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Research Article

Impact of Smoke from Wheat, Oat, and Clover Stubble Burning on Cabernet Sauvignon Grapes and Wine

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Background and Aims. Stubble burning is an agricultural practice employed by some grain growers to prepare farmland for sowing and/or to control weeds and pests. Grapegrowers and winemakers have questioned whether the resulting smoke can contaminate grapes in nearby vineyards. This study therefore sought to determine the potential for smoke from three different stubble burns to taint grapes and wine. *Methods and Results*. Excised bunches of mature Cabernet Sauvignon grapes were exposed to smoke from prescribed burning of wheat, oat, and Balansa clover stubble windrows. Environmental sensors monitored the concentration of particulate matter as a measure of smoke density, while chemical and sensory analysis established the extent to which grapes and wine were tainted by smoke. Only grapes that were positioned among the burning wheat windrows or downwind, but in close proximity (~200 m) to the oat stubble burn, were exposed to sufficient quantities of smoke to result in a detectable concentration of volatile phenols (up to 12 μg/kg), as chemical markers of smoke taint. These grapes yielded wines with two to threefold higher volatile phenol concentrations (up to 18 μg/L) than other wines, including the control wine, and low intensity, but perceptible smoke-related sensory attributes, indicative of low-level smoke taint. *Conclusions*. Chemical and sensory analyses suggest the risk of smoke taint from stubble burning is low, except where vineyards are immediately downwind and/or prolonged or repeated smoke exposure occurs. However, stubble moisture content and prevailing weather conditions affect smoke density and dispersion, and will therefore affect the potential for smoke contamination by grapes. *Significance of the Study*. This study will assist colocated grain growers and grape and wine producers to undertake commercial operations, without negatively impacting one another.

1. Introduction

Vineyard exposure to bushfire smoke can lead to "smoke taint" in wine [1–3], i.e., the perception of unpleasant "smoky," "burnt rubber," "cold ash" and "medicinal" aromas and flavours, and a "drying" sensation and/or persistent "ashy" aftertaste [4–6]. Economic losses attributed to smoke taint as a consequence of bushfires, including fires that occurred in South Australia, Victoria, Tasmania, and New South Wales during the 2019/2020 wine grape-growing season, have been estimated at several hundred million dollars [1, 7, 8]. While bushfires are a common source of smoke, and therefore cause of smoke taint, vineyard smoke exposure can also arise from prescribed burns, including stubble burning, a practice employed by grain producers to prepare farmland for sowing and/or to control weeds and pests [9, 10]. Consequently, while broadacre farming occurs near wine regions, grapegrowers and winemakers are questioning the potential for smoke from stubble burning to contaminate unharvested grapes.

Stubble refers to the residual stalks or straw that remains in fields after cereal crops have been harvested [10–12]. Agricultural biomass typically comprises varying amounts of lignin, cellulose, and hemicellulose; e.g., wheat straw contains ~10–25%, ~30–45%, and ~20–45% of these macromolecules, respectively [13]. Thermal degradation of lignin, cellulose, and hemicellulose during combustion of plant material results in the emission of volatile organic compounds [14–16], including volatile phenols (guaiacols, cresols, and syringols) which are currently used as compositional markers of smoke taint in grapes and wine in free and glycosylated (bound) forms [17–24]. Smoke arising from the combustion of stubble would similarly be expected to comprise volatile phenols; hence, while stubble burning occurs prior to the completion of harvest, grapes in nearby vineyards could be vulnerable to smoke exposure.

A recent study investigated the uptake of volatile phenols in excised bunches of Cabernet Sauvignon grapes following exposure to smoke during a pea stubble burn [25]. Chemical and sensory data provided evidence of smoke taint when grapes were positioned among the burning pea stubble windrows, but not when grapes were (~500 m) downwind of the pea paddock. The study concluded that the risk of smoke taint arising from that particular stubble burn was low, due to the rapid dispersion of smoke plumes which resulted in minimal (if any) smoke exposure occurring (at ground level) downwind [25]. This was attributed to the pea stubble burn being undertaken in accordance with guidelines for managing smoke emissions [12, 26]; i.e., dry stubble, raked into windrows, was combusted under favourable prevailing weather conditions, which improved burn efficiency and therefore facilitated smoke dispersion [25].

Previous research has shown that both smoke density and the duration of smoke exposure influence the extent to which grapes are tainted by smoke [25, 27–29]. As such, it is reasonable to expect that where stubble burns are undertaken under suboptimal conditions, e.g., where damp stubble is burned and/or weather conditions are less favourable, more smoke will be produced (due to lower burn temperatures) and/or smoke will linger (due to inadequate dispersion), thereby increasing the risk of smoke exposure (and contamination) of unharvested grapes in nearby (downwind) vineyards. Anecdotal evidence from grain growers also suggests prescribed burning of stubble from different crops might also affect the density of smoke emissions. The current study initially sought to evaluate the potential for grapes to be tainted by smoke arising from prescribed burning of three different stubbles (wheat, oat, and Balansa clover stubble). However, a combination of rainfall the day before stubble burns were carried out and light wind conditions during stubble burning exacerbated smoke emissions and therefore allowed evaluation of the risk of smoke taint arising under suboptimal conditions.

2. Materials and Methods

2.1. Stubble Burn Trials. Field trials involving exposure of excised bunches of Cabernet Sauvignon grapes to smoke from prescribed burning of wheat, oat, and Balansa clover stubble were conducted on a property (Figure 1) located in Hynam (36°56′S, 140°50′E) in the Wrattonbully wine region in South Australia. Prior to burning, the property manager raked the stubble in each of six paddocks into windrows. The paddocks were then burned (in accordance with a fire permit issued by the local council) in succession, starting with the wheat paddocks (burns 1 to 3), followed by the oat paddock (burn 4) and then the clover paddocks (burns 5 and 6), as shown in Figure 1; i.e., all stubble burns occurred on the same day (burn 1 commenced around midday; burn 6 finished after 6 pm). During burns 1, 4, and 6, grape bunches (~15 kg) were suspended on wire frames at two positions: (i) among the stubble windrows (Figure S1) and ~100 m upwind in the oat paddock during burn 1, hereafter "wheat A" and "wheat B," respectively; (ii) ~200 and ~600 m downwind in the wheat paddocks during burn 4, hereafter "oats A" and "oats B," respectively; and (i) in adjacent vineyards during burn 6, hereafter "clover A" and "clover B," respectively. Grapes (6 parcels of fruit, each ~15 kg) were hand-harvested (the afternoon before the stubble burns) from a vineyard located on the same property and stored overnight at ambient temperature, with an additional parcel (~15 kg) harvested during the oat stubble burn as the control. Each fruit parcel comprised bunches remaining after the vineyard had been machine-harvested, and total soluble solids (TSSs) were ~28°Brix (Table S1). Portable environmental sensors (R9 series, Attentis Pty. Ltd., Cheltenham, Vic., Australia) were positioned alongside the excised grape bunches during each burn to record particulate matter concentrations (i.e., $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, being particles that are ≤1, 2.5, and 10 μm in size, respectively) as a measure of smoke emissions. PM concentrations were recorded continuously (at ~1.6 min intervals) and uploaded via Wi-Fi to the manufacturer's network. Environmental data (rainfall, wind speed and direction, temperature, and humidity) recorded on the day of the stubble burn by a weather station located among vineyards on an adjacent property were provided by the vineyard manager. Rainfall data recorded prior to the stubble burn (by a weather station at the Naracoorte Aerodrome, 12.6 km from Hynam) were sourced from the Australian Bureau of Meteorology (https://www.bom.gov.au) [30].

On completion of each stubble burn trial (typically after ~1 hour of smoke exposure), grapes (50 berries, in triplicate, chosen randomly) were sampled and stored on ice (and subsequently frozen) for chemical analysis. The remaining fruit was collected (with bunches from each stubble burn and each location kept separate) and stored overnight (at ambient temperature), together with control fruit, prior to transportation to the University of Adelaide's Waite Campus for small-scale winemaking.

2.2. Winemaking. Parcels of control and smoke-affected grapes were randomly divided into three winemaking replicates (~5 kg per replicate, per treatment), destemmed, and crushed. Prior to inoculation with 300 mg/L of *Saccharomyces cerevisiae* EC1118 (Lalvin, Lallemand Australia, Edwardstown, SA, Australia), 50 mg/L of sulfur dioxide (as a 10% solution of potassium metabisulfite) and 200 mg/L of diammonium phosphate were added, and the pH of must adjusted to 3.5 (with a 20% solution of tartaric acid). Musts were fermented on skins at 25°C, with the caps plunged by hand twice daily. Wines were pressed after 7 days of fermentation and then kept at 25°C until residual sugar was <2 g/L (determined enzymatically). Malolactic fermentation was not performed; instead, wines were cold stabilised at 0°C for 2 weeks. Wines were then racked from total lees, and free SO_2 and pH were adjusted to 30 mg/L and 3.5, respectively. Wine samples were taken for chemical analysis, prior to bottling into 375 mL glass bottles under screw cap.

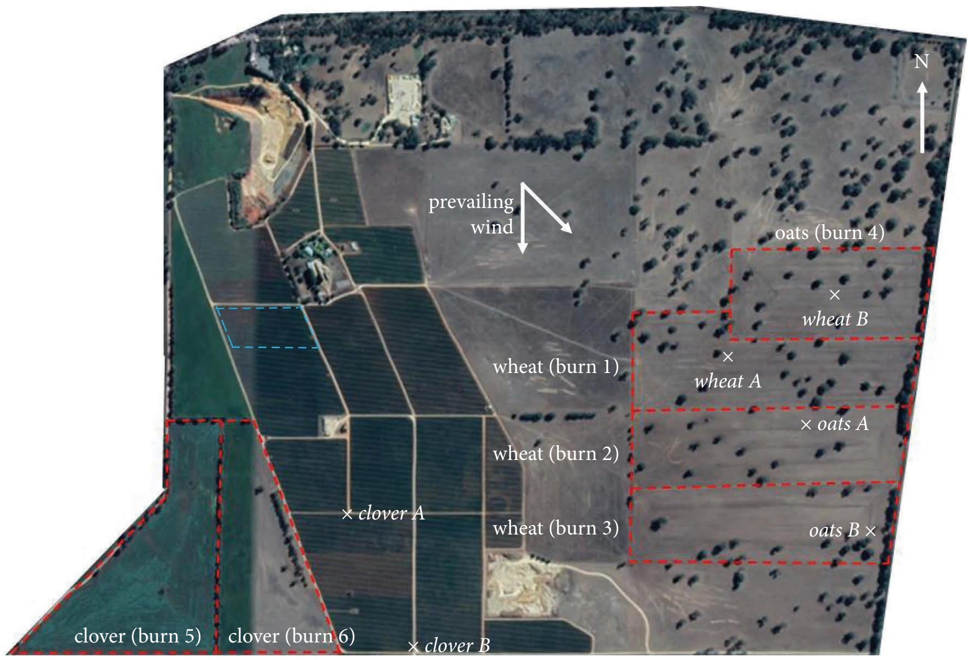


Figure 1: Schematic of the property at which prescribed burning of wheat, oat, and Balansa clover stubble was conducted, showing the location and order of each stubble burn (- - -), the position of excised Cabernet Sauvignon grape bunches and environmental sensors (denoted by ×), and the vineyard from which grapes were harvested (- - -); map sourced from Google Earth, earth.google.com/web/.

2.3. Chemical Analysis of Grapes and Wine. Juice total soluble solids (TSS, expressed as °Brix) and pH were measured (after crushing) using a hand-held digital refractometer (PAL-1, Atago, Tokyo, Japan) and a pH meter (Starter 3100, OHAUS, Port Melbourne, Vic., Australia), respectively. Grape anthocyanins and total phenolics were measured, using published methodology [31]. Basic wine chemistry parameters were determined by the Australian Wine Research Institute's (AWRI) Commercial Services Laboratory (Adelaide, SA, Australia) and comprised: alcohol, residual sugar, pH, titratable acidity (TA, as g/L of tartaric acid), and volatile acidity (VA, as g/L of acetic acid), which were measured using a FOSS WineScan analyser (Mulgrave, Vic., Australia); and red wine colour and total phenolics, measured using the modified Somers method and methyl cellulose precipitable tannin assay [32], respectively. The AWRI's Commercial Services Laboratory also measured: volatile phenol concentrations in grapes and wine using an Agilent 6890 gas chromatograph coupled to a 5973 mass selective detector (Agilent Technologies, Forest Hill, VIC, Australia); and volatile phenol glycoconjugates in grapes and wine using an Agilent 1200 high-performance liquid chromatograph equipped with a 1290 binary pump coupled to an AB SCIEX Triple Quad™ 4500 tandem mass spectrometer, with a Turbo VTM ion source (Framingham, MA, USA); in each case using published stable isotope dilution assay methods [18, 20, 33]. These publications report the preparation of internal standards (d_3-guaiacol, d_3-4-methylguaiacol, d_7-*o*-cresol, and d_3-syringol for GC-MS analysis and d_3-syringol gentiobioside for HPLC-MS/MS analysis), method validation, and instrumental operating conditions.

2.4. Sensory Analysis of Wine. Sensory evaluations were performed in a purpose-built sensory laboratory under controlled conditions. Control and smoke-affected wine replicates were initially assessed by a panel of three experienced wine researchers from the University of Adelaide to confirm there were no wine faults or obvious differences between replicates. Replicates were then blended, and wine sensory profiles were determined using the rate-all-that-apply (RATA) method [34, 35] and a panel comprising staff and students from the University of Adelaide and the Australian Wine Research Institute, and regular wine consumers ($n = 48$, 12 male and 36 female, aged between 20 and 68 years). Panellists were given a brief induction about the RATA procedure, including the importance of thoroughly rinsing the palate and resting (for at least 1 min) between samples. Wines (30 mL) were then presented monadically in covered, 4-digit coded 215 mL stemmed glasses, using a randomised order across judges. Panellists rated the intensity of 19 aroma, flavour, taste, and mouthfeel attributes adapted from previous smoke taint studies [6, 29] using 7 point scales (where 0 = "not perceived," 1 = "extremely low," and 7 = "extremely high"). Between samples, panellists rested for at least 1 min, with water and plain crackers provided as palate cleansers. Data were acquired with Red Jade software (Redwood Shores, CA, USA). Sensory panellists gave informed consent before participating in the study, which was approved by the Human Research Ethics Committee of the University of Adelaide (Ethics Approval No. H-2019-095).

2.5. Statistical Analysis. Chemical data were analysed by the one-way analysis of variance (ANOVA) using GenStat (19th Edition, VSN International Limited, Herts, UK). Sensory data were analysed by two-way ANOVA using participants as a random factor and wines as a fixed factor, with Fischer's LSD post hoc test ($P \leq 0.05$), to determine significant differences between wines, using XLSTAT (version 2021.3.1, Addinsoft, New York, NY, USA). Principal component analysis (PCA) of sensory data was performed using XLSTAT, with volatile phenol data overlaid.

3. Results and Discussion

3.1. Prevailing Weather Conditions. During the stubble burn trials, the prevailing weather conditions were mild (Figure 2). Between 12 and 6 pm, ambient air temperature ranged from 11.8 to 14.3°C, wind speed was <1 km/h, and wind gusts fluctuated between 12.3 and 21.9 km/h (averaging 17.2 km/h), from the north to northwest (Figure 1). Humidity was from 54.4 to 67.9%. No rainfall was recorded on the day of the stubble burn, but 8.6 mm was recorded on the preceding day (by a weather station at the Naracoorte Aerodrome [30]). As such, stubble was not dry.

The weather conditions (especially the low wind speed) and combustion of damp stubble likely contributed to the observed density of smoke and PM emissions (Figure 3). Prior to commencement of stubble burning, background PM concentrations were <50 μg/m^3. The PM levels recorded by the sensor positioned among the wheat windrows remained low during the first ~25 min of the wheat stubble burn, because downwind windrows were ignited first. However, elevated PM concentrations were recorded soon after ignition of windrows that were upwind of the sensor (Figure 3(a)). PM_{10} and $PM_{2.5}$ concentrations averaged 472 and 319 μg/m^3, respectively, while fruit was deployed, with concentrations up to 882 and 645 μg/m^3 being recorded; $PM_{1.0}$ concentrations were <150 μg/m^3. As a consequence, fruit positioned among the wheat windrows was exposed to smoke for ~90 min. In contrast, with the exception of one data point, PM concentrations recorded by the sensor upwind of the wheat stubble burn (i.e., in the oat paddock) remained <20 μg/m^3 (Figure 3(b)), indicating grapes deployed at this position were not exposed to smoke.

Elevated PM concentrations were also recorded during the oat stubble burn (Figures 3(c) and 3(d)). The sensor located ~200 m downwind from the oat paddock recorded much higher PM concentrations, being 56–1207 and 38–885 μg/m^3 for PM_{10} and $PM_{2.5}$, respectively (and 625 and 432 μg/m^3, on average), than the sensor located ~600 m downwind, which recorded PM_{10} and $PM_{2.5}$ concentrations of 9–369 and 4–328 μg/m^3, respectively (and 102 and 85 μg/m^3, on average). $PM_{1.0}$ concentrations of <92 and 45 μg/m^3 were recorded at these positions. These results indicate smoke emissions from the oat stubble burn were higher (i.e., more dense) than those from the wheat stubble burn, but that smoke dispersed as it moved downwind. As such, the grapes deployed during the oat stubble burn were exposed to smoke of different densities, reflecting their proximity to the burn. This is notable, given smoke density influences the uptake of volatile phenols by grapes, and thus, the extent to which smoke taint can subsequently be perceived in wine [25, 29].

The positioning of sensors (and grapes) during the Balansa clover burn was constrained by vineyard plantings and the property boundary. Sensors and grapes were deployed between vineyard blocks east of the clover paddocks (Figure 1), and the presence of smoke was apparent from PM measurements (Figures 3(e) and 3(f)); however, smoke density may have been higher further to the south (i.e., within the direct trajectory of smoke). Nevertheless, the sensors recorded PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ concentrations of 9–1101, 3–885, and 1–201 μg/m^3, respectively (97, 74 and 29 μg/m^3, on average) for clover A and 7–512, 3–444 and 1–173 μg/m^3, respectively (103, 82 and 38 μg/m^3, on average) for clover B. Differences in PM concentrations recorded at clover A vs. clover B likely reflect the relative proximity of each position: to the clover paddock, hence the highest PM concentrations were measured at clover A; and to the smoke trajectory, hence the highest overall PM concentrations were measured at clover B. Smoke emissions measured at these positions were far lower (i.e., less dense) than those recorded among the wheat windrows (wheat A) and ~200 m downwind of the oat stubble burn (oat A), but comparable to or lower than those recorded ~600 m downwind of the oat stubble burn (oat B).

Substantially, higher PM levels were reported during the aforementioned pea stubble burn [25] than those recorded in the current study. Among the burning pea stubble windrows, PM_{10} concentrations exceeded 2000 μg/m^3 [25], but only briefly (i.e., for ~5 min), because combustion of well-cured stubble established convective heat columns that achieved vertical dispersion of smoke plumes (Figure 4(a)). In the current study, combustion of damp stubble, coupled with mild prevailing conditions (i.e., wind speeds of <1 km/hr, Figure 2), resulted in smoke plumes being carried laterally (Figure 4(b)), which prolonged smoke exposure.

3.2. Grape and Wine Composition. At harvest, Cabernet Sauvignon grapes comprised TSS ranging from 27.6 to 28.6°Brix, resulting in wines with alcohol concentrations from 15.0 to 16.0% alcohol by volume (abv) (Table S1). The observed variation in fruit maturity, which also resulted in significant differences in grape pH and total phenolics, and wine acidity, colour, and total phenolics (Table S1), reflects the use of fruit remaining after commercial harvest; i.e., fruit sampled from the ends of rows may have been slightly riper than fruit sampled midrow. The increased maturity of control grapes may also reflect this fruit parcel being harvested a day later than other fruit parcels. The observed variation in grape and wine chemistry may have been avoided had fruit been randomised prior to the stubble burn trials, but logistically, this was not practical.

Volatile phenols were measured in grapes and wine as compositional markers of smoke taint (Table 1). In grapes, detectable levels of volatile phenols (i.e., ≥1 μg/kg) were only observed in fruit positioned among the wheat stubble windrows (at wheat A) or ~200 m downwind from the oat

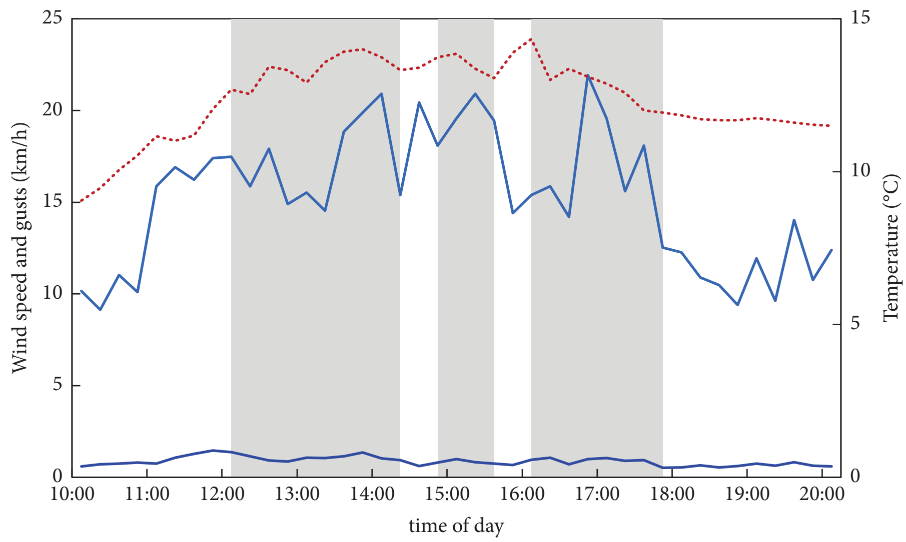


Figure 2: Wind speed (—), gusts (—), and ambient temperature (····) before, during (shaded), and after prescribed burning of wheat, oat, and Balansa clover stubble.

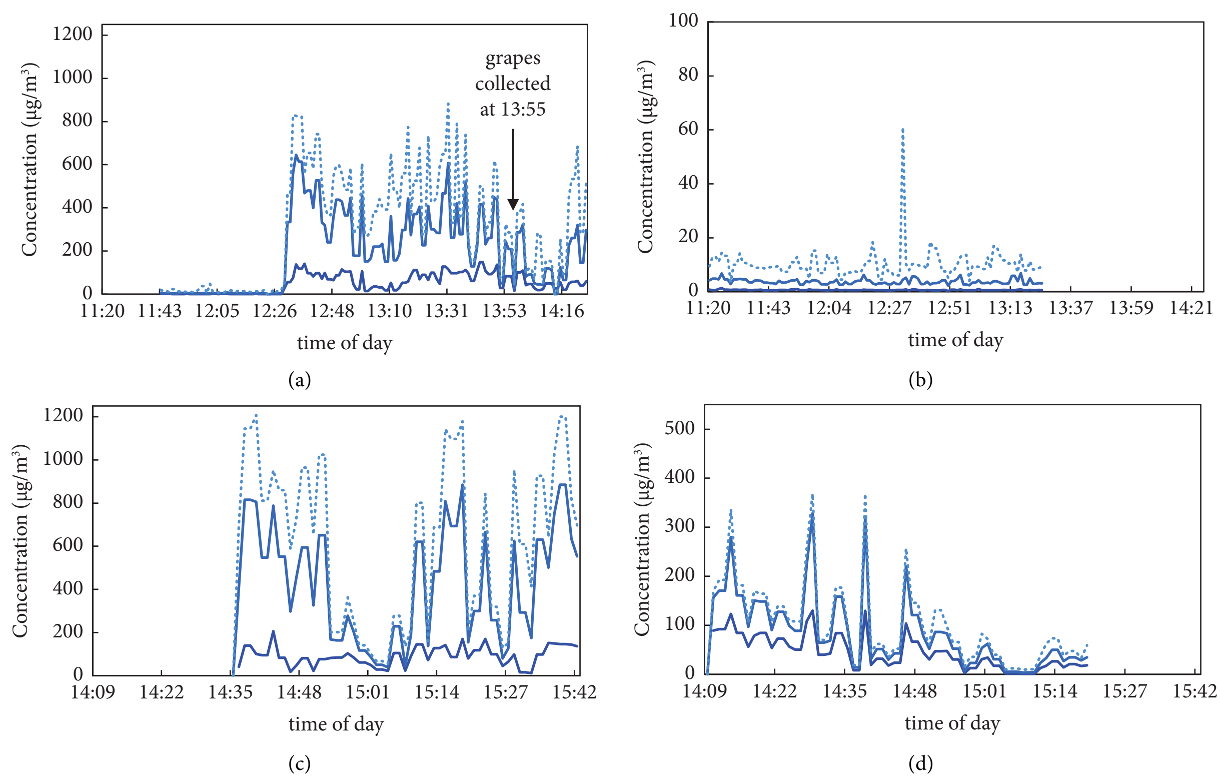
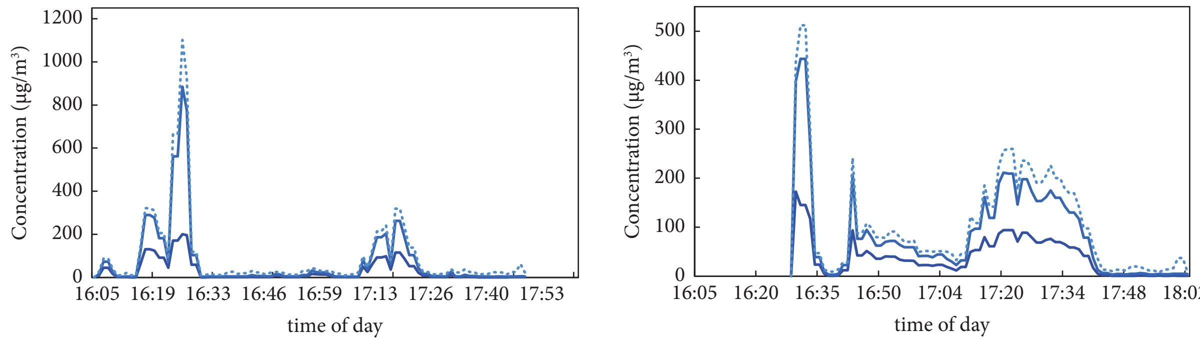


Figure 3: Continued.



(e) (f)

Figure 3: Concentrations of particulate matter (— $PM_{1.0}$, — $PM_{2.5}$, and ···· PM_{10}) measured during prescribed burning of (a, b) wheat, (c, d) oat, and (e, f) Balansa clover stubble; (a–f) PM data recorded by using sensors positioned at wheat A, wheat B, oat A, oat B, clover A, and clover B, respectively.

(a)

(b)

Figure 4: Vertical vs. lateral dispersion of smoke during prescribed burning of (a) pea stubble [25] and (b) oat stubble.

paddock (at oats A), being the positions at which the environmental sensors recorded the highest PM concentrations (Figure 3). Syringol was the most abundant volatile phenol (at 10.0 and 11.7 μg/kg for grapes at wheat A and oats A, respectively), in agreement with previous studies [25, 29], while guaiacol, 4-methylguaiacol, cresols, and 4-methylsyringol were only detected at up to 3.7 μg/kg (Table 1). Wheat A grapes had slightly higher concentrations of guaiacol, 4-methylguaiacol, syringol, and 4-methylsyringol than oats A grapes, which might suggest increased smoke contamination. This likely reflects the relative durations of smoke exposure, i.e., fruit was deployed for ~89 min during the wheat stubble burn vs. ~67 min during the oat stubble burn, rather than smoke density, which, based on averaged PM concentrations, was higher at oats A than at wheat B (Figure 3).

Table 1: Concentration of volatile phenols in control and smoke-affected grapes (μg/kg) and wine (μg/L).

		Guaiacol	4-Methylguaiacol	*o*-Cresol	*m*-Cresol	*p*-Cresol	Syringol	4-Methylsyringol
Grapes	Control	n.d	n.d	n.d	n.d	n.d	n.d	n.d
	Wheat A	3.7 ± 0.58 a	1.0 ± 0.01	2.0 ± 0.01	2.0 ± 0.01	n.d	11.7 ± 0.6 a	3.0 ± 0.01
	Wheat B	n.d	n.d	n.d	n.d	n.d	n.d	n.d
	Oats A	3.0 ± 0.01 b	n.d	1.0 ± 0.01	1.7 ± 0.58	n.d	10.0 ± 1.0 b	n.d
	Oats B	n.d	n.d	n.d	n.d	n.d	n.d	n.d
	Clover A	n.d	n.d	n.d	n.d	n.d	n.d	n.d
	Clover B	n.d	n.d	n.d	n.d	n.d	n.d	n.d
	P	<0.001	n.a	n.s	n.s	n.a	<0.001	n.a
Wine	Control	1.0 ± 0.01 d	n.d	n.d	n.d	n.d	6.3 ± 0.58 c	n.d
	Wheat A	3.0 ± 0.01 b	n.d	2.0 ± 0.01	1.3 ± 0.58	n.d	12.3 ± 0.6 b	3.0 ± 0.6
	Wheat B	1.0 ± 0.01 d	n.d	n.d	n.d	n.d	6.0 ± 0.01 c	n.d
	Oats A	3.7 ± 0.58 a	n.d	2.0 ± 0.01	1.7 ± 0.58	n.d	18.0 ± 1.7 a	2.7 ± 0.6
	Oats B	1.3 ± 0.58 d	n.d	n.d	n.d	n.d	6.7 ± 1.15 c	n.d
	Clover A	1.0 ± 0.01 d	n.d	n.d	n.d	n.d	7.7 ± 0.58 c	n.d
	Clover B	1.7 ± 0.58 c	n.d	n.d	n.d	n.d	7.3 ± 0.58 c	n.d
	P	<0.001	n.a	n.s	n.s	n.a	<0.001	n.s

Values are means of three replicates ($n = 3$) ± standard deviation; n.d, not detected. Different letters (within columns) indicate statistical significance ($P = 0.05$); n.a., not applicable; n.s., not significant. Smoke exposure occurred during prescribed burning of wheat, oat, and clover stubble; A and B denote the relative position of excised bunches of Cabernet Sauvignon grapes during each stubble burn.

The absence of detectable volatile phenols in fruit deployed at oats B, clover A, and clover B (Table 1), despite PM monitoring confirming the presence of smoke at each of these positions (Figure 3), suggests smoke density was not sufficient to cause any contamination. This was further supported by wine volatile phenol data (Table 1). Control wine contained 1 μg/L of guaiacol and 6.3 μg/L of syringol, whereas other volatile phenols were not detected. Wines corresponding to oats B, clover A, and clover B had comparable volatile phenol concentrations, with one exception: the oats B wine contained 1.7 μg/L of guaiacol, being a small, but statistically significant increase in concentration. As expected given wheat B grapes were upwind of the stubble burns, the volatile phenol content of wheat B wine was also equivalent to that of the control wine. In contrast, wheat A and oats A wines had significantly elevated concentrations of guaiacol, *o*- and *m*-cresols, syringol, and 4-methylsyringol (Table 1), with syringol again being the most abundant volatile phenol, at 12.3 and 18.0 μg/L, respectively. Interestingly, whereas wheat A grapes had higher volatile phenol levels than oats A grapes, the oats A wine had higher guaiacol and syringol concentrations than the wheat A wine. While these results provide compositional evidence of smoke contamination, it is worth noting that the volatile phenol concentrations observed in wheat A and oats A wines were comparable to those reported in previous studies, for wines that were not perceived to be smoke tainted [25, 29]. Nevertheless, the wheat A and oats A wines did contain several-fold higher volatile phenol concentrations than wines made from grapes exposed to smoke during the pea stubble burn [25]. This suggests the risk of smoke contamination does increase when prescribed burning occurs under suboptimal conditions.

Grape and wine volatile phenol glycoconjugates were also measured, but as expected given the limited time for glycosylation (i.e., <48 hours lapsed between smoke exposure and fermentation), few were detected, and none occurred at concentrations above 8 μg/kg for grapes or 10 μg/L for wine (Table S2). In grapes, small (i.e., <1 μg/kg) but significant differences were observed for 4-methylguaiacol rutinoside and syringol gentiobioside; however, no differences were observed for total grape volatile phenol glycoconjugates. In wine, modest concentration increases (i.e., <14 μg/L) were observed for the total glycoconjugates of several volatile phenols, typically for wheat A and oats A wines (relative to other wines), demonstrating some glycosylation of smoke-derived volatile phenols occurred in fruit between smoke exposure and fermentation.

3.3. Wine Sensory Profiles. Sensory analysis results showed good agreement with PM and volatile phenol data. The control wine and wines corresponding to wheat B, oats B, clover A, and clover B were characterised by fruit aromas and flavours, with comparable intensity ratings for acidity, astringency, and a drying aftertaste (Table S3). Wines made from grapes deployed at wheat A and oats A were perceived to exhibit the most intense smoke, cold ash, and burnt rubber aromas, smoky and burnt rubber flavours, and ashy aftertaste, with the oats A wine also having slightly diminished fruit expression, relative to other wines (Table S3). Although statistically significant differences were observed among several basic wine compositional parameters, including alcohol content, pH, TA, and total phenolics (Table S1), the sensory panel did not perceive significant differences in the acidity, bitterness, hotness, drying aftertaste, or astringency of wines (Table S3).

Principal component analysis (PCA) of wine sensory data (overlaid with wine volatile phenol data) showed clear separation of wheat A and oats A wines from the other wines (Figure 5). The first principal component explained 62.9% of variation and separated wines according to the intensity of cold ash and burnt rubber aroma, smoky and burn rubber flavour, and volatile phenol concentrations. The second principal

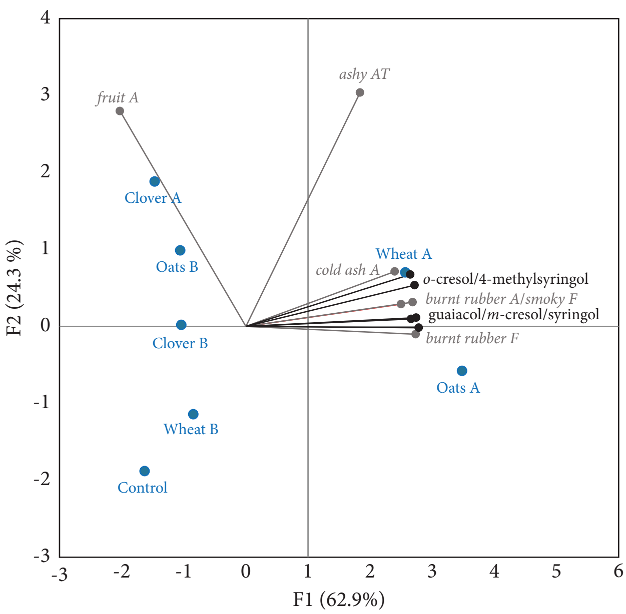


Figure 5: Principal component analysis biplot of sensory attribute ratings (overlaid with volatile phenol concentrations) for wines made from control grapes and grapes deployed during prescribed burning of wheat, oat, and Balansa clover stubble. A, aroma; AT, aftertaste; F, flavour.

component explained a further 24.3% of variation, primarily reflecting the intensity of fruit aroma and ashy aftertaste. The positioning of wheat A and oats A wines on the right side of the PCA biplot, with the remaining wines on the left side (Figure 5), provides further evidence that wines made from grapes deployed further away from the stubble burns (i.e., at oats B, clover A, and clover B) were not exposed to smoke of sufficient density, for a sufficient duration of time, to impart a perceptible smoke taint. Nevertheless, it is worth noting that although chemical and sensory data confirm grapes positioned at wheat A and oats A (and therefore, their corresponding wines) were tainted by smoke, the extent to which they were tainted was low, especially when compared with chemical and sensory data reported for smoke-tainted wines in other studies [6, 24, 29]. In the current study, grape bunches were deployed for ~1 hour, whereas cumulatively, the stubble burns occurred over several hours. As such, it is reasonable to expect that had fruit been deployed for the duration of the stubble burns, and within the direct trajectory of smoke in the case of the clover stubble burn, greater smoke exposure, and thus contamination, may have occurred. As such, had vineyards been located immediately downwind of stubble burns, there may have been some risk of a low, but perceptible level of smoke taint occurring in unharvested grapes. The risk and perceived intensity of smoke taint should decrease as smoke disperses, i.e., as a function of distance from the smoke source. Importantly, any risk of smoke taint would also be alleviated by burning dry stubble, in part, because dry stubble would burn rather than smoulder, yielding less dense smoke, but the increased burn temperatures would also assist vertical smoke dispersion via heat convection. Burning under moderately windy conditions would also be expected to improve smoke dispersion.

4. Conclusions

The potential for grapes to be tainted by smoke from stubble burning depends on both the density of smoke and the duration of smoke exposure. Combustion of windrows comprising dry stubble improves burn temperature and efficiency, thereby mitigating the propensity for stubble to smoulder (increasing particulate emissions) rather than burn, as well as establishing convective heat columns that facilitate vertical smoke dispersion. The prevailing weather conditions also affect smoke production and dispersion; stubble is more likely to smoulder under cool, still, and humid conditions, whereas moderately windy conditions will assist smoke dispersion.

In the current study, combustion of damp stubble coupled with light wind conditions generated smoke plumes that were carried laterally (i.e., close to the ground), such that elevated PM levels (~800–1200 $\mu g/m^3$ for PM_{10}) were recorded among burning wheat windrows and ~200 m downwind from the oat stubble burn. Grapes deployed at these locations were exposed to sufficient quantities of smoke that resulting wines contained detectable levels of volatile phenols and perceptible smoke-related sensory characters, which provided evidence of low-level smoke taint. The composition and sensory profiles of wines made from grapes that were either upwind, some distance downwind, or not in the direct trajectory of smoke from stubble burns were comparable to those of the control wine. This suggests that with sufficient dispersion of smoke, the risk of grapes being tainted significantly diminishes.

Where policy guidelines/codes of practice for managing smoke emissions are followed (especially the combustion of dry stubble), and vineyards are not located immediately downwind, the risk of smoke contamination by grapes is considered to be low. Nevertheless, repeated and/or prolonged smoke exposure may arise where prescribed burning is widespread (i.e., where stubble burns occurs on multiple properties in succession), and this could increase the potential for smoke taint to occur. Grain growers undertaking stubble burning also need to be aware of the weather conditions that lead to temperature inversions, a phenomenon during which warm air covers cooler air, which can trap smoke in low-lying areas, preventing dispersion and thus, potentially increasing the risk of prolonged smoke exposure to any nearby vineyards.

Beyond consideration of combustion efficiency (i.e., stubble moisture content), the area to be burned, and the prevailing weather conditions, there is little that can be done to further mitigate smoke emissions from prescribed burns. Landowners could consider alternative practices to stubble burning, which would also alleviate potential health and environmental impacts, but in some cases, burning is still considered best practice. While stubble burning is deemed to be necessary, communication with local councils, neighbouring landowners, wine industry associations, and/or the Country Fire Service is essential to ensure the risk of smoke taint to unharvested grapes is minimised. In this way, it should be possible for the grains and wine industries to work together to negate untended impacts of each industry's activities on the other.

Data Availability

The data used to support the findings of this study are included within the article and the supplementary information file.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

The following data are provided as supplementary material: Table S1: Basic composition of control and smoke-affected Cabernet Sauvignon grapes and wine. Table S2: Concentration of volatile phenol glycoconjugates in control and smoke-affected Cabernet Sauvignon grapes (μg/kg) and wine (μg/L). Table S3: Mean intensity ratings for the sensory attributes of control and smoke-affected Cabernet Sauvignon wine. Figure S1: Grape bunches (suspended on wire frames) deployed alongside environmental sensors (a) among the wheat stubble windrows (i.e., at wheat A) and (b) ~100 m upwind in the oat paddock (i.e., at wheat B). (*Supplementary Materials*)

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