Management (LTU 3.1851.01). It contributes towards meeting the project objective B5. Vineyard mitigation options. This AVR technical report was prepared in collaboration with our project leader, Professor Ian Porter from La Trobe University.

Project outcome

This project will generate knowledge, innovative technologies and processes that will directly benefit grape growers and wine companies. It will enhance Australia's wine reputation, industry profitability and Australia's competitiveness in global markets. Knowledge generated will contribute to the innovation of process and practices and aid public land management agencies to implement effective planned burn programs with reduced potential for damage for grape and wine producers.

Project background

The exposure of vineyards and grapes to smoke from bushfires and/or controlled burn events may result in 'smoke tainted' wine, that can cause serious economic losses to industry. Since 2003, major fire events have affected over $400M worth of grapes and wine that were either rejected commercially or downgraded as a result of smoke taint. The frequency of bushfires and controlled burns is expected to increase under various climate change scenarios, thus it is important that the Australian wine industry develop cost effective remediation tools to manage smoke affected grapes and wine. This collaborative component of the project (DEDJTR, La Trobe University) aims to evaluate a range of possible remedial management options and tools for dealing with smoke affected grapes and wine. The project will relate the information to critical consumer sensory thresholds of key smoke taint volatile phenols and their associated glycosides in Chardonnay, Pinot Noir and Shiraz (oaked and unoaked) using proven dilution techniques. Once these critical chemical threshold concentrations have been determined for each variety and style, the project through research at AWRI will trial options to remove smoke related free volatile phenols and their associated glycosides from affected wines, or apply treatments that will facilitate the degradation of these free volatile phenols and their glycosides in wines. Through DEDJTR's co-investment vineyard mitigation strategies will be examined for reducing the uptake and concentration of smoke taint compounds in the vine and grapes. The cost of these remediation and mitigation treatments will be carefully evaluated and reported to help industry implement cost-effective solutions in their business.

Project objectives

The objectives of the broader smoke taint project are to:

1. Establish wine quality ratings, sensory thresholds, compositional and flavour profiles and consumer preferences for smoke affected Chardonnay, Pinot Noir and Shiraz wines (oaked and unoaked) using dilution techniques;
2. Evaluate a range of remediation strategies for managing smoke affected fruit and wines in the winery. This objective aims to examine processing options and materials to remediate wines and minimise the loss to final wine quality;
3. Investigate vineyard mitigation options and strategies to identify vineyards at risk from smoke exposure, reduce the uptake of smoke taint compounds in the vine and grapes, and explore options to limit the conversion of free volatile phenols into their more difficult to remove glycosidic/bound forms. This objective aims to explore options viticulturists can implement at short notice to protect fruit from becoming smoke tainted. Options may include the use of anti-transpirants, protective sprays and modulation of glycosidase enzymes. This objective will be funded through DEDJTR co-investment;
4. Economic evaluation of remediation activities undertaken under objectives 2 and 3 above. Objective cost data for the various remediation treatments trialled in objectives 2 and 3 will be assessed by an economist and a process engineer to determine cost effective treatments for implementation.

This technical report addresses part of the aims in 2 and 3 above.

METHOD

A number of options for reducing the impact of smoke exposure on grapes in either controlled smoking trials or at sites around controlled burns were investigated. This included evaluating washing of grapes to remove smoke taint compounds from the surface of the grapes, and coating the grapes with a potentially protective barrier to reduce or prevent the smoke taint compounds from entering the grapes.

Chemicals evaluated

Raynox sunburn protectant and water softener were supplied by Colin Campbell Chemicals (Wetherill Park, Australia)

Vapor Gard was supplied by Agspec Australia (Mt Gambier, Australia)

Triton X-100 was supplied by Mallinkrodt (Lane Cove West, Australia)

Tween 80 was supplied by Sigma-Aldrich (Castle Hill, Australia)

Tween 20 was supplied by Sigma-Aldrich (Castle Hill, Australia)

Chitosan from crab shells was supplied by Sigma-Aldrich (Castle Hill, Australia)

Chitosan made from *Aspergillus Niger* was supplied by ChiBio Biotech Co. Ltd, Qingdao, China

Water soluble chitosan from mushrooms was supplied by ChiBio Biotech Co. Ltd, Qingdao, China

Oenobrett was supplied by LAFFORT® Australia

Fulvex, 4-9-4, and Sea Isolates fulvic and humic acid products were supplied by BioFlora Australia

Analytical grade 100% Acetic acid was supplied by Merck, Australia.

All water used was type 1 (ultrapure), produced by a Milli Q system (Merck)

Grapes

All experimental work was carried out using excised bunches of grapes, which have been shown in previous work to take up smoke taint compounds similarly to bunches on-vine. Australian grown red seedless grapes (*Flame*) were purchased from a local supermarket. Shiraz grapes were purchased from a vineyard in Great Western, Victoria. Chardonnay grapes were purchased from a vineyard in Drysdale, Victoria. All grapes were stored at 4°C and allowed to come to room temperature before the smoking treatment.

Grape coatings

Commercial products used to coat the fruit were prepared according to the manufacturer's directions. All chitosan solutions were prepared by dissolving the chitosan powder in aqueous 1% (v/v) acetic acid, followed by the addition of surfactant, except for water soluble chitosan which dissolved without the addition of acetic acid. Grapes were treated by dipping in solutions of the coating products, then hung up and allowed to dry (Figure 1) before being subjected to smoke in a smoking chamber.

For evaluation in-field in 2018, excised grape bunches were coated in the laboratory with an aqueous solution of 1% (w/v) *Aspergillus* chitosan, 1% (v/v) acetic acid and 0.01% (v/v) Triton X-100 surfactant, hung up to dry, then placed in a sealed plastic box for transport to the controlled burns where they were hung on racks in smoke near the fires.

For evaluation in-field in 2019, freshly excised Shiraz grape bunches were coated in the vineyard with an aqueous solution of 1% (w/v) *Aspergillus* chitosan, 1% (v/v) acetic acid and 0.03% (v/v) Tween 80 surfactant and placed on two racks to dry. These racks were then subjected to replicate smoking treatments in a smoking tent in a side by side comparison with racks of uncoated excised bunches of Shiraz grapes.

Figure 1: Freshly chitosan-coated red seedless grapes (Flame) hung up to dry.

Smoking apparatus

As shown in Figure 2, the smoking apparatus consisted of a burner constructed from a 70 L steel rubbish bin, in which barley or wheat straw were burned and smoke conveyed to a smoking chamber via a one metre length of flexible electrical conduit (20mm diam). An air inlet and smoke outlet were installed in the burner to enable the straw to burn continuously at a relatively constant rate. An adjustable ball valve on the smoke sampling outlet from the burner allowed for adjustment of the amount of smoke transferred to, and hence the concentration of smoke contained within, the smoking chamber. The smoking chamber, shown in Figure 3, consisted of a 120 L rectangular galvanised steel tool box with a wire rack located at mid-level within the box for the placement of grapes. The smoke inlet to the smoking chamber was located lower down at one end, and a 6.8 W fan placed in front of the inlet to draw smoke into, and circulated it around, the chamber.

For evaluation of grape coatings in-field in 2019, a similar arrangement was used except the smoking chamber was replaced by a tent, and three portable fans used to circulate the smoke around the tent to ensure uniform smoke density. Grape bunches were placed on wire racks approximately 80 cm above the floor of the tent, which allowed for good circulation of smoke within the tent.

Figure 2: Smoking apparatus showing the burner (far right), smoking chamber (steel box), smoke detector (to the left of the smoking chamber), and computer for monitoring smoke levels in real time.

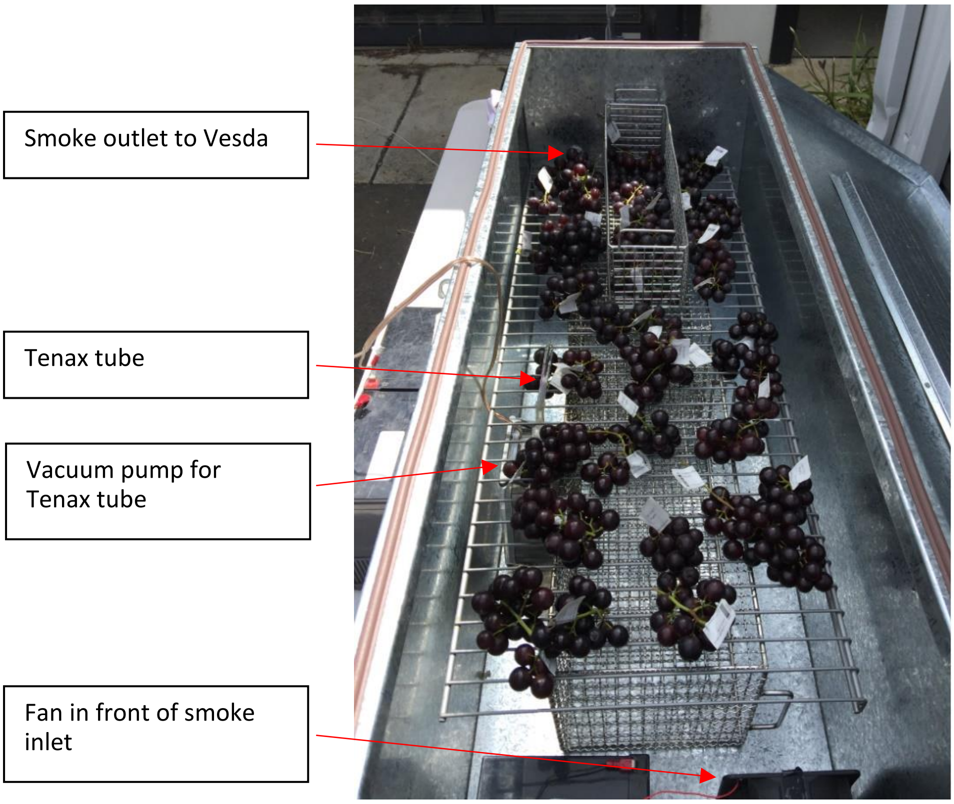

Figure 3: Inside the smoking chamber, showing the fan in front of the smoke inlet, random arrangement of grape bunches on a wire rack within the chamber, Tenax tube and vacuum pump, and smoke outlet to the Vesda smoke detector.

Smoke measurement

Smoking chamber

The smoke particulate concentration inside the smoking chamber was monitored using a Vesda smoke detector, sampling from a port at the same height as the grapes, at the opposite end to the smoke inlet. Smoking experiments were conducted for a period of one hour with the aim of maintaining the smoke at approximately 20% obscuration per metre, which had been shown in previous work (Porter, Kilmister et al. 2015) to cause suitably high levels of smoke taint compounds in grapes. To allow for a continual influx of fresh smoke to the chamber, the Vesda was run with an unrestricted inlet, and drew air from the chamber at approximately 40 L/min.

The phenol composition of the smoke within the chamber was measured by capturing a smoke sample on a sorbent tube containing Tenax resin. The sorbent tube was placed centrally inside the smoking chamber, at the height of the grapes and air drawn through the tube at approximately 50 ml/min using a calibrated vacuum pump. The phenols were subsequently desorbed from the resin with ethyl acetate, derivatised with Bis-silyltrifluoroacetamide/1 % trimethylchlorosilane (BSTFA/1 % TMCS) and analysed using an Agilent 7890A GC coupled to an Agilent 5975C mass selective detector (GC-MS).

Smoking tent

The smoke particulate concentration inside the smoking tent was monitored using a Vesda smoke detector placed centrally within the tent, and an appropriate length of PVC tubing used to allow sampling of the smoke at the same height as the grapes. Smoking experiments were conducted for a period of 45 min with the aim of maintaining the smoke at approximately 20% obscuration per metre.

The phenol composition of the smoke was measured as per the smoking chamber, with the Tenax sorbent tube placed very close to smoke detector inlet.

Grape analysis

Grapes were analysed for 23 phenols in both free and bound (glycoconjugated) forms using the method described by Allen, Bui et al. (2013). Briefly, the phenols were extracted from the grapes by homogenisation and centrifugation, followed by re-extraction of the tissue pellet with methanol. The combined juice/methanol extract was then subjected to solid phase extraction to separate the free and bound phenols and clean up these fractions ready for derivatisation with BSTFA/1 % TMCS and GC-MS analysis.

RESULTS AND DISCUSSION

Speed of uptake of smoke taint compounds by grapes

Preliminary smoking chamber work aimed to determine how quickly smoke taint compounds entered grapes, an important factor when trying to mitigate the effects of smoke, or prevent the uptake of taint compounds by grapes. Washing with water has been suggested by industry to be a possible strategy for mitigation of taint, but this would be reliant on how quickly the compounds entered the grape and how often you would need to wash with water. Grapes were smoked at approximately 20% obscuration for one hour and the grapes then analysed for both free and bound smoke taint compounds at regular intervals for up to 7 days. The guaiacol results from some of these experiments are shown in Figure 4.

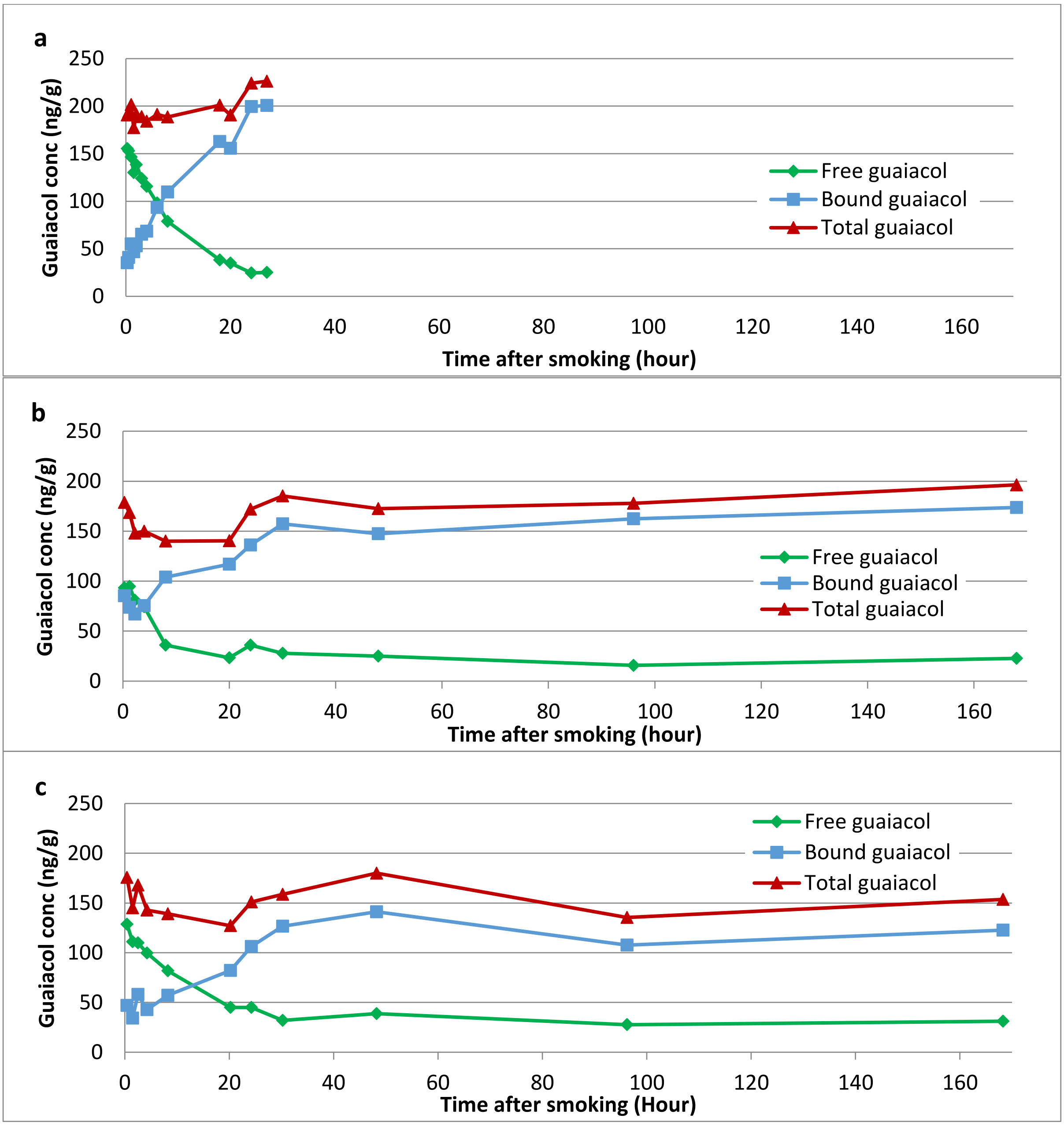

Figure 4: Concentrations of free, bound, and total (free plus bound) guaiacol in (a) red seedless, (b) Shiraz and (c) Chardonnay grapes after smoking for one hour at 20% obscuration.

Although not a direct measure of the uptake of guaiacol by the grapes, the compounds need to be absorbed by the grapes before they can be converted to the bound (glycoconjugated) forms, and these results show that this conversion proceeds quickly, with the conversion of free guaiacol to the bound form almost complete within a day. A similar trend was observed for all smoke taint compounds although the larger molecules, such as syringol, took slightly longer to convert. These results show that any treatment to remove smoke taint compounds from the surface of grapes would need to be performed immediately after smoke exposure to significantly reduce the uptake of smoke taint compounds by grapes, for a very high smoke concentration, short term exposure such as was modelled in these experiments. For a more typical, lower concentration exposure over a much longer time period (for example 1-3 days), the smoke taint compounds would need to be continually washed from the grapes during the smoke exposure as a significant amount of smoke taint compounds would already be absorbed by the grapes by the time the smoke exposure had finished.

Removal of smoke taint compounds from grapes by washing

After smoking grapes at approximately 20% obscuration for one hour, a number of bunches were washed in Milli Q water immediately (within 5 min of completion of smoking) then analysed for both free and bound smoke taint compounds and the results compared to unwashed bunches from the same smoking experiment. The results, shown in Figure 5, show that on average (n=4), washing with water reduced the grape guaiacol and syringol concentrations by 11-12% compared to unwashed grapes, presumably by removing some of the smoke taint compounds present on the surface of the grapes. The washed grapes still smelled strongly of smoke, indicating that there were still high levels of smoke taint compounds present on the skin of the grapes.

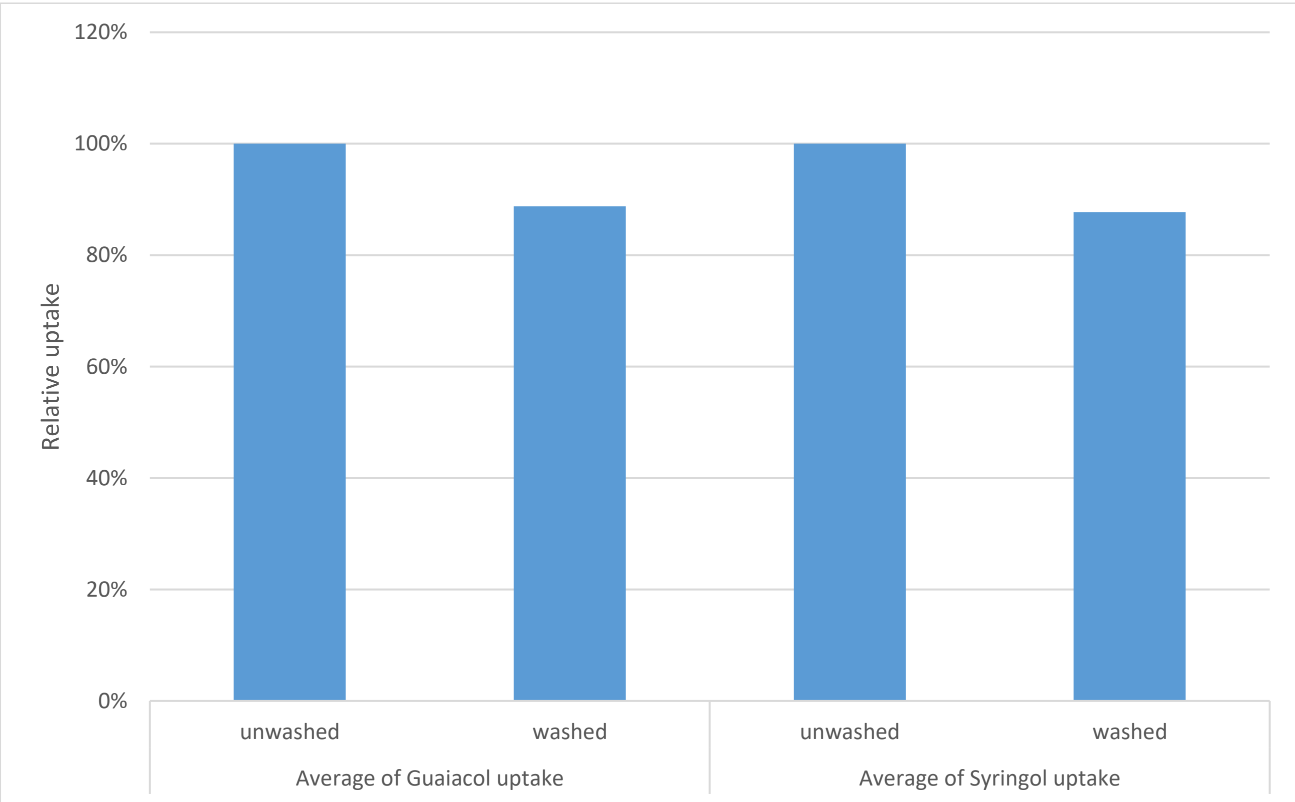

Figure 5: Concentrations of total (free plus bound) guaiacol and syringol in water-washed compared to unwashed red seedless (Flame) grapes after smoking for one hour at 20% obscuration.

Coatings applied to grapes to reduce uptake of smoke taint compounds

A number of coating materials were investigated, ranging from commercial products registered for use on grapes such as Vapor Gard (antitranspirant) and Raynox (sun protectant) to natural products such as the biopolymers Chitosan and Dextran, and three commercially available fulvic and humic acid preparations.

Antitranspirants and sunburn protectants

Results show that non-polar organic coatings such as the terpene polymer Vapor Gard, shown in Figure 6, and the wax-based Raynox caused an increase in the uptake of smoke taint compounds, presumably by increasing the affinity of the grape surface for the relatively non-polar phenolic smoke taint compounds.

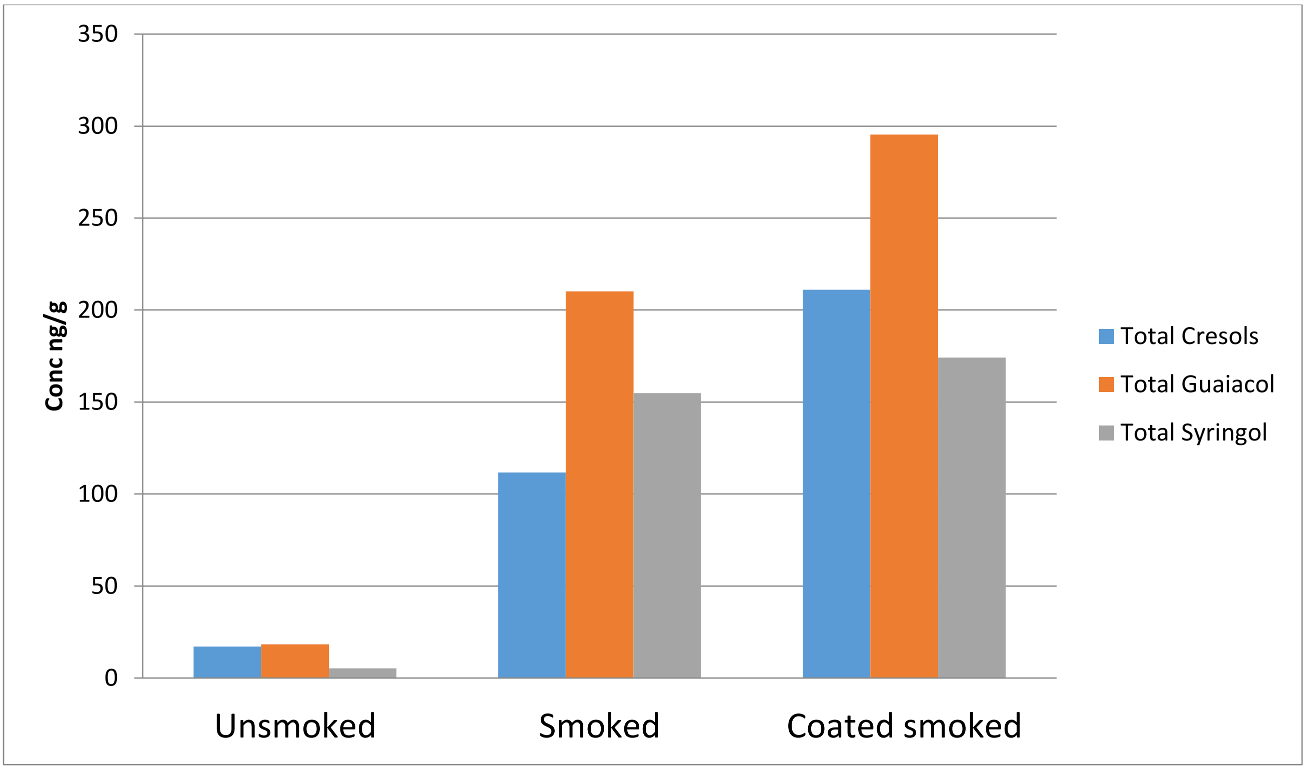

Figure 6: Concentrations of total (free plus bound) guaiacol in unsmoked, uncoated, and Vapor Gard coated Chardonnay grapes after smoking for one hour at 20% obscuration.

Chitosan and dextran

Dextran and Chitosan are bioploymers, Dextran is a glucose polymer produced by bacteria, and Chitosan is a modified glucose polymer made from chitin, which is sourced from the cell walls of fungi or the shells of crustaceans. Dextran and crab-derived chitosan were initially prepared as grape coating solutions containing 0.1% Triton X-100 surfactant, as recommended by Romanazzi, Gabler et al. (2009). The surfactant was necessary to allow the solutions to wet and adhere to the waxy surface of the grapes. Results of the initial smoking trial are shown in Figure 7, which shows the chitosan to be effective at reducing the uptake of smoke taint compounds by grapes by 67% for guaiacol and 55% for syringol. Dextran increased the uptake, most likely due to the effect of the surfactant which was later shown to increase the uptake when applied on its own to grapes. Later studies investigated the effect of different types of chitosan (crab-derived, *Aspergillus*-derived, water soluble mushroom-derived, Oenobrett), different surfactants (Triton or food grade surfactants, Tween 20 and Tween 80), and surfactant concentration. The best performing chitosan coatings were crab-derived and *Aspergillus* formulations, shown in Figure 8, which also shows the effect of different surfactant concentrations. The *Aspergillus* chitosan was much cheaper than the crab-derived product and, given its similar performance to the crab-derived chitosan, it was considered the best choice for application in-field. *Aspergillus*-derived chitosan is also an approved product for use in wine making (for fining wine), although it is unknown what effect the grape coating would have on the wine making process.

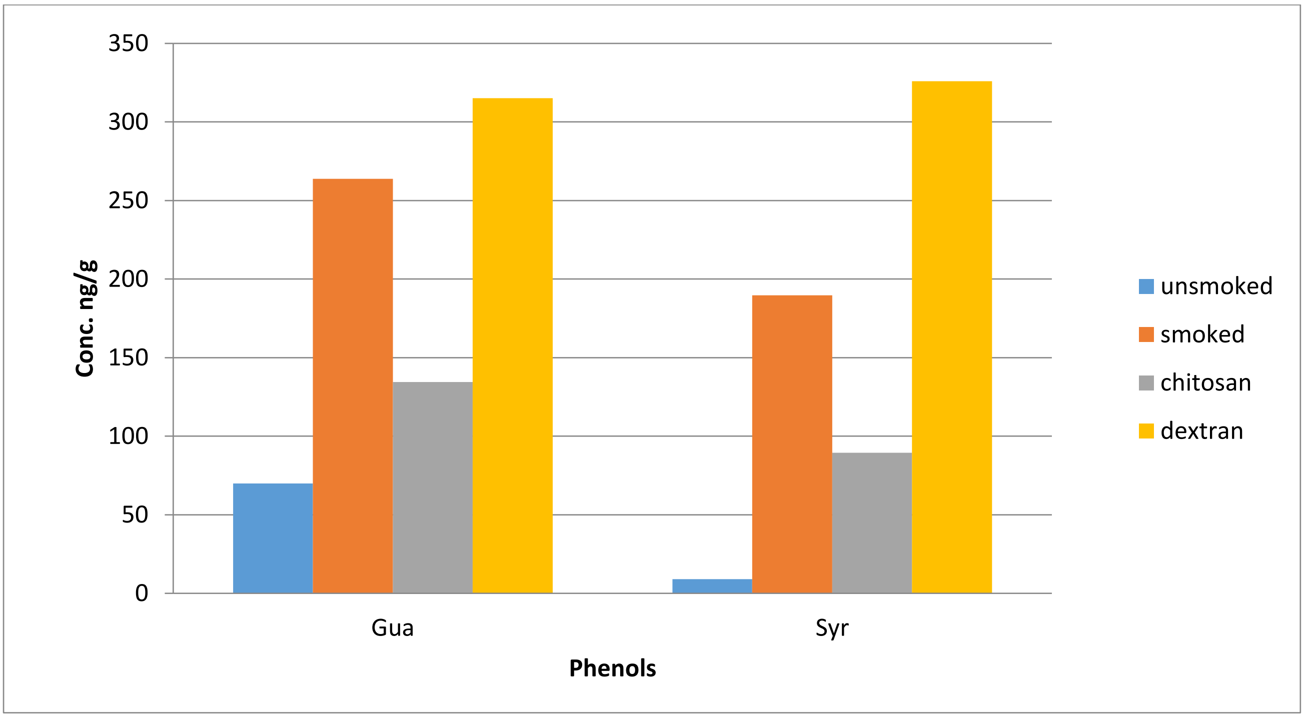

Figure 7: Concentrations of total (free plus bound) guaiacol and syringol in unsmoked, smoked uncoated, and smoked chitosan and dextran coated red seedless *(Flame)* grapes after smoking for one hour at 20% obscuration.

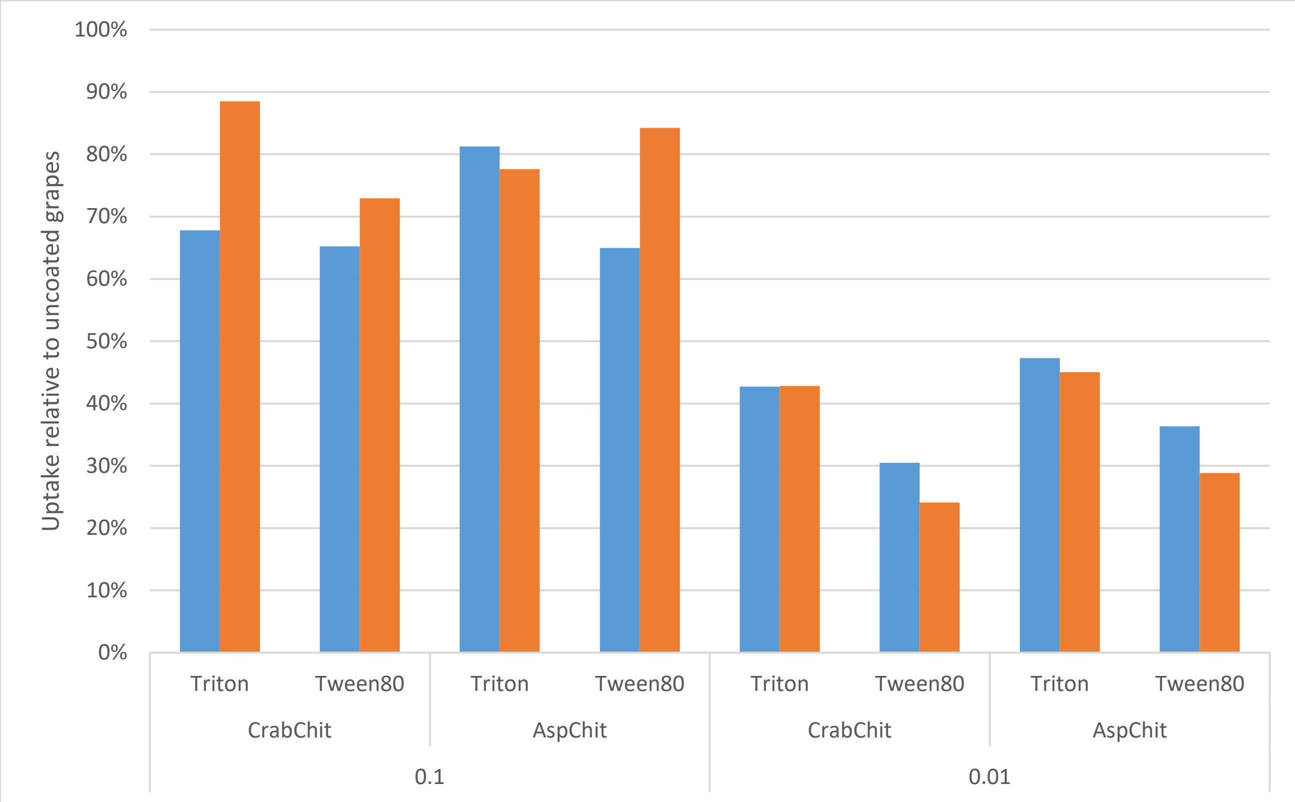

Figure 8: Uptake of total (free plus bound) guaiacol and syringol, relative to uncoated grapes, in chitosan coated red seedless (Flame) grapes after smoking for one hour at 20% obscuration. Coatings are combinations of 1% crab or *Aspergillus*-derived chitosan, with either Triton or Tween-80 surfactant at either 0.1% or 0.01%.

It is not clear why some chitosan products performed better than others. Oenobrett, for instance, a *Brettanomyces* treatment for wine which consists of chitosan and enzymes, showed no efficacy at reducing the uptake of smoke taint compounds. Two properties of the chitosan products which could cause differences in performance are the molecular weight range of the chitosan polymer and the degree of deacetylation achieved during the process of conversion of chitin to chitosan. As we were not provided with this information for some of the products tested it was not possible to make any conclusions as to the effect of these properties.

Application of chitosan in-field

Application of chitosan coatings to excised bunches which were then exposed to controlled burn smoke in-field during autumn 2018 proved largely unsuccessful, but were more successful in 2019. Our experience in 2019 indicates that we may have used insufficient surfactant (0.01%) to properly coat the grapes in 2018. Incomplete drying of the coatings prior to transport to the burn location, and 'sweating' of the grapes in transit, combined with the physical effects of vibration and movement may also have significantly reduced the integrity of the chitosan coating leading to generally poor outcomes. Low smoke levels from the controlled burns used during experiments in 2018 in many instances also made any differences in uptake less obvious.

Application of Aspergillus chitosan to excised bunches of Shiraz grapes in-field followed by controlled smoking in a tent in 2019 proved more successful. This experiment showed a 30-60% reduction in smoke taint compound uptake, depending on the compound. The high levels of wax on the skins of the Shiraz grapes required a surfactant concentration of 0.03% to enable wetting and coating of the grapes, as opposed to the less waxy red seedless grapes which were able to be coated with a solution containing only 0.01% surfactant. This difference in surfactant concentration may explain the slightly lower reduction in uptake of smoke taint compounds for the Shiraz grapes as higher surfactant concentrations have been shown to reduce the effectiveness of the chitosan coatings, as shown in Figure 8.

The spray application of chitosan in a commercial vineyard is as yet untested but would be expected to show reduced efficacy due to the inability to completely coat grape bunches on-vine compared to the dip application method used for the present trial. The high viscosity of the chitosan solution also needs to be evaluated to determine if it is amenable to application by commercial sprayer, and if not, further research may be needed to identify lower viscosity preparations.

Fulvic and humic acids

The three fulvic and humic acid preparations used in the controlled smoking trials were found to increase the uptake of smoke taint compounds, however a surfactant was required for these products to be able to effectively adhere to the surface of the grapes. As surfactants tend to increase the uptake of smoke taint compounds this may have affected the performance of these products. Two of the products, although increasing levels of smoke taint phenols above the uncoated smoked grapes, did however show lower levels of smoke taint compounds compared to grapes coated with the surfactant alone, showing that these products have some efficacy in blocking or absorbing the smoke taint compounds, however this was not pursued further as chitosan showed much greater promise as a potential barrier compound.

CONCLUSION

This study showed that of the nine products screened, only chitosan products were able to reduce the uptake of smoke taint compounds into grapes effectively, with a reduction of 30 to 60%. This demonstrated that potential exists to consider use of these products in commercial vineyards to protect against smoke, but further application studies in field and cost/benefit information is required to determine practical ways to use the sprays.

The trials demonstrated that commercially available fruit coatings, such as antitranspirants and sun protectants based on relatively low polarity organic material such as polymers and waxes are not able to reduce the uptake of smoke taint compounds by grapes, in fact they tend to increase the uptake and as such care should be taken not to apply these compounds if there is a risk of grape exposure to smoke from any source, but particularly controlled burns and bushfires. Biopolymers show some promise, with chitosan in particular achieving very good reductions in the uptake of smoke taint compounds. For logistical reasons the application of a chitosan coating in-field was restricted to excised grape bunches smoked in a tent, which resulted in similar reductions in uptake as were achieved in laboratory scale smoking experiments. The spray application of chitosan in a commercial vineyard is as yet untested but would be expected to show reduced efficacy due to incomplete coating of grape bunches on-vine.

RECOMMENDATIONS

Further screening of chitosan products and analysis of their properties would allow the identification or development of a chitosan product with optimum properties for the prevention of uptake of smoke taint compounds by grapes. This could also lead to the identification of other coating materials which could have better efficacy, easier application or lower cost than chitosan coatings.

Further work with chitosan application in-field would allow the development of an effective product and application technique which can be used by viticulturists to protect their crops in the event of high risk of smoke exposure of their vineyard.

Industry must be made aware of fruit coatings which increase the uptake of smoke taint compounds, such as antitranspirants and wax-based sunburn protectants, and advised not to apply these types of compounds in the vineyard if there is the risk of smoke exposure.

As these products were unable to fully prevent the uptake of taint compounds, a cost/benefit analysis would need to be conducted under different levels of smoke densities and smoke taint risk.

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Impact of distance and fuel source on the profile of smoke taint compounds

Agriculture Victoria Research Technical Report

VICTORIA State Government | Jobs, Precincts and Regions

AGRICULTURE VICTORIA

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Project RDC Number: RRD4P 15-02-033

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EXECUTIVE SUMMARY

The exposure of vineyards and grapes to smoke from bushfires and/or controlled burn events may result in 'smoke tainted' wine, that can cause serious economic losses to industry. Since 2003, major fire events have affected over $400M worth of grapes and wine that were either rejected commercially or downgraded as a result of smoke taint. The frequency of bushfires and controlled burns is expected to increase under various climate change scenarios, thus it is important that the Australian wine industry develop cost effective remediation tools to manage smoke affected grapes and wine. This collaborative DEDJTR, La Trobe University and AWRI project funded by DAWR and Wine Australia evaluated a range of possible remedial management options and tools for dealing with smoke affected grapes and wine. This Technical Report investigates the effect of fuel source and distance on the profile and concentration of smoke taint compounds in smoke, grapes and wine.

This study showed differences in the profile of smoke taint compounds produced from the combustion of different fuels. It was also found that the concentration of smoke taint compounds in the air decreases dramatically with distance from controlled burns. This was assumed to be due to dilution with clean air and also through several degradation processes such as photooxidation. The profiles of smoke taint compounds was found to change substantially with distance from controlled burns, with some compounds reducing to undetectable levels within 5 km of controlled burns. At this stage it is possible that 5 km may be a safe distance for vineyards downwind from typical controlled burns due to the typically very low concentrations of smoke taint compounds present in the air at this distance, however this has not been proven to be a safe distance at this stage. Our measurements also showed that smoke from bushfires poses a much greater risk than controlled burns, with significant concentrations of smoke taint compounds measured up to 15 km from the 2019 Bunyip bushfire in Victoria.

The profile of smoke taint compounds taken up by grapes and carried into wine was found to be similar to the profile of the compounds measured in the smoke. As different smoke taint compounds display different flavours and aromas, differences in smoke composition may lead to differences in the perception of smoke taint in wines, professional sensory studies will be conducted to develop smoke thresholds that can be used by industry to predict smoke taint. This will be the first time this has been done globally.

INTRODUCTION

This technical report is a deliverable for the project Mitigation of Climate Change Impacts on the National Wine Industry by Reduction in Losses from Controlled Burns and Wildfires and Improvement in Public Land Management (LTU 3.1851.01). It contributes towards meeting the project objective B5. Vineyard mitigation options. This AVR technical report was prepared in collaboration with our project leader, Professor Ian Porter from La Trobe University.

Project outcome

This project will generate knowledge, innovative technologies and processes that will directly benefit grape growers and wine companies. It will enhance Australia's wine reputation, industry profitability and Australia's competitiveness in global markets. Knowledge generated will contribute to the innovation of process and practices and aid public land management agencies to implement effective planned burn programs with reduced potential for damage for grape and wine producers.

Project background

The exposure of vineyards and grapes to smoke from bushfires and/or controlled burn events may result in 'smoke tainted' wine, that can cause serious economic losses to industry. Since 2003, major fire events have affected over $400M worth of grapes and wine that were either rejected commercially or downgraded as a result of smoke taint. The frequency of bushfires and controlled burns is expected to increase under various climate change scenarios, thus it is important that the Australian wine industry develop cost effective remediation tools to manage smoke affected grapes and wine. This collaborative component of the project (DEDJTR, La Trobe University) aims to evaluate a range of possible remedial management options and tools for dealing with smoke affected grapes in the vineyard. The results will be related to critical sensory thresholds for the key smoke taint volatile phenols and their associated glycosides in Chardonnay, Pinot Noir and Shiraz (oaked and unoaked). Once these critical chemical threshold concentrations have been determined for each variety and style, other studies by AWRI will trial options to remove smoke related free volatile phenols and their associated glycosides from affected wines, or apply treatments that will facilitate the degradation of these free volatile phenols and their glycosides in wines. The cost of these remediation and mitigation treatments is being carefully evaluated and reported to help industry implement cost-effective solutions in their business.

Project objectives

The objectives of the broader smoke taint project are to:

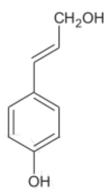
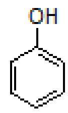
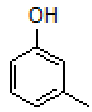
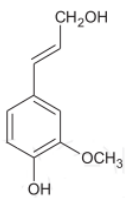
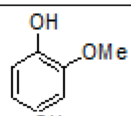
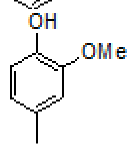
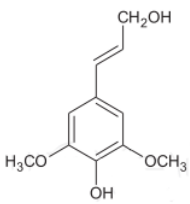
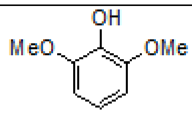
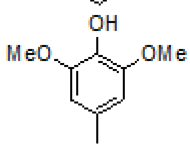
1. Establish wine quality ratings, sensory thresholds, compositional and flavour profiles and consumer preferences for smoke affected Chardonnay, Pinot Noir and Shiraz wines (oaked and unoaked) using dilution techniques;
2. Evaluate a range of remediation strategies for managing smoke affected fruit and wines in the winery. This objective aims to examine processing options and materials to remediate wines and minimise the loss to final wine quality;
3. Investigate vineyard mitigation options and strategies to identify vineyards at risk from smoke exposure, in addition providing options to decrease uptake of smoke taint compounds in the vine and grapes, and link with work by AWRI to explore options to limiting the conversion of free volatile phenols into their more difficult to remove glycosidic/bound forms. This objective aims to explore options viticulturists can implement at short notice to protect fruit from becoming smoke tainted. Options considered include the use of anti-transpirants, protective sprays and modulation of glycosidase enzymes (AWRI). This objective has been funded through DEDJTR co-investment;
4. Economic evaluation of remediation activities undertaken under objectives 2 and 3 above. Objective cost data for the various remediation treatments trialled in objectives 2 and 3 will be assessed by an economist and a process engineer to determine cost effective treatments for implementation.

This technical report addresses part of the aims in 3 above.

METHOD

Smoke from fires contains thousands of different compounds, however the key compounds in smoke that influence taint in grapes and wine have been reported to be volatile phenolic compounds such as guaiacol, 4 methyl-guaiacol, cresols (*o-, m- and p-*), syringol and 4-methylsyringol (Krstic, Johnson et al. 2015). These phenols are formed as degradation products of the lignins in the burning biomass. The lignins are formed from combinations of three precursors - p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol – and thermal degradation of these gives rise to the phenols shown in table 1. The amount of lignins and relative proportions of each of the alcohol precursors can vary substantially between plant species and between different plant components (eg. wood, bark, leaves) (Lourenço and Pereira 2018), meaning the levels of the degradation products would be expected to vary in the resulting smoke. Wine grapes exposed to smoke from bushfires or controlled burns can absorb these phenols, which are in turn passed on to the wine. Sufficiently elevated levels of phenols can impart unpleasant characters to the wine, including burnt, smoky, medicinal and dirty aromas and flavour attributes. It should be noted that many grape varieties contain natural low levels of some smoke taint compounds, and these levels can vary substantially between varieties, however it is the elevated levels caused by smoke exposure that causes smoke taint.

Table 1: Lignin precursor compounds and major degradation products of concern for smoke taint in grapes and wine

Lignin precursor		Major degradation products	
p-coumaryl alcohol		Phenol Cresols	 
coniferyl alcohol		Guaiacol 4-methylguaiacol	 
sinapyl alcohol		Syringol 4-methylsyringol	 

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Degradation of phenols in the atmosphere occurs due to a number of mechanisms including reaction with hydroxyl and nitrate radicals. The reaction of phenols with hydroxyl radicals is induced by photooxidation and is the major daytime degradation pathway, whereas reaction with nitrate radicals is the predominant night time pathway (Wayne, Barnes et al. 1991, Khan, Cooke et al. 2015). Studies have shown that more highly substituted phenols show a more rapid rate of degradation, with methoxy substitution giving a much greater rate increase than methyl substitution (Lauraguais, Bejan et al. 2015, Lauraguais, El Zein et al. 2016). This means syringol (2,6-dimethoxyphenol) would be expected to degrade in the atmosphere at a significantly greater rate than guaiacol (2-methoxyphenol), and 4-methylsyringol would be expected to degrade more quickly than syringol, so the profile of the phenols in the smoke would be expected to change over time as the smoke ages. Air temperature is also expected to play a role in the depletion of phenols from smoke, for example by condensation of the less volatile compounds such as syringol, however due to logistical and practical considerations this study focuses purely on the effect of smoke age as a function of distance from a fire.

The aim of this work was to measure these changes in smoke composition as smoke ages and travels away from the fire, thus giving a measure of the relative abundance of the various smoke taint compounds in the smoke. This change in concentration and profile of the various smoke taint compounds could thus give an indication of the risk of taint from smoke of various ages, and an indication of the expected sensory characteristics imparted on the wine. Although 23 compounds were measured in smoke, grapes and wine, in both the free and bound forms, to simplify the visualisation of these changes in smoke composition, the data shown in this report focuses on the key smoke taint compounds mentioned above, and grape results expressed as the total (free + bound) of each of these smoke taint compounds.

Smoke measurement

Smoke measurements were made in controlled burns (fresh smoke) and at various distances from controlled burns and bushfires. The smoke particulate concentration (smoke density) was measured using a Vesda smoke detector, sampling through a 1 metre length of PVC pipe, placing the smoke inlet approximately 1.2 metres above the ground. Where necessary, a 4.9 m telescopic pole was used when sampling smoke directly above a fire. Smoke was conveyed to the Vesda via a suitable length of 20mm diameter flexible PVC electrical conduit. Smoke measurements were conducted for variable lengths of time, governed by the duration of smoke at a particular site, and prevailing weather conditions. The smoke 'dose' at each measurement site was calculated as the area under the Vesda plot, which is the cumulative total of each reading multiplied by the duration of that reading.

The phenol composition of the smoke at each measurement site was measured by capturing a smoke sample on a sorbent tube containing Tenax® resin. The sorbent tube was placed as close as possible to the smoke inlet to the Vesda and air drawn through the tube at 100 ml/min using a calibrated vacuum pump. The phenols were subsequently desorbed from the resin with ethyl acetate, derivatised with Bis-silyltrifluoroacetamide/1 % trimethylchlorosilane (BSTFA/1 % TMCS) and analysed using an Agilent 7890A GC coupled to an Agilent 5975C mass selective detector (GC-MS).

Grapes

In most cases, smoke measurements were accompanied by 'sentinel' grape bunches – excised bunches of grapes exposed to the exact same smoke as was measured by the Vesda smoke detector and sampled on Tenax tube. The use of these sentinel bunches was to provide a mechanism which would simulate similar uptake by vines in a vineyard. Previous work has shown that excised bunches were able to take up smoke taint compounds similarly to bunches on-vine. Grapes used as sentinels were harvested from the phylloxera exclusion zone (PEZ) of Victoria so they could be used in all experiments throughout Victoria. Similarly, Shiraz grapes were purchased from a vineyard in Great Western, Victoria, Chardonnay grapes were purchased from vineyards in Drysdale, Victoria and Faraday, Victoria and Pinot Noir grapes were purchased from a vineyard in Faraday, Victoria. All grapes were stored at 4°C and allowed to come to room temperature before smoke exposure. Where measurements were made at a site within the PEZ, local grapes were sourced to avoid biosecurity issues. Where possible, grapes samples were also taken from in situ vines within vineyards exposed to smoke from controlled burns or bushfires. After treatment, grapes were sealed in zip-lock plastic bags prior to transport to the laboratory for chemical analysis. Where measurements took place in a phylloxera infested zone (PIZ), grapes were frozen and permits obtained prior to removal of the grapes from the PIZ.

Wine

In 2018, six 25 kg consignments of grapes from a vineyard exposed to bushfire smoke were made into small-scale wines. These consisted of 3 varieties (Pinot Noir, Pinot Grigio and Prosecco), each harvested from locations approximately 0.5 km and 1.2 km from the nearest edge of the fire. Small-scale wines were made at a commercial winery in Cheshunt, Victoria from grapes exposed to different levels of smoke from both controlled burns and bushfires. The production of these wines was to quantify the effect of different smoke exposures on the degree of smoke taint in the wines, although professional sensory testing is still to be done. Wines were made using a standardized method without any exposure to oak barrels or chips to avoid artificially masking the levels of some taint compounds in the wine.

Grape and wine analysis

Grapes and wine were analysed for 23 phenols in both free and bound (glycoconjugated) forms using the method described by Allen, Bui et al. (2013). Briefly, the phenols were extracted from the grapes by homogenisation and centrifugation, followed by re-extraction of the tissue pellet with methanol. The combined juice/methanol extract or wine was then subjected to solid phase extraction to separate the free and bound phenols and clean up these fractions ready for derivatisation with BSTFA/1 % TMCS and GC-MS analysis.

RESULTS AND DISCUSSION

Profile of smoke taint compounds from burnt vegetation

Measurement of smoke from controlled burns showed that different vegetation gave different profiles for the smoke taint compounds in smoke across the wide range of fuels sampled during this project (Table 2). The results showed that eucalypt forest emitted a higher proportion of syringyl derivatives (syringol:guaiacol ratio of around 1.5-2.5) compared to grasses (syringol:guaiacol ratio of 0.6-1.1), which gave off predominantly phenol derivatives. This is consistent with the lignin composition of these fuels (Lourenço and Pereira 2018) but raises the question of whether the sensory detection of smoke taint in wine is influenced by the fuel source. Previous studies have considered the fuel source as having little impact on smoke taint in wine (Kelly, Zerihun et al. 2012).

Table 2: A selection of typical fuel sources from controlled burns and the profile of phenols measured directly over the fires. Results expressed as concentration of smoke taint compound relative to guaiacol.

Fuel	Phenol	Total cresols	Guaiacol	4-methyl guaiacol	syringol	4-methyl syringol
eucalyptus log	0.60	0.52	1.00	0.72	3.89	2.10
eucalyptus log	1.51	1.47	1.00	0.93	2.69	2.66
mountain ash	1.05	0.75	1.00	0.77	1.98	2.04
eucalyptus log -very hot burn	1.71	1.03	1.00	0.66	1.72	1.17
leaves, bark, grass	1.50	1.29	1.00	0.73	1.67	1.33
grass	1.37	1.04	1.00	0.48	1.12	0.91
wattle pods, grass, casuarina	1.41	1.83	1.00	0.69	0.92	0.62
grass	2.74	1.78	1.00	0.65	0.68	0.35
grass	2.38	1.53	1.00	0.69	0.59	0.29

Change in the profile of smoke taint compounds with distance from fires

Controlled burns

The results of 53 smoke measurements conducted in 2017 are shown in Figure 1. These measurements were taken approximately one metre above the fires and at various distances up to 27 km away from the fires, where smoke was able to be measured at ground level. These results show the expected reduction in smoke taint compound concentration as the smoke moved away from the fires. The reductions are considered to be mostly due to dilution of the smoke with clean air, but degradation of the compounds is also expected to cause significant reductions. Figure 1 also shows that syringol and 4-methylsyringol concentrations decrease more rapidly than the other compounds, with neither compound measured in smoke greater than 5 km from the controlled burns. This is consistent with the findings of Lauraguais, Bejan et al. (2015) and Lauraguais, El Zein et al. (2016), whose studies showed syringol to degrade more quickly than guaiacol in controlled experiments simulating the atmospheric degradation of methoxylated phenols. Although a safe distance from controlled burns is yet been determined, this data indicates that 5 km upwind of a vineyard may be a safe distance in typical low wind conditions, as the concentrations of all smoke taint compounds have typically reduced to very low levels within this distance. It should also be noted that in many cases the smoke from controlled burns rose high into the atmosphere, and very little smoke was able to be measured at ground level. In these situations a significantly shorter distance between controlled burns and vineyards may allow sufficient protection against smoke taint in grapes and wine.

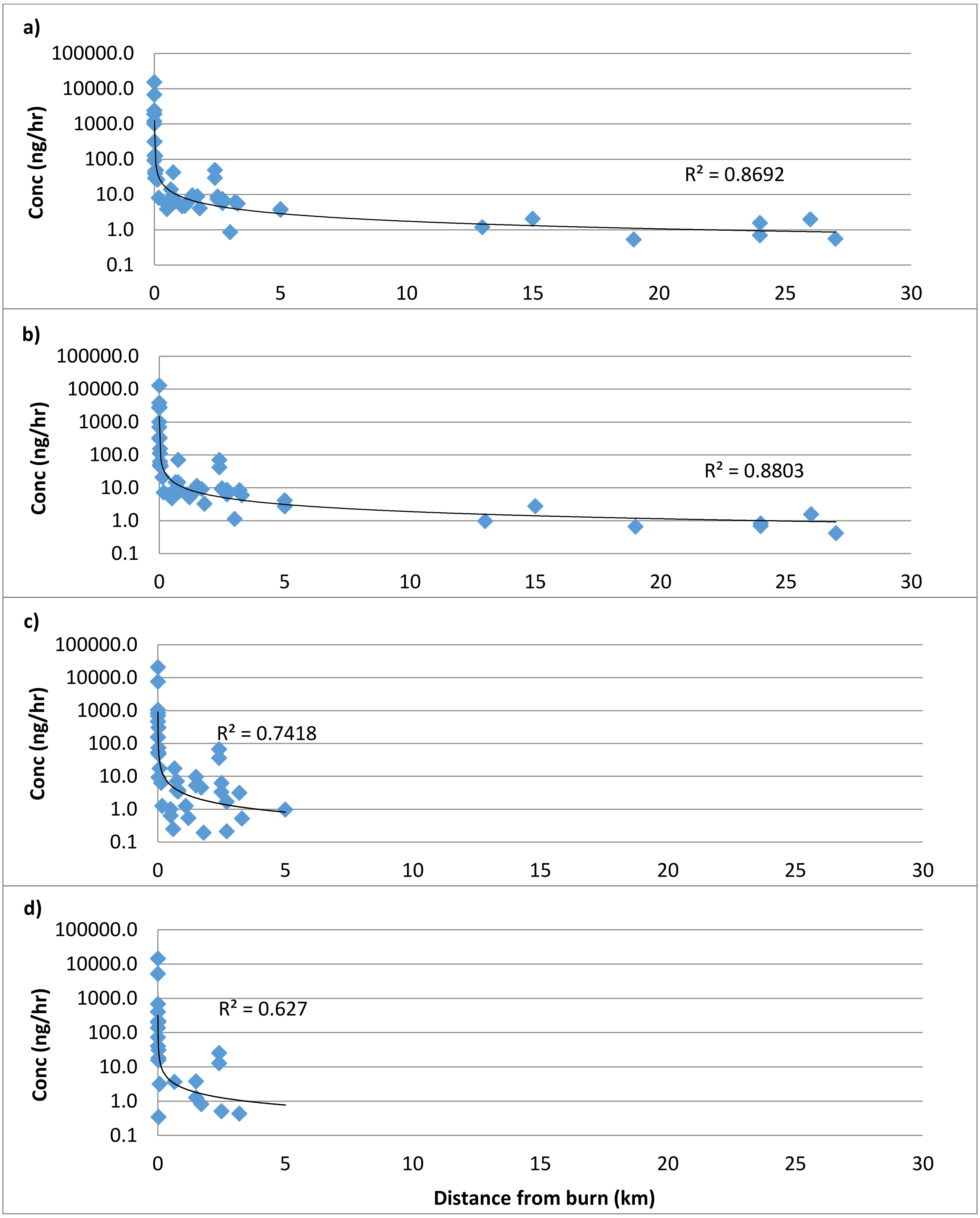

Figure 1: Changes in concentration (log scale) of four major taint compounds; (a) cresols, (b) guaiacol, (c) syringol and (d) 4-methylsyringol in smoke with distance from controlled burns. Data presented from 53 sites sampled in 2017. Note: Syringol and 4-methylsyringol were not detected beyond 5 km from controlled burns.

Controlled burns in moderate winds

Some controlled burns were conducted in moderately windy conditions (15-25km/h) where vegetation was relatively sparse and the wind was needed to help propagate the fire. These burns are generally cooler due to the lower fuel loads, resulting in less heat-induced uplift of the smoke plume and, combined with the higher wind speed, there is concern that these conditions pose a greater risk of smoke taint in nearby vineyards than typical controlled burns in low winds and with higher fuel loads.

Measurements at various distances from the Little River-Bulban Rd controlled burn in 2017 and Grampians-Plantation controlled burn in 2019 showed that for small burns such as these (< 100 ha), dilution and degradation of the smoke taint compounds with distance resulted in low concentrations of smoke taint compounds at ground level less than 1 km downwind from the fires. Considering the short duration of the fires, these concentrations were considered too low to cause sensory smoke taint in wine. At Little River (Figure 3a), smoke taint compound levels in air decreased exponentially with distance from the burn, and a corresponding effect was observed in grapes (Figure 3b). Smoke was not measured greater than 200 m from this burn as the smoke plume had lifted and smoke concentrations at ground level were deemed insignificant. At the Grampians-Plantation controlled burn the smoke was able to be measured at a greater distance from the fire, however a similar dramatic decrease in the concentrations of smoke taint compounds with distance was observed, as shown in Figure 4. The uptake of smoke taint compounds by Chardonnay, Pinot Noir and Shiraz grapes showed a similar trend to the smoke composition, in both concentration and profile of the smoke taint compounds.

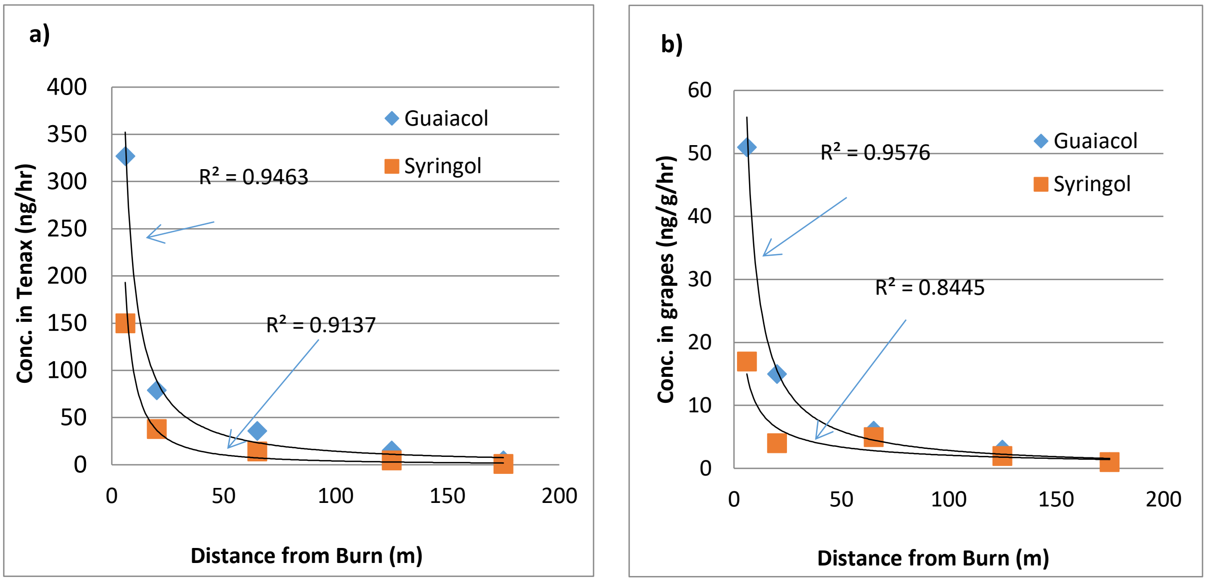

Figure 3: Concentrations of guaiacol and syringol in (a) smoke samples collected on Tenax® tubes and (b) excised bunches of red seedless grapes as a function of distance from a controlled burn at Little River in 2017.

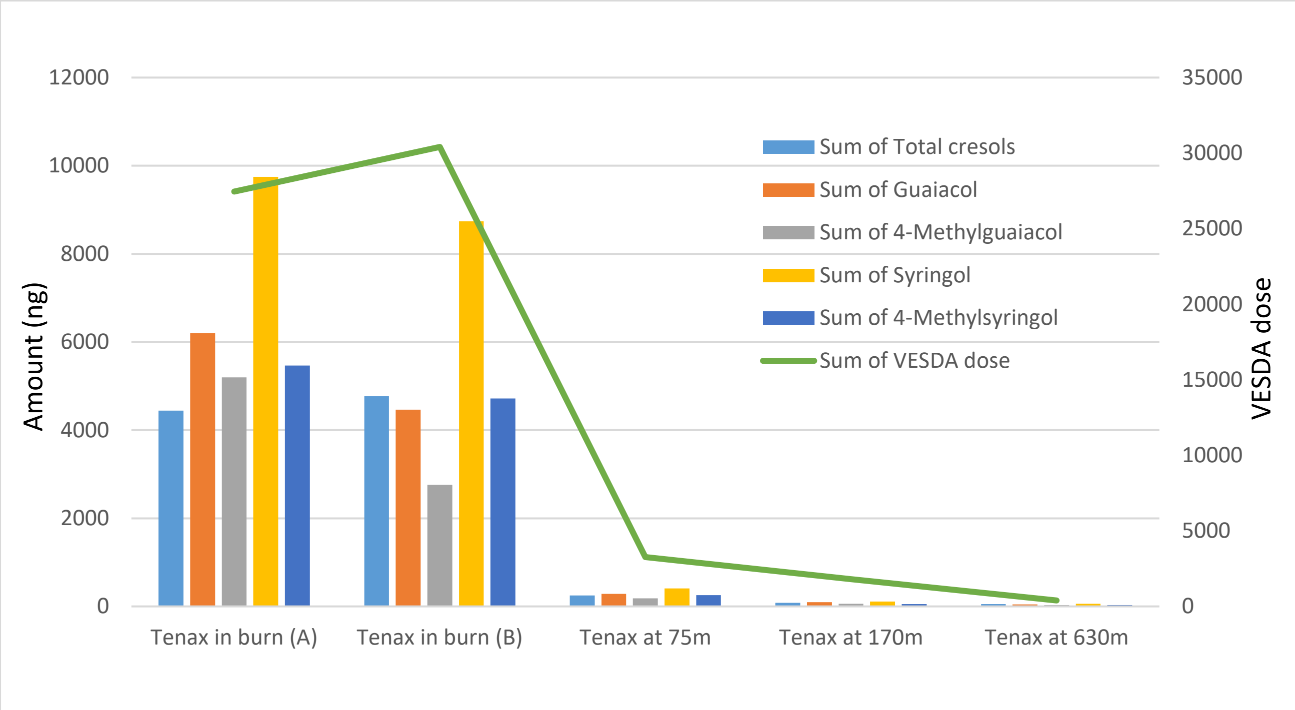

Figure 4. Mass of smoke taint compounds captured on Tenax® tubes and VESDA dose at various distances downwind from the 2019 Grampians-Plantation controlled burn.

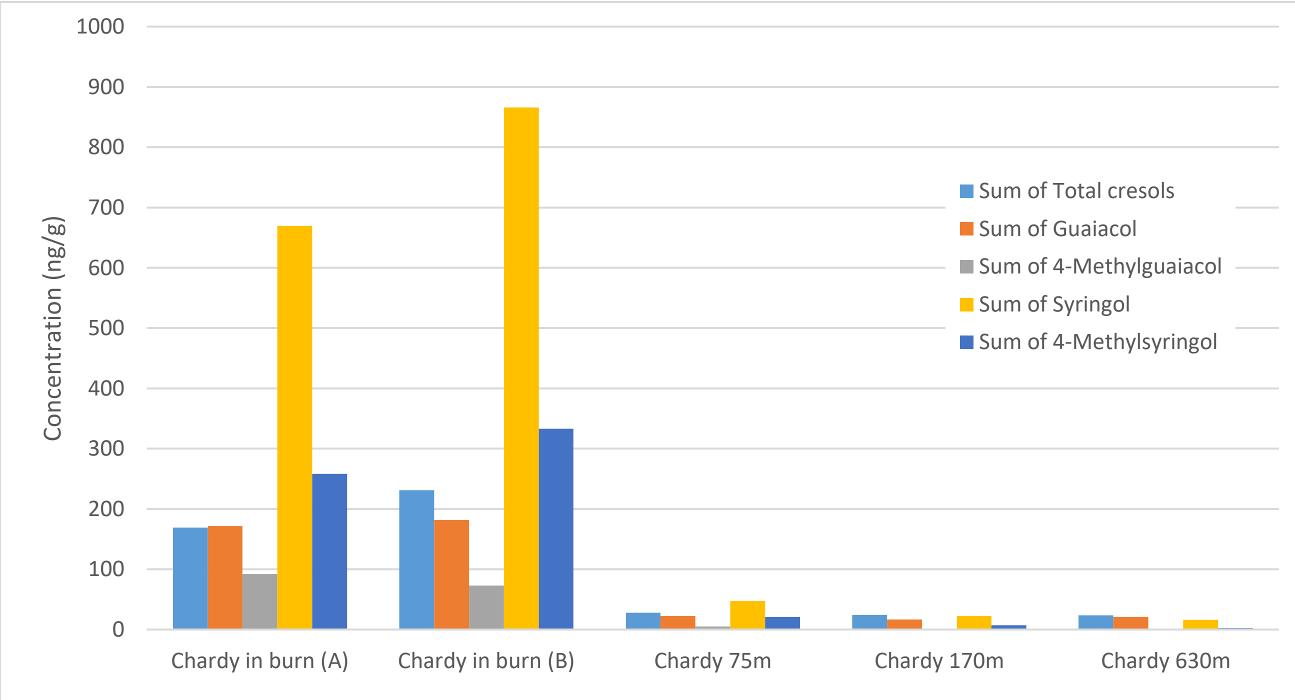

Figure 5. Smoke taint compounds in Chardonnay grapes placed at various distances downwind from the 2019 Grampians-Plantation controlled burn.

Bushfires

Bushfires present a much higher risk of smoke taint in grapes and wine than controlled burns due to the potentially much larger volume of smoke and also the atmospheric conditions such as high winds, which may carry compounds further before they degrade. Anecdotal evidence from the 2009 Victorian Black Saturday bushfires indicates the occurrence of smoke taint in a vineyard 50-60 km from the nearest fire.

Our measurements in vineyards within 15 km to the north and north west of the 2019 Bunyip bushfire in Victoria showed significant doses of smoke as measured by Vesda smoke detector. Measurement of the chemical composition of the smoke also showed the presence of significant levels of smoke taint compounds at all sites. Levels generally decreased with increasing distance from the fire, as shown in Figure 6. The highest levels were measured at Beenak (6 km from fire), followed by Gladysdale (11 km) and Hoddles Creek (15 km). Gembrook (4 km) was an anomaly as it was the closest vineyard to the fire, yet it recorded the lowest levels of smoke and smoke taint compounds. It is assumed that this was due to its location to the north west of the fire, as opposed to the other vineyards which were to the north, and as such it was not directly downwind of the bushfire. The profile of smoke taint compounds also changed with distance from the fire, with the proportion of syringol and 4-methylsyringol decreasing relative to the cresols and guaiacol. Gembrook showed the lowest proportion of syringol and no 4-methylsyringol, indicating that the smoke had aged considerably before reaching this vineyard.

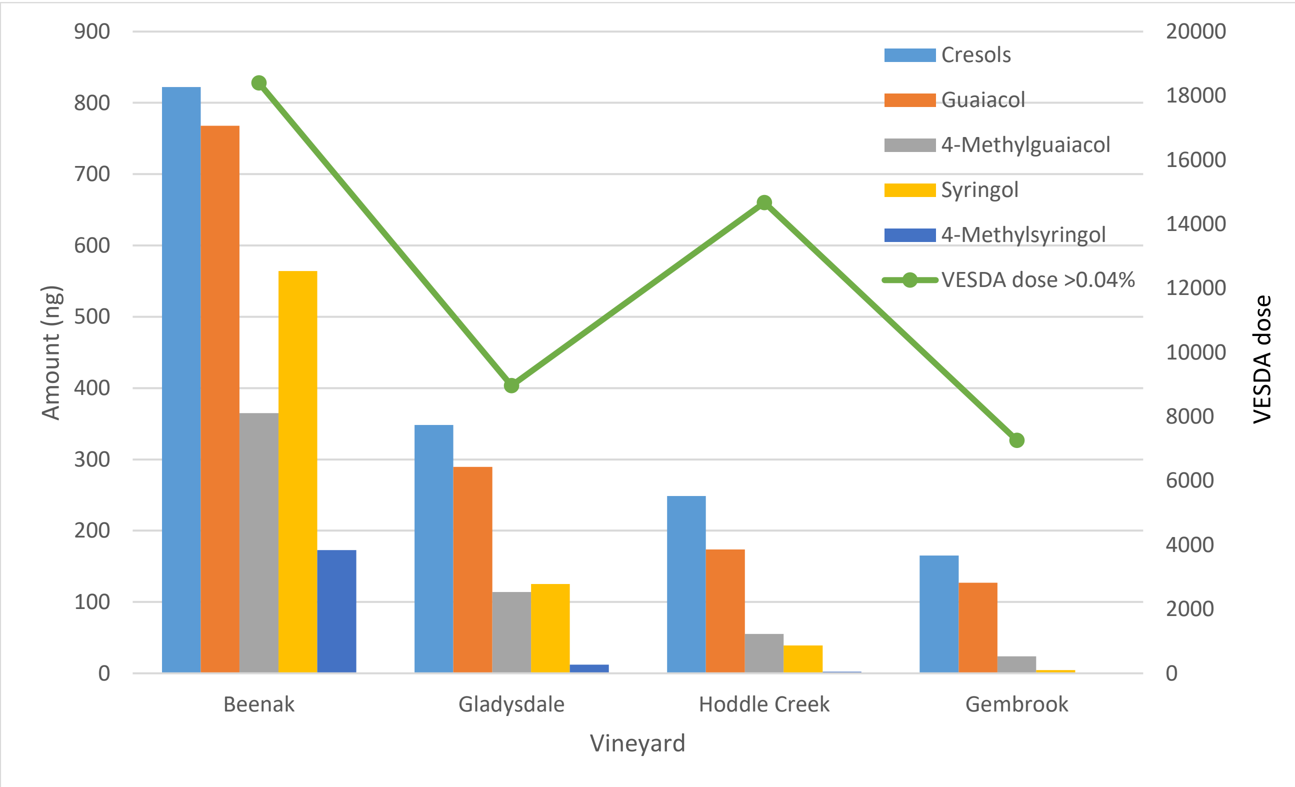

Figure 6. Mass of smoke taint compounds captured on Tenax® tubes in vineyards to the north and north west of the Bunyip bushfire during the period 4-14 March 2019, and corresponding smoke dose measured by Vesda smoke detector.

Grapes were sampled from the Beenak and Gladysdale vineyards at the beginning and end of the smoke exposure period and the results are shown in figure 7. The Pinot Noir grape sample from Beenak showed elevated levels of cresols, guaiacol, 4-methylguaiacol, syringol and 4-methylsyringol after smoke exposure, which is consistent with the presence of these compounds at significant concentrations in the air. The Chardonnay grape sample from Gladysdale showed elevation of cresol levels after smoke exposure. Shiraz grapes were only sampled from the Hoddles Creek vineyard after smoke exposure and showed similar levels of guaiacol and syringol to unsmoked Shiraz grapes from

Great Western. However, these grapes showed elevated levels of 4-methylguaiacol and 4-methylsyringol, indicating definite exposure to smoke containing these compounds. This is not consistent with the measured smoke exposure, which showed virtually no 4-methylsyringol. It should be noted that this sample came from a separate vineyard approximately 400 m west of the smoke sampling location, and it is possible that smoke levels or smoke composition were different at this vineyard.

These results show the much greater risk of smoke taint from bushfires compared to controlled burns. Whereas controlled burns showed insignificant levels of smoke taint compounds greater than 5 km from a burn, the Bunyip bushfire caused downgrading or rejection of grapes from the Beenak vineyard, 6 km from the fire, and elevated levels of smoke taint compounds in grapes from vineyards up to 15 km away. Had the winds been stronger or blown from a southerly direction more often, these levels could have been even higher.

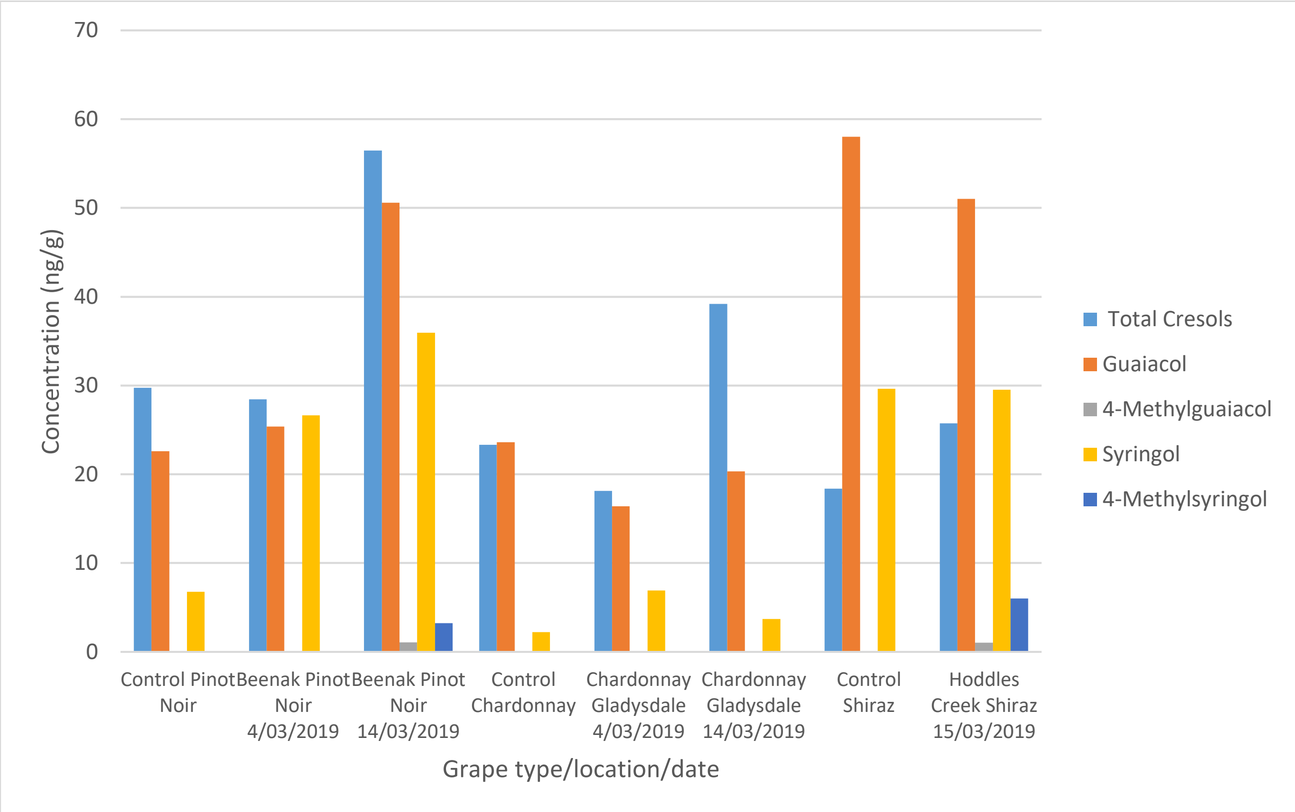

Figure 7. Concentrations of smoke taint compounds measured in control grapes and grapes from vineyards to the north of the Bunyip bushfire sampled before and after the air monitoring period from 4-14 March 2019.

At the time of writing, corresponding wine samples from these vineyards were not available for analysis, however grapes and small-scale wines produced from a vineyard affected by smoke from the 2018 Myrrhee-Boggy Creek Road bushfire near Whitfield in Victoria demonstrate how distance can affect the profile of smoke taint compounds in both grapes and wine, as shown in Figures 8 and 9. All grape samples harvested 1.2 km from the fire showed lower levels of syringol than the corresponding variety harvested 0.5 km from the fire. No 4-methylsyringol was found in samples at 1.2 km, whereas levels of 4-15 ng/g were found in samples at 0.5 km. Guaiacol levels in Pinot Noir were also lower at 1.2 km than at 0.5 km. Similar distance effects were seen in wines produced from these grapes although the profiles of the smoke taint compounds did vary. This may be due to natural variations in the levels of these compounds in the different grape varieties. Winemaking technique may also alter the profile - wines fermented on-skins, such as Pinot Noir, would be expected to extract greater amounts of smoke taint compounds from the fruit than wines made off-skins, such as Pinot Grigio and Prosecco.

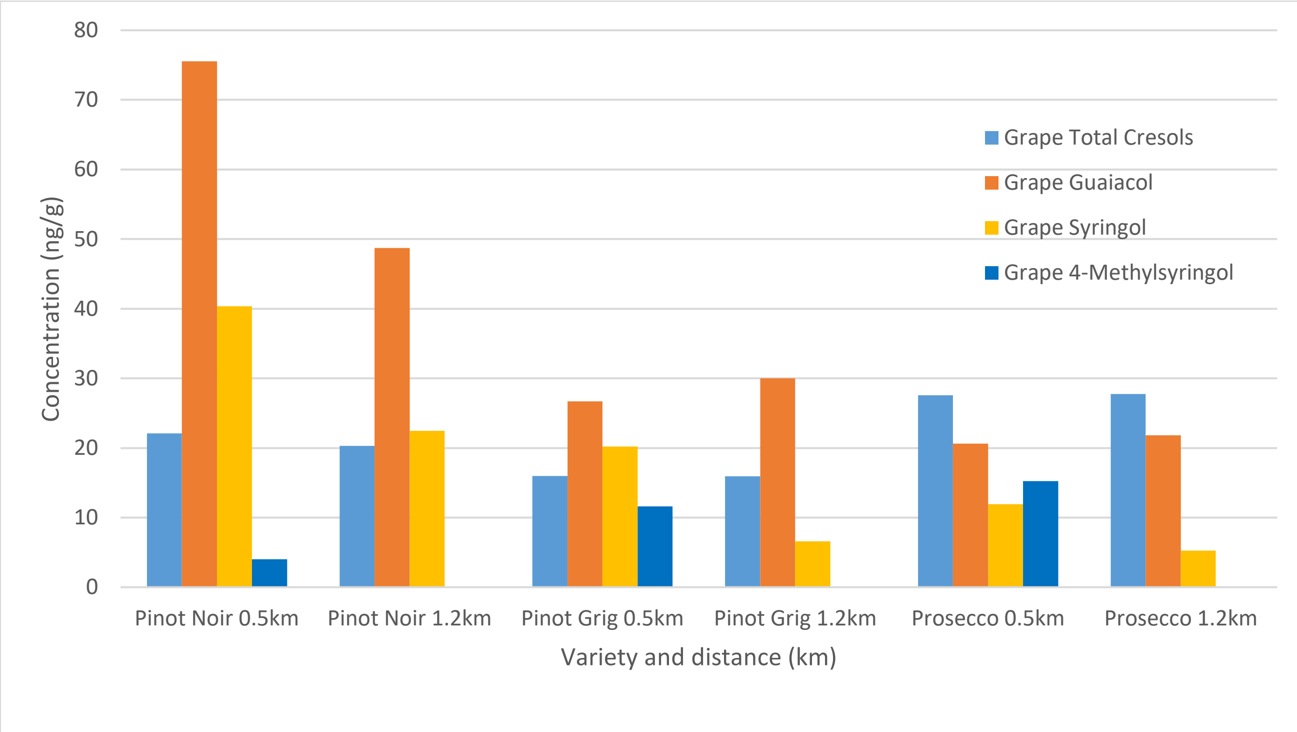

Figure 8. Concentrations of smoke taint compounds and distance from the fire for Pinot Noir, Pinot Grigio and Prosecco grapes sourced from a vineyard affected by smoke from the 2018 Myrrhee-Boggy Creek Road bushfire.

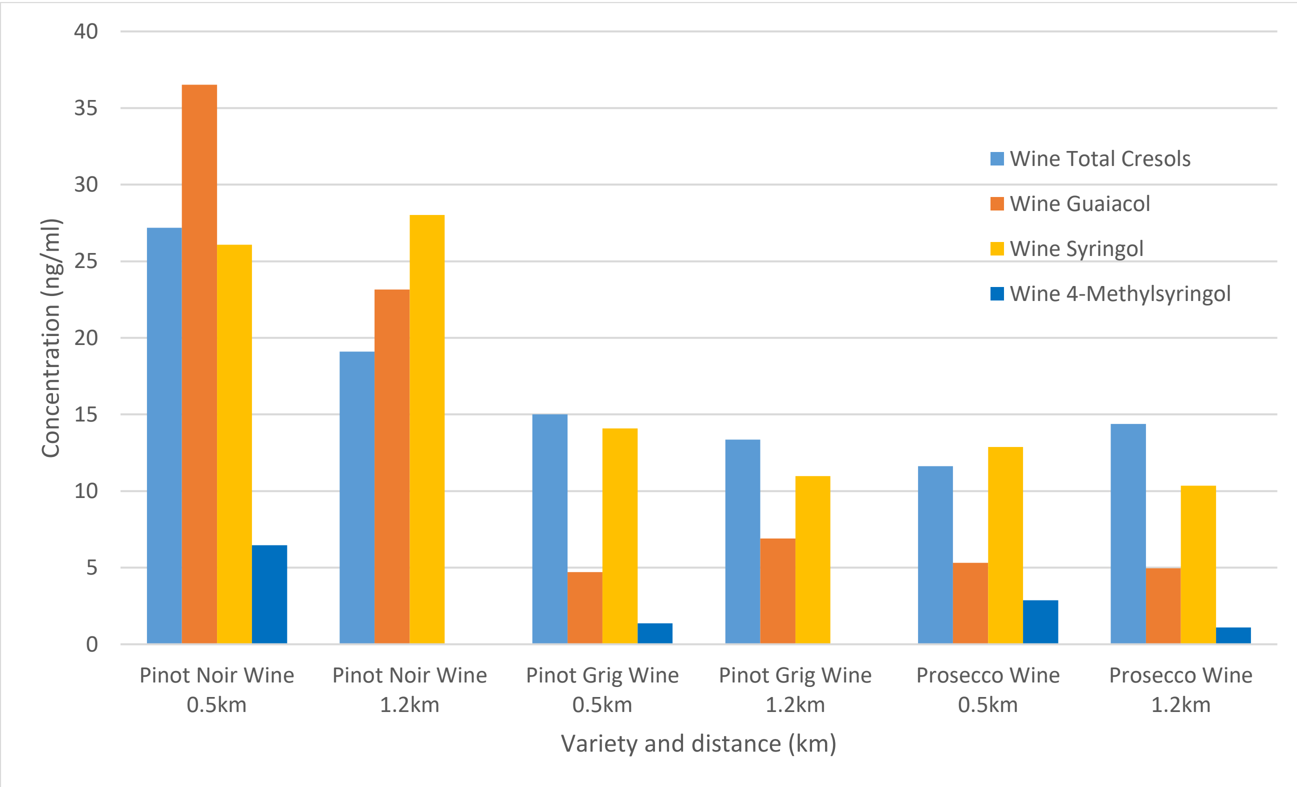

Figure 9. Concentrations of smoke taint compounds and distance from the fire for small-scale wines produced from Pinot Noir, Pinot Grigio and Prosecco grapes sourced from a vineyard affected by smoke from the 2018 Myrrhee-Boggy Creek Road bushfire.

CONCLUSION

This study showed differences in the profile of smoke taint compounds produced from the combustion of different fuels, and that the concentration of smoke taint compounds in smoke decreases dramatically with distance from fires. It also showed the profiles of smoke taint compounds change substantially with distance from a fire, with syringol and 4-methylsyringol concentrations decreasing more quickly than guaiacol, and neither syringol nor 4-methylsyringol were found in air greater than 5 km from controlled burns. At this stage it is possible that 5 km may be a safe distance for vineyards downwind from typical controlled burns conducted in reasonably still climatic conditions in Autumn. This safe distance is being proposed because of the very low concentrations of smoke taint compounds present in the air at this distance, however further studies are required to ensure this threshold is accurate. Our measurements also showed that smoke from bushfires poses a much greater risk than controlled burns, with significant concentrations of smoke taint compounds measured up to 15 km from the 2019 Bunyip bushfire in Victoria.

The profile of smoke taint compounds taken up by grapes and carried into wine was also shown to be similar to the profile of the compounds measured in the smoke. As different smoke taint compounds display different flavours and aromas, differences in smoke composition may lead to differences in the perception of smoke taint in wines. Professional sensory studies will be conducted to develop smoke thresholds that can be used by industry to predict smoke taint. This will be the first time this has been done globally.

RECOMMENDATIONS

Controlled burns should not be conducted less than 5 km upwind of vineyards with grapes on the vine if there is a risk of the smoke staying at ground level.

Sensory analysis of wines is necessary to assess the effect of differing smoke taint compound profiles within the smoke, grapes and wine.

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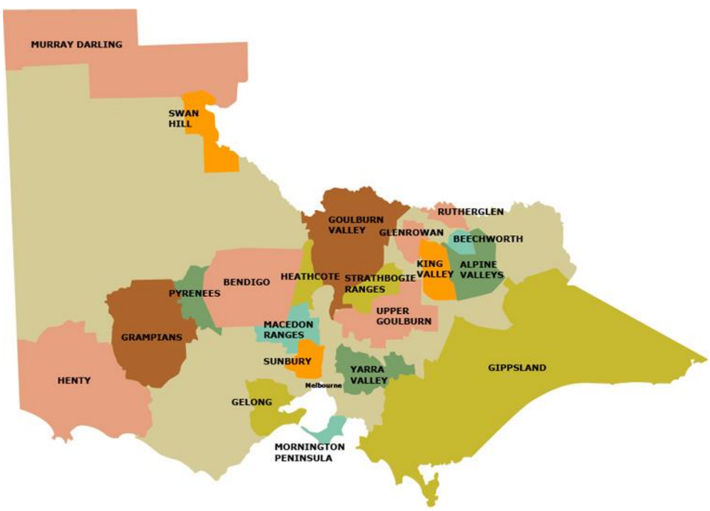
Protocols for fire managers to minimise smoke taint in wine

AGRICULTURE VICTORIA

Controlled burns at any time during the grape growing season may result in the absorption of smoke taint compounds into berries and leaves. The optimum time for prescribed burning is in late summer or early autumn. This coincides with key berry development phases when most grape varieties are very susceptible to smoke taint.

Wine grape production is a valuable industry to Victoria. It provides local employment and supports many regional communities through tourism. The following protocols aim to provide advice to fire managers on how to reduce the risk of berries absorbing smoke from prescribed burns and how to minimize smoke taint compounds in wine.

- Identify and contact vineyards and wineries located close to land where FFMVic or CFA controlled burns are likely to occur.



- Conduct twice-yearly meetings with local and regional wine industry associations (see map) to discuss the current Joint Fuel Management Program (JFMP) for the region.
- Invite growers and industry to raise concerns to FFMVic and CFA over controlled burns when the JFMP is released.
- Encourage growers who are concerned about specific burns to use the Planned Burns Victoria System on the FFMVic website to see when burns are planned and if necessary to set up automatic notification about timing of specific burns.
- Update vineyards and wineries prior to burns so that FFMVic and CFA are informed of seasonal issues that may assist fire managers with planning and undertaking burns. Continued communication may give fire managers the opportunity to burn in other areas or to undertake extra burns due to an early grape harvest.
- Prioritise burns so they occur after harvest in areas considered to be at high risk of contaminating vineyards with smoke taint.
- Avoid conditions which prevent the smoke plume from rising, such as inversion layers and burning late in the day
- Plan to avoid burns creating smoke that immediately drifts into vineyards, as research has shown that fresh smoke poses a much greater risk than older smoke. Research to date has indicated that some smoke taint compounds do not travel more than 5 km from prescribed burns conducted under typical low-wind conditions. This indicates that vineyards >5 km from burns are at relatively low-risk of smoke taint.
- Avoid repeated exposure of a vineyard to smoke during the season as research has also shown that smoke taint has a cumulative effect over time.
- Conduct smoke modelling to estimate smoke dispersion during and after burns.

For more information, please contact, Agriculture Victoria Research on 136186 or Prof Ian Porter at La Trobe University on 1300 528 762

This document is also available in PDF format at http://www.hin.com.au/current-initiatives/smoke-taint-research

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Protocols for vineyard managers to minimise smoke taint from prescribed burns

The optimum time for prescribed burning is in late summer or early autumn. This coincides with key berry development phases when many grape varieties are most susceptible to the absorption of smoke taint. Prescribed burning in winter or spring will reduce the impact on wine production but these burns are less effective and more expensive due to damp undergrowth and low ambient temperatures.

The following protocols aim to provide advice to vineyard managers on how to reduce the risk of berries absorbing smoke from prescribed burns and how to minimize smoke taint compounds in wine.

- Advise local and regional FFMVic and CFA fire management staff of your location, your enterprise, varieties (early and late ripening), anticipated harvest dates, size and contact details. This can be done as an individual or as a regional industry group.
- Conduct a twice-yearly meeting to discuss the current Joint Fuel Management Program (JFMP) for your region (see https://www.ffm.vic.gov.au/bushfire-fuel-and-risk-management/joint-fuel-management-program). The JFMP covers the next 3 years of burns to take place. Information can be given to fire managers to allow planning to take into account any burns near your location.
- Use the Planned Burns Victoria System on the FFMVic website (see https://plannedburns.ffm.vic.gov.au/) to determine when burns are planned and if necessary to set up automatic notification about timing of specific burns.
- Update local and regional FFMVic fire management staff prior to and during harvest to give fire managers the opportunity to burn in other areas or to undertake extra burns in your area due to an early harvest.
- Measure smoke density, timing, duration and composition to determine the risk of berries absorbing smoke taint compounds (see DJPR fact sheet "Measuring smoke intensity and smoke composition in vineyards"). The risk of smoke taint absorption by berries varies during the season (see DJPR fact sheet "Smoke taint risk and management in vineyards").
- Test grapes for smoke taint compounds at an accredited laboratory within two weeks of harverst, such as the Australian Wine Research Institute or Vintessentials. Visit www.awri.com.au or https://www.vintessential.com.au/ for guidelines for assessing vineyards and grapes for smoke taint.
- Minimise the risk during the winemaking process of contamination with smoke taint compounds in leaf and woody tissue by hand harvesting and reducing Matter Other than Grapes (MOG) in the ferment.
- Minimise skin contact time in the fermentation and implement early press cutoff to reduce the extraction of smoke compounds from skins.
- Conduct a mini bench top ferment of smoke affected grapes to produce a small-scale wine when particularly concerned. Send grape and wine sample to the Australian Wine Research Institute or Vintessentials for analysis and interpretation.
- There is evidence that the perception of taint may increase during storage, so it may be wise to market smoke affected wines for earlier consumption.

For more information, please contact Agriculture Victoria Research on 136186, or Prof Ian Porter at La Trobe University on 1300 528 762

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AGRICULTURE VICTORIA

Smoke taint BCA for premium wine grapes in Victoria (cool climate regions)

North East, Central Victoria, Port Phillip and Gippsland wine growing regions
Benefits evaluated over 30 years
Evaluated at farm-gate

manual inputs
stochastic input (calculation)
stochastic output (calculation)

	Totals over 30 years	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Research costs ($m)	1.38	1.38															
Costs for early warning system (EWS) ($m)																	
Up-front investment in field-based smoke detection network		1.0															
On-going network maintenance			0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Total costs		1.0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
PV total EWS costs	5.1	1.00	0.24	0.23	0.22	0.21	0.20	0.19	0.19	0.18	0.17	0.16	0.16	0.15	0.14	0.14	0.13
Production volumes and values																	
Total area of plantings (ha)			11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400
- Yield (t/ha)			5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
- Price ($/t)			1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Gross value ($m)			94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1
Total production (t)			62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700
Assessed bushfire impact in each year																	
- Volumes above sensory threshold with quantitative evaluation (t)			11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74
- Suspect volumes with subjective assessment (relatively high) (t)			1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177
- Suspect volumes with quantitative evaluation (relatively low) (t)			588	588	588	588	588	588	588	588	588	588	588	588	588	588	588
Damages in each year with subjective assessment ($m)																	
- Discard grapes judged above sensory threshold			15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832
- Losses to higher volumes of suspect grapes (50% processed wine downgraded)			3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010
Total damages			18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841
PV damages without EWS and protective spray ($m)	310.9		18.049	17.290	16.563	15.866	15.199	14.560	13.947	13.361	12.799	12.261	11.745	11.251	10.778	10.325	9.890
Protective spray of 'boarder-line' grapes ($m)			0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
PV treatment costs	0.4		0.022	0.021	0.020	0.019	0.019	0.018	0.017	0.016	0.016	0.015	0.014	0.014	0.013	0.013	0.012
Damages in each year with EWS and protective sprays ($m)																	
- Discard grapes above sensory threshold (as above!)			15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832
- Losses to lower volumes of suspect grapes (spraying 50% effective)			1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505
Total damages			17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337
PV damages with EWS and protective spray ($m)	286.1		16.607	15.909	15.240	14.599	13.985	13.397	12.833	12.294	11.777	11.281	10.807	10.352	9.917	9.500	9.100

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Research costs ($m)															
Costs for early warning system (EWS) ($m)															
Up-front investment in field-based smoke detection network															
On-going network maintenance	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Total costs	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
PV total EWS costs	0.13	0.12	0.12	0.11	0.11	0.10	0.10	0.09	0.09	0.09	0.08	0.08	0.08	0.07	0.07
Production volumes and values															
Total area of plantings (ha)	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400	11400
- Yield (t/ha)	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
- Price ($/t)	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Gross value ($m)	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1	94.1
Total production (t)	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700	62700
Assessed bushfire impact in each year															
- Volumes above sensory threshold with quantitative evaluation (t)	11766.744	11766.744	11766.744	11766.744	11766.744	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74	11766.74
- Suspect volumes with subjective assessment (relatively high) (t)	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177	1177
- Suspect volumes with quantitative evaluation (relatively low) (t)	588	588	588	588	588	588	588	588	588	588	588	588	588	588	588
Damages in each year with subjective assessment ($m)															
- Discard grapes judged above sensory threshold	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832
- Losses to higher volumes of suspect grapes (50% processed wine downgraded)	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010	3.010
Total damages	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841	18.841
PV damages without EWS and protective spray ($m)	9.474	9.076	8.694	8.329	7.978	7.643	7.321	7.014	6.719	6.436	6.165	5.906	5.658	5.420	5.192
Protective spray of 'boarder-line' grapes ($m)	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
PV treatment costs	0.012	0.011	0.011	0.010	0.010	0.009	0.009	0.009	0.008	0.008	0.008	0.007	0.007	0.007	0.006
Damages in each year with EWS and protective sprays ($m)															
- Discard grapes above sensory threshold (as above!)	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832	15.832
- Losses to lower volumes of suspect grapes (spraying 50% effective)	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505	1.505
Total damages	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337	17.337
PV damages with EWS and protective spray ($m)	8.718	8.351	8.000	7.663	7.341	7.032	6.737	6.453	6.182	5.922	5.673	5.434	5.206	4.987	4.777

Net benefits to growers	
- additional costs ($m)	6.9
- reduced damages ($m)	24.8
PV net benefits ($m)	31.7
B/C ratio	3.6

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ASSUMPTIONS & DATA ENTRY	**MEAN**	**MIN**	**MAX**	*Comments on assumptions*
Discount rate				
CPI (%)	2.5%			
Nominal discount rate (%)	7.0%			*https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/FlagPost/2018/October/Discount-rates*
Real discount rate (%)	4.4%			
Research costs ($m p.a for 3 years)	0.46			
Investment in field-based smoke detection network ($m)	1.000			*Early warning system adopted by whole industry in year zero*
On-going network maintenance ($m p.a.)	0.25			
Wine grape production				
Area under production (ha)	11400			*http://data.daff.gov.au/data/warehouse/9aas/2013/AustWineGrapesFinAndBusPerf/AustWineGrapesFinAndBusPerf_v1.0.0.pdf*
- Total production (t)	62700			*http://data.daff.gov.au/data/warehouse/9aas/2013/AustWineGrapesFinAndBusPerf/AustWineGrapesFinAndBusPerf_v1.0.0.pdf*
- Yield (t/ha)	5.5	4.0	7.0	*http://data.daff.gov.au/data/warehouse/9aas/2013/AustWineGrapesFinAndBusPerf/AustWineGrapesFinAndBusPerf_v1.0.0.pdf*
Orchard-gate price for premium wine grapes ($/t)	1500	1000	2000	*http://data.daff.gov.au/data/warehouse/9aas/2013/AustWineGrapesFinAndBusPerf/AustWineGrapesFinAndBusPerf_v1.0.0.pdf*
- Wine cost ($/l)	5116			
- multiple	3.4			*see 'value add' worksheet.*
Variable costs ($/ha)				
- Hand harvesting	800			*https://winesvinesanalytics.com/features/article/53452/Moving-Toward-Mechanical*
- Chemicals	50			
Likelihood of damages				*The risk of smoke exposure causing a perceptible taint in wine is a function of the stage of grapevine growth and development, the grapevine variety exposed, smoke concentration, duration of exposure and the volatile phenol concentration and composition of the actual smoke.*
- Portion of crop above threshold for damages in given year	19%			*Say the likelihood of a severe impact (i.e. all grapes above sensory threshold) is 20% in a given year (i.e. low likelihood event). This assumption is based on the frequency of extreme droughts and hence more severe and widespread bushfires*
- Portion of crop boarder-line for damages with quantitative evaluation	0.9%			*Assume 5% error in identifying grapes above threshold with quantitative evaluation*
- Portion of crop boarder-line for damages with subjective evaluation	1.9%			*Assume 10% error in identifying grapes above threshold with subjective evaluation*
Treatment costs (protective spray)				
- Cost (delivered) ($/ha)	1000			
- Application cost ($/ha)	40			
- Number of treatments (sprays)	2.0	1	3	